Tensiometer-Controlled Medium Frequency Topsoil Irrigation: A Technique to Improve Agricultural Water Management

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Abstract

An improved irrigation management technique was found to prevent over-irrigation and under-irrigation, thus decreasing the long term danger of waterlogging and salinisation of irrigated soils, and promoting the highest yield per unit water during short term scarcity.

The management technique consisted of keeping the soil moisture in the top 0–0,45 m layer at a high water potential and the moisture in the subsoil at a low water potential, except during pre-planting irrigation. This was achieved by medium frequency irrigation dependent on different tensiometer threshold readings for the topsoil and the subsoil.

The technique was tested and found to have operated well on citrus under drip irrigation at Zebediela, on wheat under sprinkler and drip irrigation at Groblersdal and on wheat and soybeans under drip and microjet irrigation near Pretoria.

Because of the rather accurate water application under this management technique the tensiometer readings were also used to calculate water usage and seasonal range of evapotranspiration/pan evaporation ratios of the abovementioned crops. These figures may be used for irrigation planning, but for daily management they should only be used in combination with tensiometers.

1. Introduction

For centuries agricultural crops have been irrigated to obtain more constant and higher yields than have been possible with natural rainfall. However, prolonged irrigation often induced saline conditions in soil, resulting in the decline of crop yields and often in total production loss. The cause of the salinisation was very often *over-irrigation* or *under-irrigation*.

Over-irrigation causes a high ground water table on a poorly permeable layer in the subsoil. The ground water and salts move upward by capillary action and after consumption and evaporation of the soil moisture, the salts remain and accumulate on the soil surface and in the topsoil.

With under-irrigation the water infiltrates only into the topsoil and over the years the salts in the irrigation water accumulate there. Examples of over-irrigation can be found on the Vaalharts Government Water Scheme (Streutker, 1977) and commonly on irrigated lands along rivers. Examples of under-irrigation are scarce, but sometimes found under drip irrigation (Streutker, 1974).

Salinisation due to over-irrigation can be prevented by leaching the accumulated salts out of the root zone and removing them from the soil profile through artificial or natural drainage systems. In the case of under-irrigation leaching can be accomplished only by natural rainfall. In both cases, however, the cause of salinisation is not eliminated, viz. insufficient control of water application. Inefficient control and resulting inefficient water usage can be found under most irrigation systems, such as flood, sprinkler and micro irrigation.

The efficiency of water application is determined by the design and daily management of the irrigation system. A possible difference between the water discharge at the head and at the tail-end of the system can be diminished by changing the system itself. On the other hand it is also possible to decrease differences in water discharge by means of more flexible management of the system, e.g. by employing different irrigation times and irrigation frequencies at different discharge points. Today such intensive management, by means of many necessary man-hours for a semi-permanent system or by means of expensive automation of a permanent system, might appear not to be economically feasible for some crops. One has to bear in mind, however, that a decreasing water supply in the long term or a sudden water scarcity due to drought in the short term, both followed by a drop in food production, must necessarily change the economic criteria in such a way that intensive management, to obtain a higher efficiency of water usage, is made possible. In such a case the correct intensive management procedures ought to be known for immediate application.

From the foregoing it follows that in the long term waterlogging and salinisation of soil can be prevented so that permanent crop production may be maintained, and that during short term scarcities of water (and food) the highest crop yield per unit water can be obtained provided that efficiency of water application and management of the irrigation system are maximised.

This paper describes how over-irrigation was prevented by

Finally, a series of pilot-scale experiments using raw sewage sludge and raw domestic refuse are in progress. Owing to the long period required for the *Ascaris* ova viability test, the results will only be available at a later stage.

These results form the basis for the suggestion that a maturation period of at least seventy days must be adhered to during the manufacture of sludge-enriched compost utilising a weekly turning and watering. Routine investigations into the incidence of viable ova in fifty six days old compost from plants using sewage sludge or humus tank effluent, regularly showed the presence of viable ova (Steer and Nell, 1976). This confirms the findings that maturation should continue for at least seventy days.

The inability of mechanized plants to eliminate ova according to the predictions of laboratory experiments is probably due to insufficient mixing and watering during maturation as well as irregular temperature distribution in the non-homogenous compost during pre-fermentation and maturation. More regular turning and watering of windrows may reduce the time required for *Ascaris* ova elimination to only fourteen days (Nell and Steer, 1976). Similarly, efficient temperature distribution in liquid sewage sludge during pasteurisation at 70°C for only thirty minutes inactivated all viable *Ascaris* ova (Nell and Steer, 1975).

Conclusions

The period of windrow maturation should be maintained for at least seventy days to ensure *Ascaris* ova inactivation, provided that temperatures of ⩾65°C are generated. The turning and watering of windrows should be undertaken at least once a week throughout the whole of the maturation process.

The use of humus tank effluent for moisture control during maturation should be avoided since the time available for inactivation of *Ascaris* ova introduced by this source may be insufficient.

Acknowledgements

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improving the daily management of sprinkler, microjet and drip irrigation. It demonstrates how proper irrigation management in five case studies was assisted by tensiometers which controlled the use of high to medium frequency water application. Moreover, it shows how crop water usage and evapotranspiration/pan evaporation ratios changed favourably because of improved water management.

2. Theory

Over-irrigation means that an excess quantity of the irrigation water given drains out of the root zone and disappears into the subsoil. Although in general over-irrigation is unknown in quantity, it can, in some cases be measured, e.g. by means of the increased discharge of a subsurface drain after irrigation or by means of the outflow from a lysimeter. However, over-irrigation or water movement in the soil can also be calculated using Darcy's law which states that V = K.I, *viz.* the velocity of moisture movement between two points (V in mm/day or mm/d) is the product of the hydraulic conductivity (saturated or unsaturated) of the soil (K in mm^2/kPa) and the gradient of the water potential between both points (I in kPa/mm). The total water potential gradient (∅) between a point at a depth of 0,9 m and another point at a depth of 1,2 m below the soil surface can be obtained from the matric potential values (ψ) of two tensiometers and from the gravitational potential (H) at both depths respectively. The hydraulic conductivity can be derived from the K − ψ curve of the 0,9 − 1,2 m soil layer.

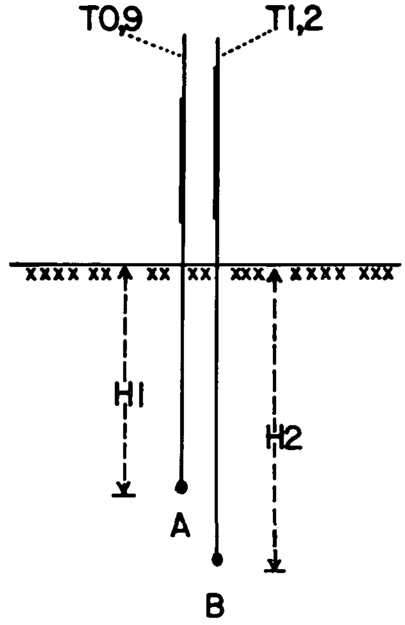

Figure 1
The total water potential gradient between two points A and B can be obtained from the matric potential values of two tensiometers at A and B, and from the gravitational potential (H) or the depth of each point

2.1 Example

The depth of the porcelain cup of the tensiometer $T_{0,9}$ is 900 mm and of $T_{1,2}$ is 1 200 mm. The gravitational potential of water at point A is therefore $H_1 \cong -9$ kPa and at point B it is $H_2 \cong -12$ kPa. When it is known that the matric potentials of water at point A and point B, or the respective tensiometer readings ψ, are $T_{0,9} = -12$ kPa and $T_{1,2} = -11$ kPa (see also Fig. 6.1; 8 − 19 Sept.), then:

$$I = \frac{\phi A - \phi B}{A - B} = \frac{(\psi 0{,}9 + H_1) - (\psi 1{,}2 + H_2)}{A - B}$$

$$= \frac{(-12 + -9) - (-11 + -12)}{-900 - (-1200)}$$

$$= \frac{-21 + 23}{+300} = 0{,}0067 \downarrow \text{kPa/mm}$$

On the K-ψ curve (see Fig. 5, Z-curve), a K-value is found for $\psi = (-12 + -11)/2$ of 250 mm^2/kPa. d, so V = 0,0067 kPa/mm × 250 mm^2/kPa. d = 1,67 mm/d. When daily 5 mm water (per unit area) is applied to a crop by means of a permanent system, and 1,67 mm water disappears beneath a depth of 0,9 m, an over-irrigation of 33% of the total quantity of irrigation water occurs.

Suppose the manager of the irrigation system continues to irrigate at a rate of 5 mm/d, but changes the application rate, the duration and the frequency of irrigation in such a way that $T_{0,9} = -26{,}7$ kPa and $T_{1,2} = -25{,}5$ kPa (see Fig. 6.6; 8 − 19 Sept.), then in accordance with the above calculation I = 0,006 kPa/mm, K = 13 mm^2/kPa. d and V = 0,08 mm/d. Thus over-irrigation is reduced to a mere 1,6% of the irrigation water initially applied.

The idea is that after the pre-planting irrigation, when the whole soil profile contains water of a *high* potential (e.g. −12 kPa, or a *low* tensiometer reading), irrigation water is regularly applied to the topsoil to maintain there a high water potential, while the subsoil at a depth of about 0,9 m is allowed to dry out to a *low* water potential where the $T_{0,9}$ reading is lower than about −25 kPa (giving a *higher* reading). This ultimate value changes somewhat per soil type. In other words, the lower the water potential (that is the higher the tensiometer reading) the lower the velocity of soil moisture movement.

Thus the measurement and prevention of over-irrigation is based on two principles, *viz.*

(i) the calculation of moisture movement by means of tensiometer readings, and

(ii) accurate irrigation management by means of high frequency irrigation.

Tensiometers do play a very important role. The tensiometer readings are first used to calculate I and thereafter to find K.

The former type of calculation was used during a reconnaissance survey of commercial drip irrigation systems in order to obtain the downward soil moisture movement, and to evaluate the irrigation efficiency (Streutker, 1973).

In the literature the above calculation has been used in reverse, namely to obtain the velocity of capillary moisture movement from a shallow water table upwards to the root zone of a crop (*inter alia* by Richards & Moore, 1952; Gardner & Fireman, 1958 and Streutker, 1971). Richards (1965) found the use of the above equation not sufficiently precise to estimate the flow velocity (V).

High frequency irrigation means water application of such a short duration as well as short intervals that exactly the same volume of water is added to the root zone as is used by the crop. The possibility of that type of irrigation is described by, among others, Rawlins (1973). Rawlins and Raats (1975) pointed out that the costs of automation of a permanent system to apply high frequency irrigation can be greatly cancelled out by the decreased use of high priced fertiliser and water. Excessive frequent fertilisation especially of sandy soils, in order to counteract the leaching of fertiliser by conventional irrigation management, becomes superfluous in view of the possible accuracy of high frequency irrigation.

3. Materials and Methods

After the reconnaissance survey in 1972 and 1973, during which over-irrigation was often found under commercial drip systems, more intensive research was conducted at the Zebediela Citrus Estate in 1974 and 1975 to improve the application efficiency of the drip irrigation system. The research lasted till the end of 1975. In 1975 and 1976 the research programme was extended to Groblersdal and to Pretoria with the aim of also achieving high irrigation efficiencies using a sprinkler and a drip system on wheat (Loskop Experimental Station) and a microjet and a drip system on wheat and soybeans (experimental plot of the Soil and Irrigation Research Institute, at the Horticultural Research Institute, Roodeplaat, near Pretoria).

3.1 Soils

Properties such as texture, bulk density and saturated hydraulic conductivity (K) of the Shorrocks and Makatini soil series (MacVicar *et al.* 1977), considered in these studies, are summarized in Table 1.

3.2 Tensiometers, moisture retention curves and K—ψ curves

For the control of each type of irrigation management one or two sets of tensiometers with mercury manometers were used (Figs. 2 and 3). A set of tensiometers comprised $T_{0,3}$; $T_{0,6}$; $T_{0,9}$ and $T_{1,2}$. The tensiometers were installed at a distance of 2 m from a sprinkler line, 0,3 m from a microjet line midway between two jets, and 0,3 m from a dripper. The moisture retention curves for depths of 0,3 m, 0,6 m, 0,9 m and 1,2 m in the soil profile were obtained from gravimetric moisture determinations of soil samples taken during the installation of the tensiometers as related to tensiometer readings. Readings were taken twelve hours after installation. These values were supplemented by many measurements made on soil samples obtained by auger close to the porcelain cups during the course of the investigation.

The unsaturated hydraulic conductivity (K) was obtained as a function of soil moisture potential (ψ) by means of the application of the theoretical pore-interaction model of Millington and Quirk (1959), for P = 1, making use of the above moisture retention curve. The necessary $K_{saturated}$-value was measured on undisturbed soil samples in permeameters using Darcy's law.

3.3 Over-irrigation and correct irrigation

The volume of over-irrigation or percolation of irrigation water (in *l*/d) beneath a depth of 0,9 m was obtained by means of two methods. Firstly, the calculated velocity of soil moisture movement from two tensiometer readings (in mm/d) was multiplied by the irrigated area (in m^2). A less continuous, but better overall assessment of over-irrigation over a larger area was obtained using the second method which involved hand-augering holes along and at right angles to two dripper lines or one microjetline. On several occasions, about 16 h after the last irrigation and just before the next irrigation, holes were augered at a distance of 0,3 m from each other and over a distance of about 2 m. At every 0,15 m of depth a soil sample was taken and the moisture measured. The soil moisture volume percentages of all the samples at different depths were plotted in a 2 m cross section and isolines of volumetric moisture content were drawn. The areas between every two lines with a moisture percentage greater than field capacity gave an impression of over-irrigation on these specific dates.

TABLE 1
PROPERTIES OF THE FOUR SOILS

Place	Soil Series	Soil Depth (m)	Texture >CS*	CS	MS	FS	silt	clay	Bulk Density (kg/m³)	K-sat 10^3 × (mm²/kPa.day)
Zebediela	Shorrocks	0 – 0,3	10	24	23	32	3	18	1500	
		0,3 – 0,6	0	25	21	31	3	20	1500	153,5
Groblersdal	Shorrocks (with GWT)	0,7 – 0,9	19	33	19	30	3	15	1500	212,1
Groblersdal	Makatini	0,45	2,1	19	11	23	5	42	1450	
		0,75	2,4	17	9	22	7	45	1500	14,8
Pretoria	Shorrocks	0,35	0	7	22	36	6	29	1610	
		0,60	0	8	23	33	7	29	1600	89,0

* >CS is given as a percentage of the total soil mass

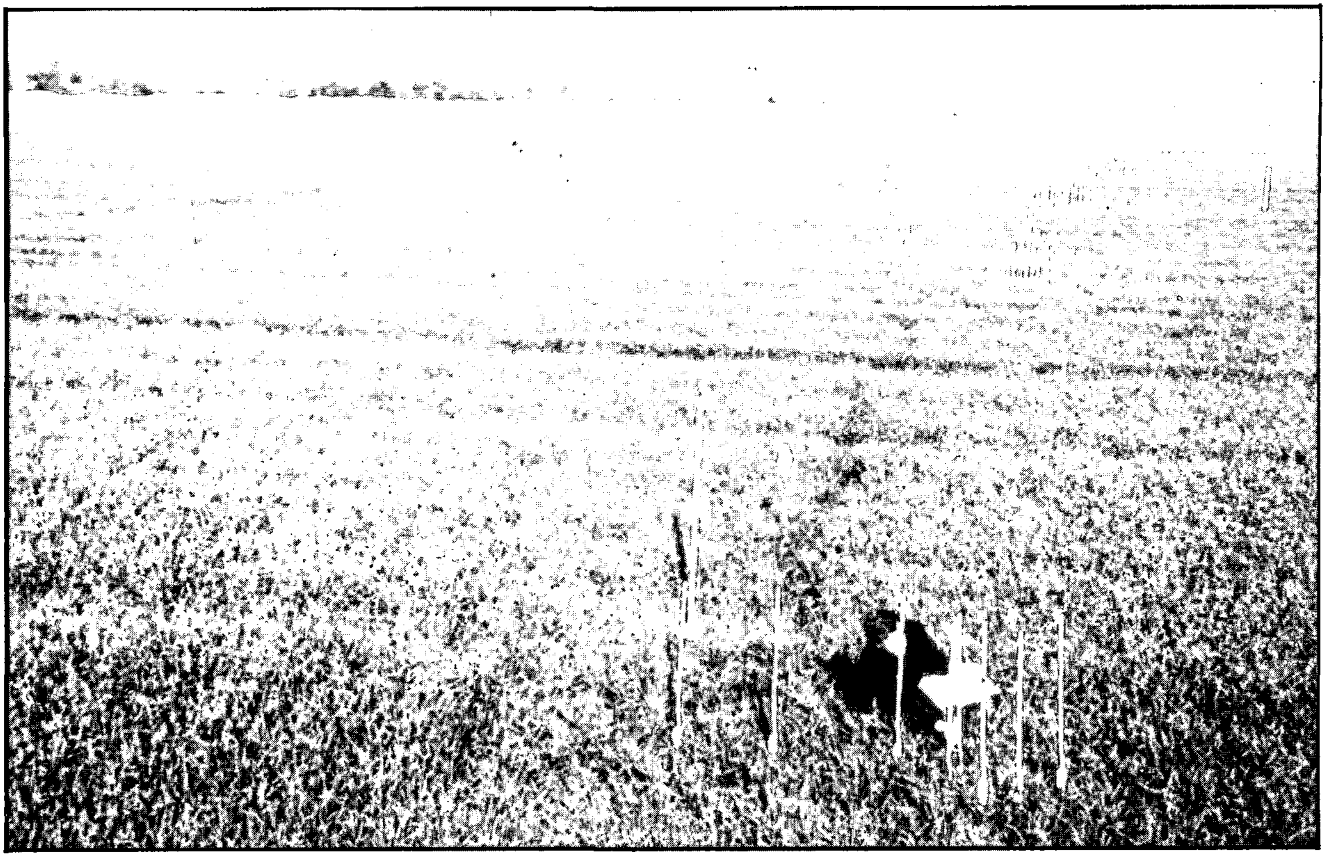

Figure 2
A view of the Groblersdal experimental field on Shorrocks soil. Note the sets of tensiometers for each type of irrigation management

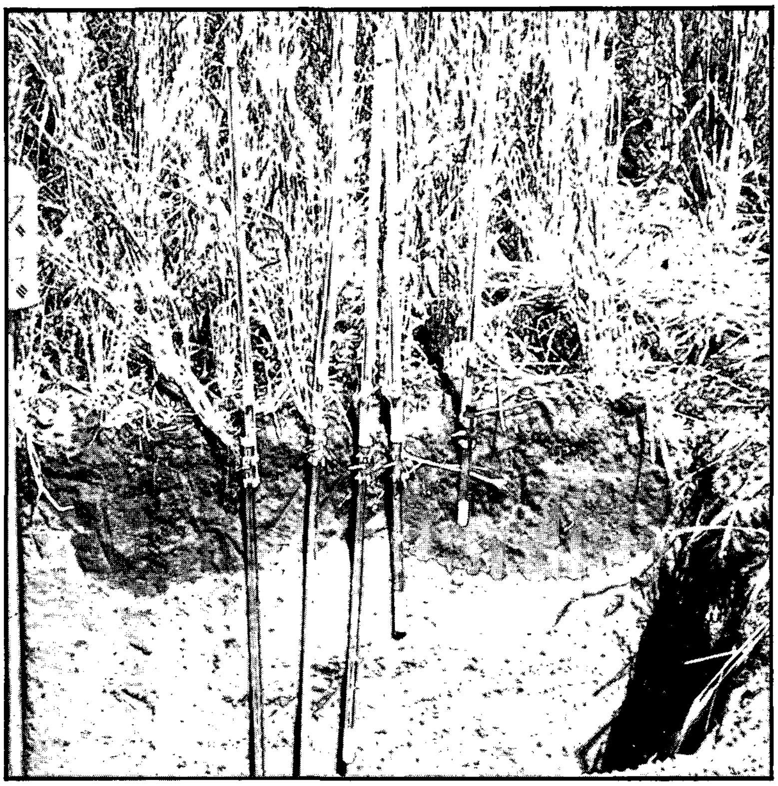

Figure 3
Tensiometers at depths of 0,15 m, 0,3 m, 0,6 m, 0,9 m and 1,2 m. The clear soil moisture front is not a natural one under good irrigation, but created for demonstration

3.4 Water usage and crop yield

The water usage of crops was calculated for several periods of a growing season or for the whole season. The periods were defined by the above dates when soil samples were taken, or from one irrigation to the next. The total water usage during a period is the sum of the quantity of irrigation water applied, rain water and the difference in soil moisture between the beginning and the end of that period, minus the calculated percolation. This water usage was compared with the evaporation from a Class A pan during the same period and resulted in the ET-plant/E-pan ratios. The Class A pans at Zebediela, Groblersdal and Roodeplaat (Pretoria) were situated at a weather station with a grassed surface.

The yield of navel oranges was not obtained. The seed and straw yields of wheat, and the seed yield and residues of soybean plants were obtained for three to nine replicates per irrigation or management treatment and compared with the water usages of the respective crops. Details are given in the following section.

3.5 Details of five irrigation systems and irrigation managements

The variation in irrigation management consisted of keeping the soil moisture in the top layer (mainly) of the soil profile constantly at different levels of water potential. These levels were, for each of the five cases, one or more of the following:

(i) the "very wet topsoil" management,

(ii) the "wet topsoil" management,

(iii) the "very moist" topsoil management, and

(iv) the "moist topsoil" management,

as defined by a predetermined threshold value of tensiometer reading which differed in each case. Other variations were:

(i) dryland conditions (no irrigation),

(ii) irrigation at certain physiological stages of the crop,

(iii) fixed frequency irrigation ("commercial" irrigation), and

(iv) irrigation according to water demand as based on the varying constellations of environmental factors.

3.5.1 Drip irrigation of citrus trees on Shorrocks soil at Zebediela

Commercial drip system. In 1971 ten year old Washington navel orange trees, spaced in a 6,2 m × 6,5 m pattern, were provided with a drip system with the following characteristics: one dripper line per one row of seven trees; four drippers per tree on the tree canopy border line; application rate 7 *l*/h per dripper.

Experimental drip system. For 1974 one dripper line per one row of seven trees; four drippers per tree; application rate 6 *l*/h per dripper. For 1975 the same as for 1974, except that eight drippers per tree were also used.

Irrigation management. Under commercial management there was a daily application of 2,4 h (67 *l* water per day per tree), except on Sundays and directly after rain. Under the experimental management of 1974 water was applied at a frequency of two to three applications per day, each being limited to a duration of 0,5 h and being given at regular intervals between 08h00 and 17h00, every day except Sunday.

The number of irrigations per day was chosen in such a way that a tensiometer at a distance of 0,3 m from a dripper and at a depth of 0,3 m ($T_{0,3}$) always showed a value from zero to −25 kPa (wet), while the tensiometers at the same distance from the dripper but at a depth of 0,9 m and 1,2 m always indicated a value smaller than −25 kPa (moist). For 1975 the management criteria were for the "very wet topsoil" management $T_{0,3}$ between 0 and −15 kPa, and $T_{0,9}$ and $T_{1,2}$ smaller than −25 kPa; and for the "wet topsoil" management $T_{0,3}$ between 0 and −25 kPa, and $T_{0,9}$ and $T_{1,2}$ smaller than −25 kPa.

3.5.2 Sprinkler and drip irrigation of Inia-wheat on Shorrocks soil at Groblersdal

Experimental sprinkler system. (Fig. 2). In 1975 the system consisted of laterals with five sprinklers each having a distance of 12 m between sprinklers. The spacing between the laterals was about 30 m, so that there was no overlapping, and every lateral was used for a different type of irrigation management. Water application was measured at a distance of 2 m from the lateral, where the tensiometers were installed and the wheat was harvested.

Experimental drip system. There were two parallel dripper lines 42 m in length and 1 m apart. Dripper spacing along the line was 0,6 m and the application rate 3,7 *l*/h per dripper. There was a ground water table between 1,2 and 1,7 m below the soil surface.

Irrigation management. The growing season was from 27 May – 20 October. Under the sprinkler system, after the germination irrigation, four treatments (different types of management) were applied: i) no irrigation; ii) irrigation at flowering and at soft dough stage; iii) fortnightly irrigation (approximating commercial irrigation); and iv) irrigation based on average daily maximum air temperature, soil coverage of the crop canopy and crop lushness, according to a nomogram (Nieuwoudt, 1970). The management of the dripper lines conformed to an irrigation duration of 0,5 h and several irrigations. Even though for the management no. iv the quantity of irrigation water was calculated by means of the nomogram, the water application was always done in such a way that there was no moisture replenishment in the subsoil, as indicated by the teniometers. This applied to the other types of management as well.

3.5.3 Drip irrigation of Inia-wheat on Makatini soil at Groblersdal

Experimental system. In 1976 the drip system consisted of eighteen units. Each unit comprised two dripper lines of 10 m long and 0,6 m apart. Spacing between drippers was 0,6 m and the application rate was 3,6 *l*/h per dripper. The distance between each two units was 1,5 m.

Irrigation management. The growing season was from 1 July to 5 November. The different types of management were: i) no irrigation; ii) irrigation at pipe, flowering and soft dough stage;

iii) $T_{0,3}$ between 0 and −70 kPa ("moist topsoil" management); and iv) $T_{0,3}$ between 0 and −20 kPa ("wet topsoil" management). The irrigation duration for the latter two managements was one hour, and the frequency one to several times a day.

3.5.4 *Microjet and drip irrigation of Inia-wheat on Shorrocks soil at Pretoria*

Experimental system. In 1976 the system consisted of 42 microjet and 12 drip units. Each unit comprised two dripper lines (similar to the Groblersdal system), or one microjet line. The microjet line was 0,8 m above the soil surface with microjets at 1 m intervals along the line, facing down and delivering 21 *l*/h per jet. All wheat experiments under 5.2, 5.3 and 5.4 received a fertilizer application of 100 kg N and 40 kg P/ha.

Irrigation management. The growing season was from 15 June to 9 November. The types of managements were: i) $T_{0,3}$ between 0 and −70 kPa ("moist topsoil" management); ii) $T_{0,3}$ between 0 and −40 kPa ("very moist topsoil" management); and iii) $T_{0,3}$ between 0 and −20 kPa ("wet topsoil" management). The irrigation duration was 1−3 h (for 4 *l*/h dripper) and 0,5 h (for microjets), one or several times a day.

3.5.5 *Microjet and drip irrigation of soybeans (SSS. 3) on a Shorrocks soil at Pretoria*

Experimental system. During the 1976/'77 growing season the system consisted of three drip and three microjet units. Each unit comprised four rows of soybean plants, each with one dripper line or one microjet line. The growing season was from 15 December to 7 April.

Irrigation management. Management in principle was the same as for wheat in 1976.

4. Results and Discussion

4.1 Moisture retention curves and K—ψ curves

The moisture retention curves for three layers of the four soils are shown in Fig. 4. Each curve is the mean of the indicated spread of points (the moisture retention area). The spread of the points can be caused by the heterogeneity of soil bulk density, by differences amongst tensiometers due to incomplete degassing, and by reading and sampling errors. The soil samples were taken 16 h after the last irrigation of the previous day to coincide with the desorption phase after irrigation, so as to counteract the influence of hysteresis on the spread of the points. The moisture retention curve (area) obtained *in situ* in the soil profile can therefore be used with more confidence for irrigation management than the moisture retention curve obtained from one or a few disturbed soil samples in a pressure plate. The positions of the two laboratory curves to the right of the companion field curves show the differences between laboratory and field measurements. Talsma (1963) obtained similar differences and attributed these differences to hysteresis and to a larger volume of confined air in the field soil profile.

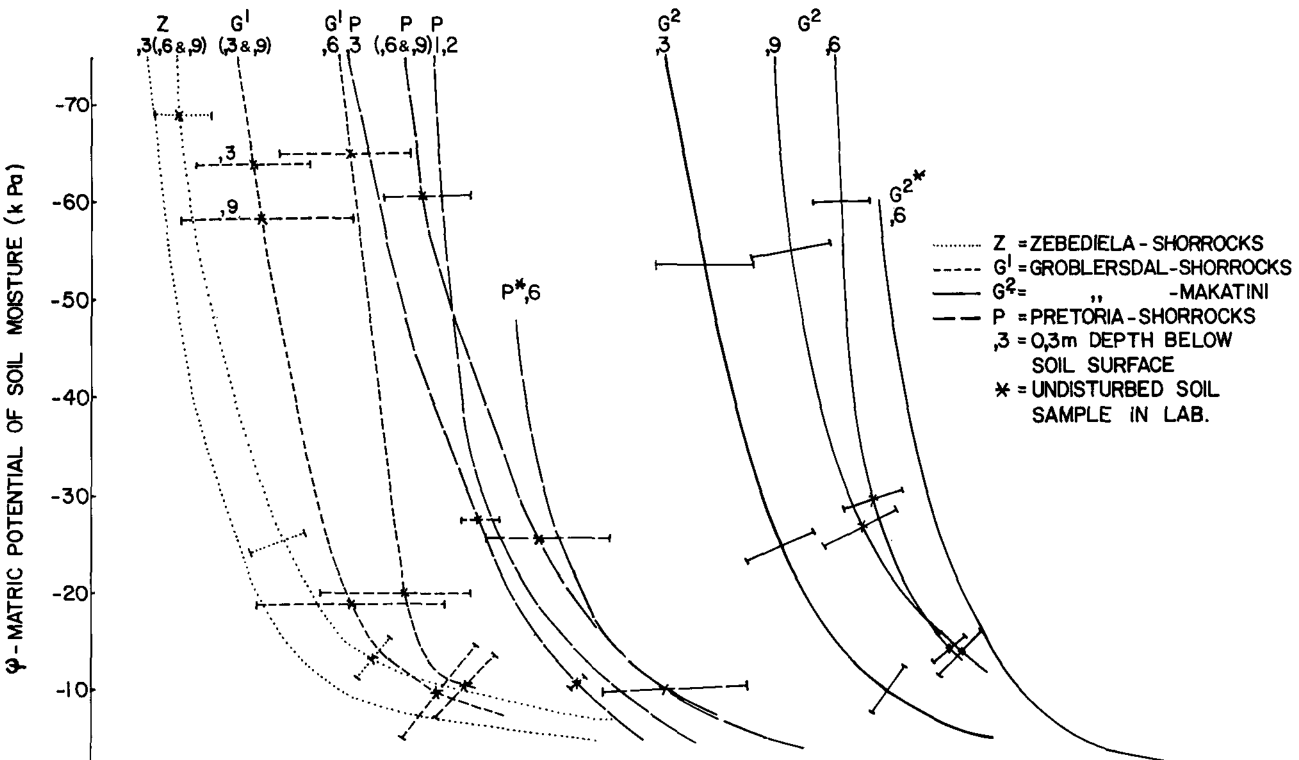

Figure 4
Moisture retention curves for three layers of four soils

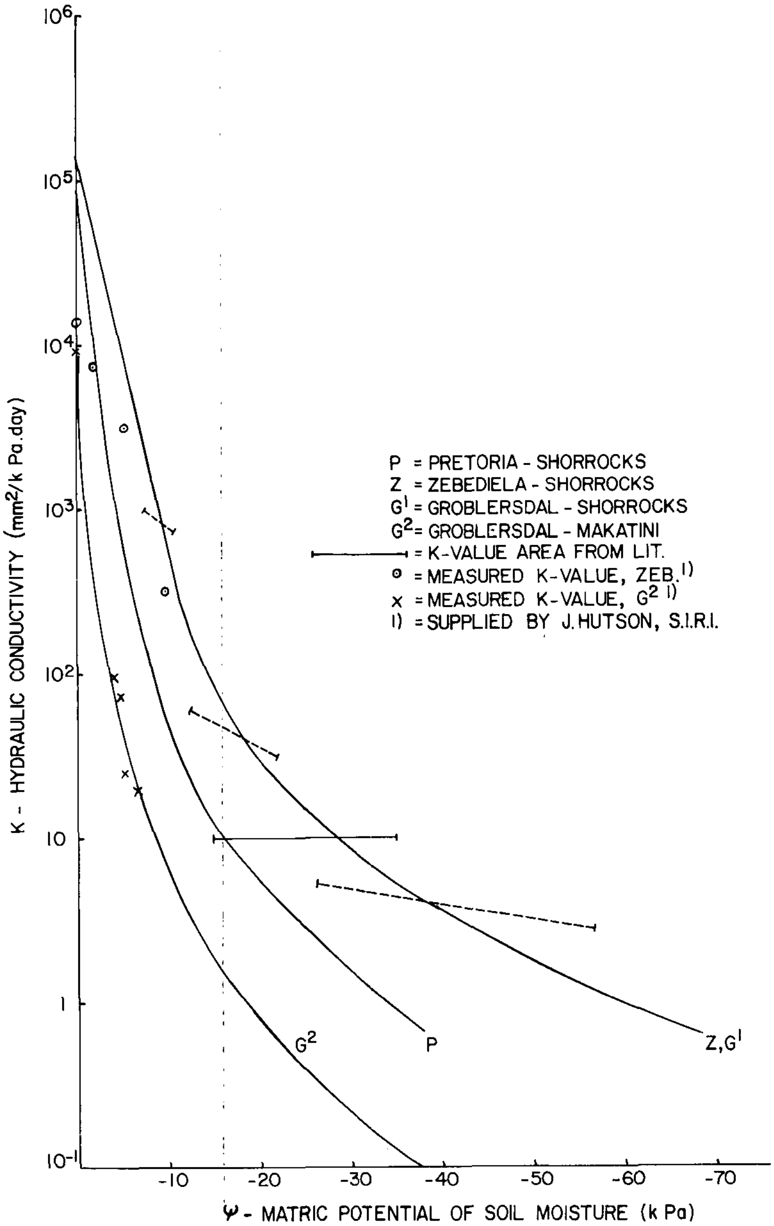

Figure 5
$K-\psi$ curves for the depth of 0,9 m for four soils

The positions of the moisture retention curves in Fig. 4 and of the $K-\psi$ curves in Fig. 5 are in proportion to the clay percentages of the four soils. In contrast with the Z-, G^1- and P-curves of Fig. 5, which are matched to the value of $K_{saturated}$, the G^2-curve is calculated using the indicated measured values of $K_{unsaturated}$.* The positions of the curves correspond to those in the literature, where it was found that $K_{unsaturated}$ is smaller than 10 mm^2/kPa. d, when the moisture potential is less than −34 kPa in a fine sandy loam and in a clay soil (Gardner & Fireman, 1958), between −22 kPa and −35 kPa in a clay loam and a fine sand soil (Wesseling & Wit, 1966) and between −15 kPa and −35 kPa in a silt loam and sand, and loam to loamy fine sand soil (Richards & Moore, 1952).

4.2 Over-irrigation and improvement of irrigation management

4.2.1 *Drip irrigation of citrus trees on Shorrocks soil*

The results from the investigation into the *commercial management* of the drip irrigation of the navel orange trees at Zebediela are, for 1975, summarised in Figs. 6.1 and 6.2; Figs. 7.1 and 7.2 and Figs. 8.1 and 8.2.

The matric potential of the soil moisture at a depth of 0,9 m and 1,2 m close to the dripper *on the sunlit side* (northern side) of the tree (Fig. 6.1) and the potential close to the dripper on the *shaded side* (southern side) of the tree (Fig. 6.2)

*By courtesy of Mr J.L. Hutson, Soil and Irrigation Research Institute

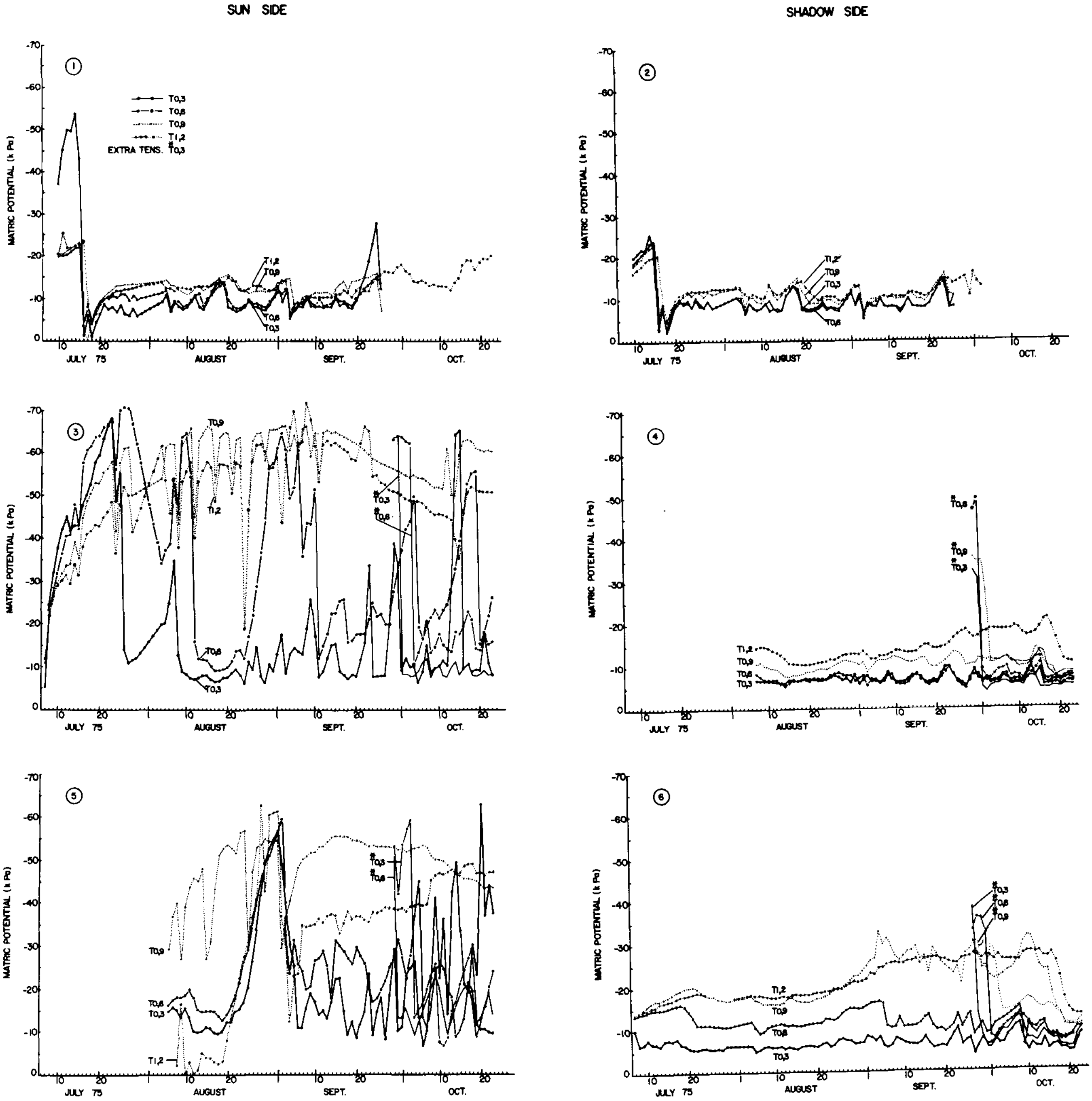

Figure 6
Tensiometer graphs depicting: 1) and 2) over-irrigation on the sunlit side and on the shaded side of the orange tree under commercial irrigation at Zebediela; 3) and 4) good irrigation and over-irrigation respectively under the "very wet topsoil" irrigation management; and 5) and 6) good irrigation on both sides of the tree under the "wet topsoil" irrigation management

was about −12,5 kPa. This is a high value and means over-irrigation. The velocity of moisture movement through the 0,9−1,2 m soil layer into the subsoil on the sunlit side during July−September, was calculated from the small potential differences between $T_{0,9}$ and $T_{1,2}$ and 0,3 m distance from a dripper. It was 1,9 mm/d (10−25 Aug.) and 1,7 mm/d (8−19 Sept.). (See Table 2 and the calculation under "Theory".) At a distance of 0,6 m from the same sunlit dripper the velocity of moisture movement through the 0,9−1,2 m soil layer was 0,6 mm/d and 1,3 mm/d for the respective periods (the tensiometer graphs for the 0,6 m distance from a dripper are not provided).

A much greater velocity of moisture movement to the subsoil was calculated near the dripper on the shaded side, namely for the 0,3 m distance 3,2 mm/d and 5,0 mm/d respectively for the abovementioned periods, and for the 0,6 m distance 2,6 mm/d and 2,6 mm/d respectively. With these results an over-irrigation of 17 *l*/d and 21 *l*/d per tree for July−September was calculated for the respective periods, of which 4−7 *l*/d on the sunlit and 13−14 *l*/d on the shaded side drained away (Table 3).

TABLE 2
VELOCITY OF SOIL MOISTURE MOVEMENT (mm/day) IN RELATION TO IRRIGATION MANAGEMENT, SUNLIT SIDE OR SHADED SIDE OF AN ORANGE TREE, AND DISTANCE FROM DRIPPER (↓ DOWNWARD IS OVER-IRRIGATION AND ↑ UPWARD IS CAPILLARY MOVEMENT)

Irr.	Commercial				"Very Wet Topsoil"				"Wet Topsoil"			
Position	Sunlit Side		Shaded Side		Sunlit Side		Shaded Side		Sunlit Side		Shaded Side	
Dist. from dripper (m)	0,3	0,6	0,3	0,6	0,3	0,6	0,3	0,6	0,3	0,6	0,3	0,6
Period												
1–31/10/74	0,05↑	0,08↑	4,60↓	1,40↓	—	—	—	—	0,18↑	0,12↑	0,50↓	0,30↓
1–20/11/74	0,28↓	0,20↑	2,80↓	0,40↓	—	—	—	—	—	—	—	—
10–25/8/75	1,90↓	0,60↓	3,20↓	2,60↓	0,01↑	0,14↑	9,00↓	2,00↓	—	—	0,67↓	0,18↓
8–19/9/75	1,70↓	1,30↓	5,00↓	2,60↓	0,00↑	0,09↑	3,40↓	1,50↓	0,16↑	0,07↓	0,08↓	0,17↑
1–20/10/75	—	—	—	—	0,02↑	0,09↑	2,80↓	1,60↓	0,00↑	0,05↓	0,20↓	0,08↑

TABLE 3
SOIL MOISTURE MOVEMENT BENEATH A DEPTH OF 0,9 m (l/day PER ONE TREE) IN RELATION TO IRRIGATION MANAGEMENT, AND SUNLIT OR SHADED SIDE (↓ OVER-IRRIGATION AND ↑ UPWARD CAPILLARY MOVEMENT)

Irrigation	Commercial		"Very Wet Topsoil"		"Wet Topsoil"	
Position	Sunlit Side	Shaded Side	Sunlit Side	Shaded Side	Sunlit Side	Shaded Side
Period						
1–31/10/74	0,4↑	6,7↓	—	—	0,6↑	1,6↓
1–20/11/74	0,8↑	3,3↓	—	—	—	—
10–25/8/75	3,9↓	13,3↓	0,6↑	13,9↓	—	1,2↓
8–19/9/75	6,5↓	14,3↓	0,4↑	8,6↓	0,2↓	0,7↑
1–20/10/75	—	—	0,4↑	8,7↓	0,2↓	0,2↑

Whereas one tree was supplied daily with 67 *l* of irrigation water the above figures indicate that 25% – 31% of that water was over-irrigated.

During October 1975 no measurements were taken, but from the measurements of October and November 1974 an over-irrigation of 6 *l*/d and 3 *l*/d respectively was calculated, particularly on the shaded side (Table 3). Over-irrigation for those months was 9,5% and 3,5% respectively. Thus considerable over-irrigation occurred during July, August and September (evaporation from the Class A pan was 5 mm/d, 6 mm/d and 7,5 mm/d respectively), while during October and November (when evaporation was 10 mm/d and 8 mm/d respectively) over-irrigation decreased and finally ceased.

This conclusion can also be drawn from Figs. 7.1 and 7.2 and Figs. 8.1 and 8.2. The soil moisture profiles for 20 September 1975 clearly show that a great part of the root zone (0 – 0,6 m) and of the subsoil was wetter than field capacity (12 – 13,5%). This indicated, therefore, that moisture was draining out. The soil moisture profiles of 28 October (Fig. 8) confirm that considerably less moisture above 12 – 13% was draining out, and mainly on the shaded side.

The results from the research on the tensiometer controlled management of the *experimental drip system* are summarised in Figs. 6, 7 and 8, and in Tables 2 and 3. There was a low potential of the soil moisture (this is a high reading in Fig. 6) at a depth of 0,9 m and 1,2 m near the dripper *on the sunlit side*

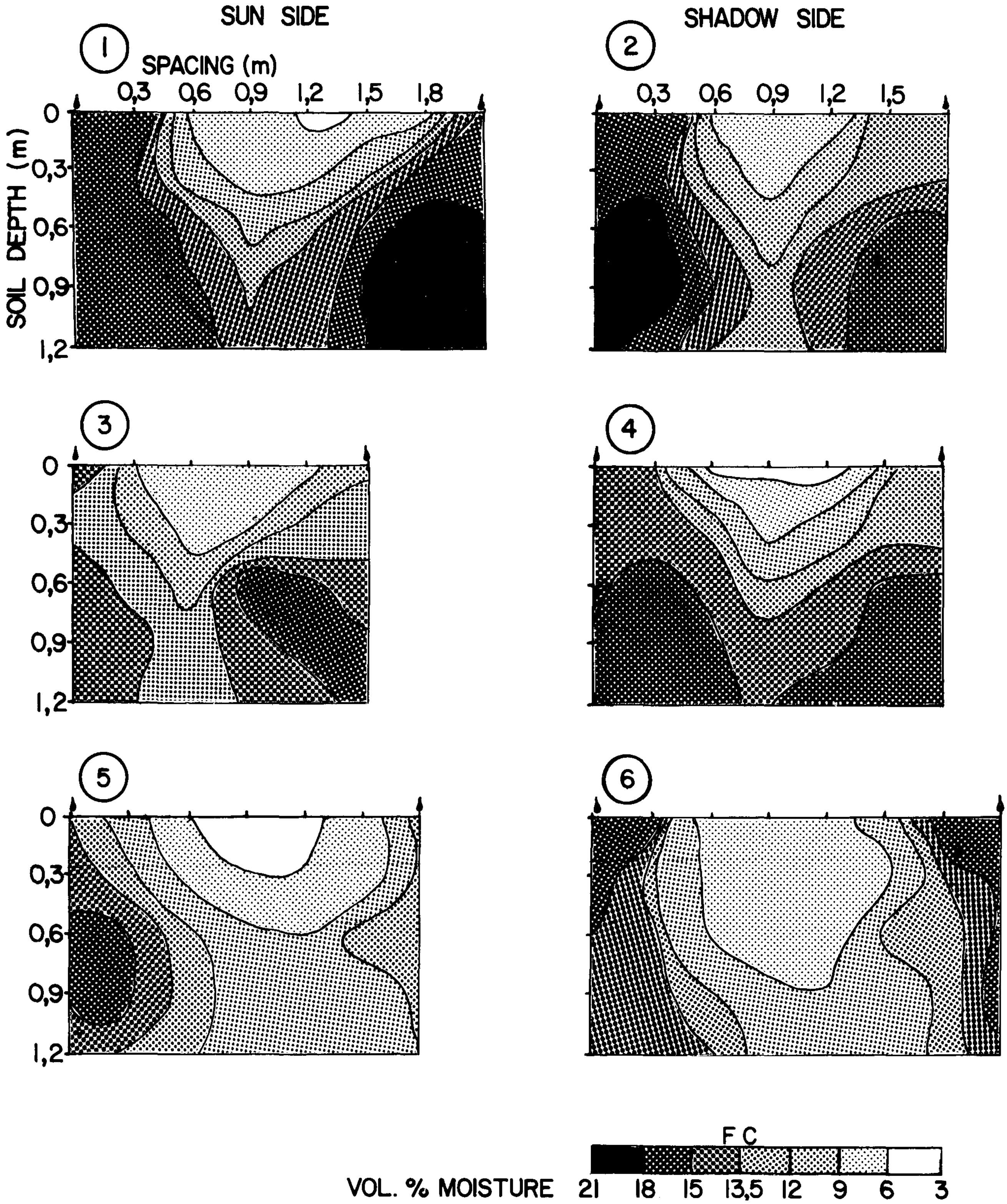

Figure 7
Soil moisture profiles from the sunlit side and the shaded side of orange trees at Zebediela on 20 Sept. 1975 depicting: 1) and 2) over-irrigation under commercial irrigation management; 3) and 4) good irrigation and over-irrigation under the "very wet topsoil" irrigation management; and 5) and 6) good irrigation under the "wet topsoil" irrigation management (♦ = dripper and FC = field capacity)

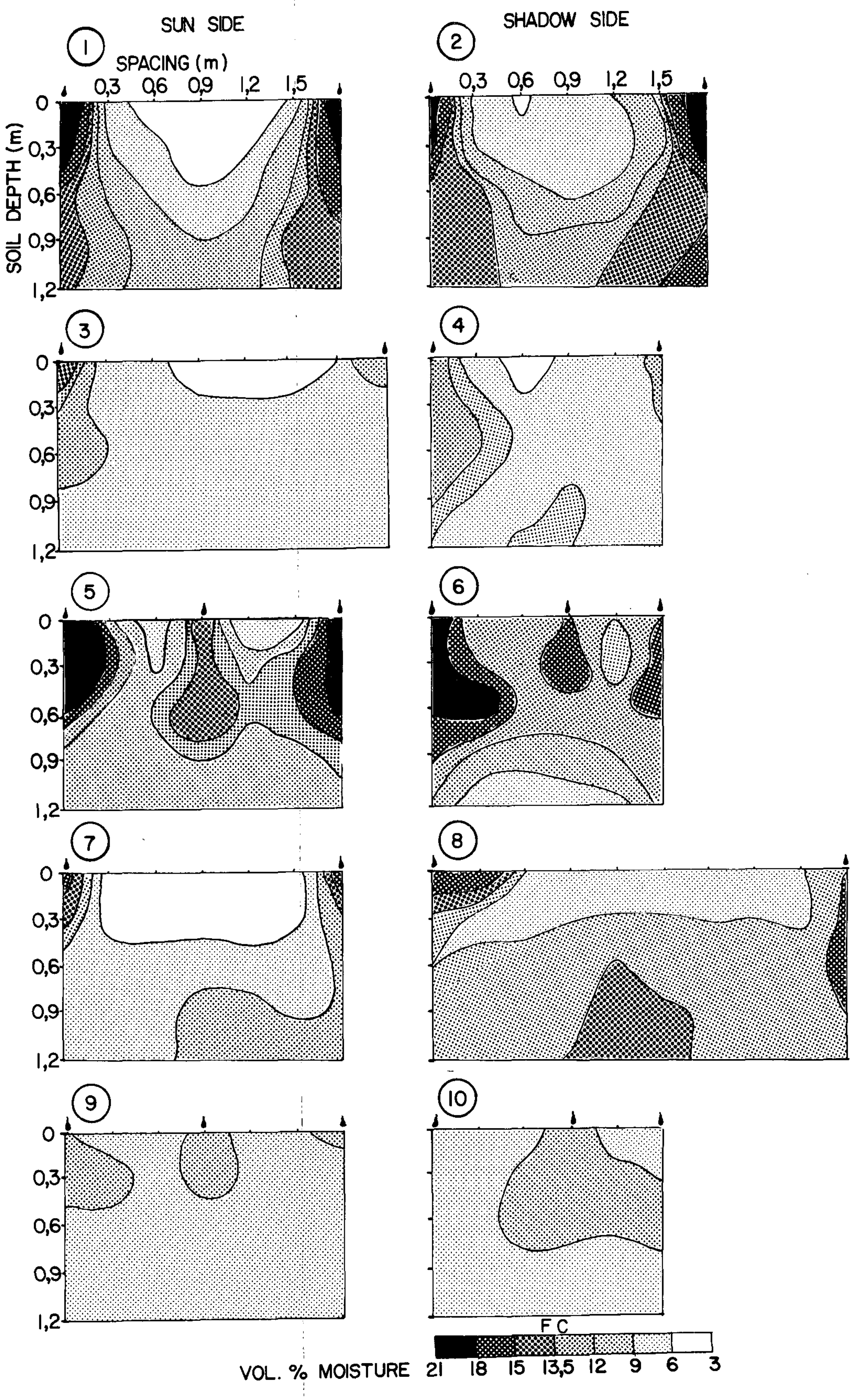

Figure 8

Soil moisture profiles of orange trees at Zebediela on 28 Oct. 1975 depicting: 1) and 2) some over-irrigation under commercial irrigation management; 3) and 4) under-irrigation under "very wet topsoil" irrigation management for four drippers per tree, and 5) and 6) very good irrigation under eight drippers per tree; 7) and 8) under-irrigation under "wet topsoil" irrigation management for four drippers, and 9) and 10) under-irrigation under eight drippers as a result of the "very wet topsoil" and "wet topsoil" high frequency irrigation management ($T_{0,3}$ between 0 and −15 kPa, and $T_{0,3}$ between 0 and −25 kPa respectively). On the *shaded side* low potentials were only found under the "wet topsoil" management (Fig. 6.6). *Under the "very wet topsoil" management* the velocity of moisture movement in an upward direction, through the 0,9−1,2 m soil layer on the sunlit side during 10−25 August was 0,01 mm/d and 0,14 mm/d, for distances of 0,3 m and 0,6 m from a dripper respectively; that is, about 0,6 l/d per tree (Tables 2 and 3). On the shaded side it was 9 mm/d and 2 mm/d downward respectively; that is, 13,9 l/d per tree draining out.

During the period of 8−19 September and 1−20 October the capillary (upward) moisture movement continued on the sunlit side, while the drainage on the shaded side decreased to 2,8 mm/d and 1,6 mm/d for distances of 0,3 m and 0,6 m from a dripper respectively; that is, 8,7 l/d per tree draining out. Thus under the "very wet topsoil" management (36 l/per tree) over-irrigation was 23−37% of the water applied for the above periods.

Under the "wet topsoil" management about 0,2 l/d drained away on the sunlit side (for September and October), and 1,2 l/d on the shaded side during August, (see calculation under "Theory"), while 0,7 l/d and 0,2 l/d capillary rise was calculated on the shaded side for September and October. Under this management (24 l/d per tree) the over-irrigation was 0−5%. This "wet topsoil" management at last succeeded in decreasing the moisture movement through the 0,9−1,2 m soil layer on the shaded side in such a way that potential values smaller than −25 kPa, or higher tensiometer readings were obtained (Fig. 6.6).

The above percentages over-irrigation were calculated by means of the mean $K-\psi$ curve. When the two boundary curves of the $K-\psi$ *area* in Fig. 5 were used, the following values of over-irrigation were calculated: 12−26 l/d (commercial management); 6−11 l/d ("very wet topsoil" management); and 0,4−1,5 l/d ("wet topsoil" management). This is 18−39%, 17−31% and 0−6% of the total quantity of irrigation water respectively.

Soil moisture profiles in Figs. 7.3 and 7.4 for the "very wet topsoil" management indeed show that in September there was more moisture above field capacity (12−13,5%) and draining away, than was the case in the moisture profiles in Figs. 7.5 and 7.6 for the "wet topsoil" management. However, there was little difference between the moisture profiles for October for both types of irrigation management. From Figs. 8.3 and 8.4, and Figs. 8.7 and 8.8 it is clear that too little water was

Figure 9
A soil moisture profile below a dripper under good "wet topsoil" irrigation management

applied by the four drippers per tree. As a consequence, and because of the great distance between two drippers, the moisture volume in the topsoil was insufficient, especially in the case illustrated by Fig. 8.7. During the period of "wet topsoil" management only 24 *l*/d per tree were applied, in comparison with 36 *l*/d and 67 *l*/d under the "very wet topsoil" management and commercial management respectively.

The next step in the improvement of the tensiometer controlled soil moisture supply was to use, from 29 September onwards, eight drippers per tree. From the tensiometer graphs of Figs. 6.3 and 6.5 it is clear that the moisture potential in the subsoil on the sunlit side remained low (and the reading high) from that date. On the shaded side the $T_{0,9}$-readings remained high for two weeks, but afterwards irrigation water supplied moisture to the subsoil and the readings dropped. The combination of irrigation duration and irrigation frequency used was incorrect. The results of applying a good "very wet topsoil" management with eight drippers per tree are shown by the moisture profiles of Figs. 8.5 and 8.6, and Fig. 9, namely a supply of soil moisture to a depth of 0,7 m and a rather good moisture distribution in the 0—0,7 m soil layer. Most citrus roots were in the 0—0,7 m soil layer. Under the "wet topsoil" management the same pattern of moisture supply was found (Figs. 8.9 and 8.10), but as a consequence of a break in the irrigation water feeder line for three days, just before soil sampling, the moisture percentages shown are misleading.

A possible improvement of uniformity of moisture supply, over-irrigation and water usage by means of two microjets per tree (as used by Bredell, 1977) instead of eight drippers, was not investigated.

From the above investigation it is evident that by a change in irrigation management less irrigation water was used during July and during the critical flower stage in August and September. In periods of water scarcity tensiometer controlled management can be applied to obtain the highest possible yield with the available quantity of irrigation water. In periods of abundant water, attention should be paid to the possible danger of under-irrigation or drying up of the soil profile at the sunlit side, when the emitters are exposed to the sun. Emitters should always be placed in the shade of the tree.

4.2.2 *Sprinkler and drip irrigation of wheat on Shorrocks soil with a shallow ground water table (GWT)*

The tensiometer graphs of Fig. 10 depict the moisture withdrawal by wheat under dry land farming and under four different types of irrigation management on a Shorrocks soil (with a high ground water table, GWT) at Groblersdal.

Under dry land farming all the readily available soil moisture in the 0—0,9 m soil layer was used by August 15 (Fig. 10.1). This caused an upward capillary potential gradient. The capillary moisture movement, through the 0,9—1,2 m soil layer and into the bottom of the 0—0,9 m root zone, was calculated for the period 11 July — 30 Sept. by means of the several potential gradients between $T_{1,2}$ and $T_{0,9}$ and the companion K-values from Fig. 5, yielding a total of 59 mm water. Only a very small amount of water could have been directly withdrawn by the roots from the 1,4—1,7 m GWT, because only a single root was found beneath 0,9 m depth.

Apart from this upward-moving water, the wheat also withdrew moisture from the 0—0,9 m soil layer. From tensiometer graphs down to values of —70 kPa, and Figs. 4 and 5, moisture thus withdrawn was calculated to be 84 mm. Moreover, at the start of the growing season a germination irrigation of 14 mm was applied, and at the end of the season 4 mm rain had fallen. The total water usage was approximately 59 mm + 84 mm + 18 mm, i.e. 161 mm.

From the tensiometer graphs of the critical stage irrigation management the same capillary moisture supply was calculated as under dry land farming, namely 59 mm (Fig. 10.2).

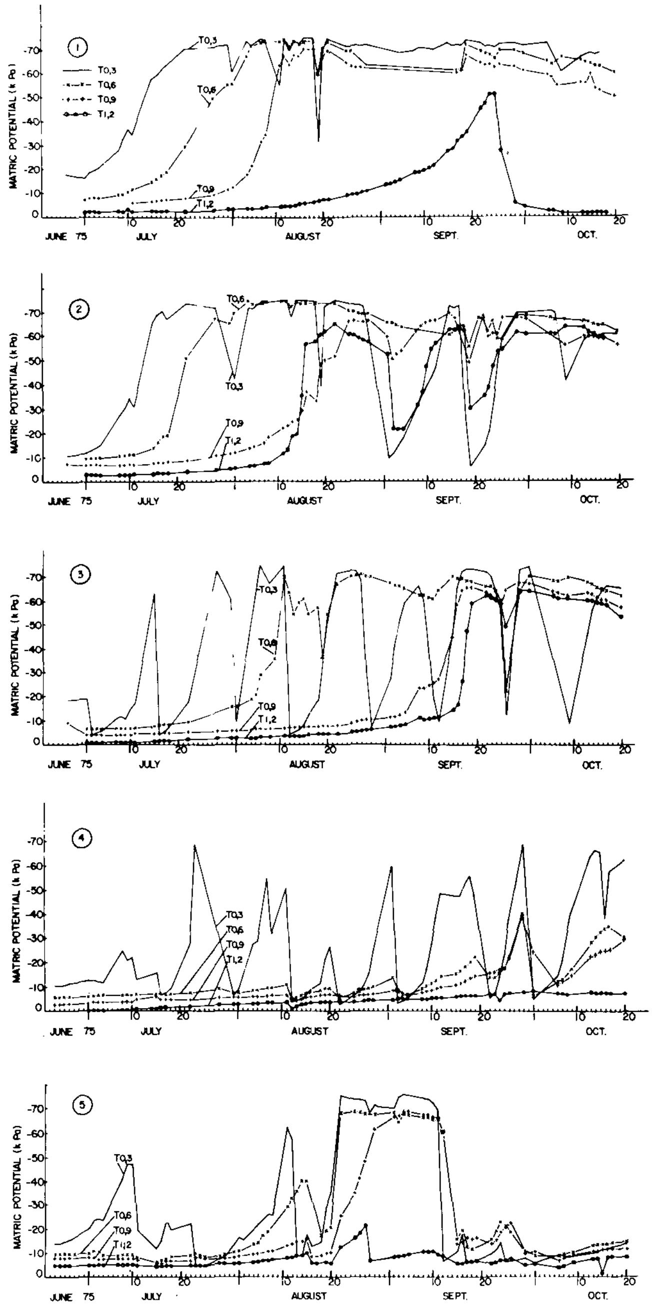

Figure 10
Tensiometer graphs depicting moisture withdrawal and replenishment for wheat on the Shorrocks soil of Groblersdal under 1) dry land farming, 2) sprinkler irrigation at only two critical plant stages, 3) commercial sprinkler irrigation management, 4) nomogram sprinkler irrigation management and 5) drip irrigation management

The 63 mm irrigation at flowering stage and the 64 mm irrigation at soft dough stage, based on calculation by means of tensiometer readings and moisture retention curves (Fig. 4), replenished the moisture in the root zone without any drainage to the subsoil. The difference between the moisture in the root zone at the start and at the end of the season was 84 mm. The total water usage (capillary moisture + soil moisture + total irrigation) was approximately 59 mm + 84 mm + 145 mm, i.e. 288 mm.

The tensiometer controlled commercial irrigation management (irrigation once per fortnight and eight irrigations in total) also succeeded in replenishing the moisture in the topsoil only (Fig. 10.3). This was achieved with eight applications of between 30 mm and 56 mm each. In comparison with the normal (not tensiometer controlled) commercial irrigation practice of 50 mm per irrigation per fortnight at Groblersdal, this means a water saving of 400 mm minus 322 mm, i.e. 78 mm. The total water usage (capillary moisture + soil moisture + total irrigation) was approximately 12 mm + 46 mm + 340 mm, i.e. 398 mm.

Under the tensiometer controlled nomogram irrigation management there were ten irrigations which in general replenished the moisture in the topsoil to approximately 0,6 m depth (Fig. 10.4). During some irrigations there was however over-irrigation and moisture supply to the 0,9—1,2 m soil layer. During the greatest part of the growing season the subsoil was very wet because of the shallow GWT.

From the tensiometer graphs an average velocity of capillary moisture movement of 3,5 mm/d was calculated, i.e. 100 mm in total. According to the tensiometer readings and Fig. 4, 16—30 mm water at the most could have replenished the moisture to field capacity in the 0—0,6 m layer, without over-irrigation. From the nomogram ten applications of between 16 and 45 mm were calculated. Thus the tensiometer graphs $T_{0,6}$, $T_{0,9}$ and $T_{1,2}$ reflect an irrigation regime which was somewhat too wet. On the one hand the presence of the shallow GWT hindered the use of the nomogram, but on the other hand it served as a buffer to prevent possible errors (under-irrigation). The total water usage (capillary moisture + soil moisture + total irrigation) was approximately 100 mm + 46 mm + 325 mm, i.e. 471 mm.

Under the tensiometer controlled high frequency drip irrigation management no capillary moisture movement occurred during the first part of the season. (Fig. 10.5). During the period 20 Aug.—15 Sept. the calculated capillary moisture used was 44 mm. There was no difference between the moisture in the root zone at the start and at the end of the season. The total water usage (capillary moisture + irrigation) was approximately 44 mm + 438 mm, i.e. 482 mm.

In this section it is shown that under the nomogram sprinkler irrigation and under the drip irrigation management the irrigation frequency increased, while for both types of management more water was used than under commercial sprinkler irrigation management. For the respective wheat yields the reader is referred to section 3.

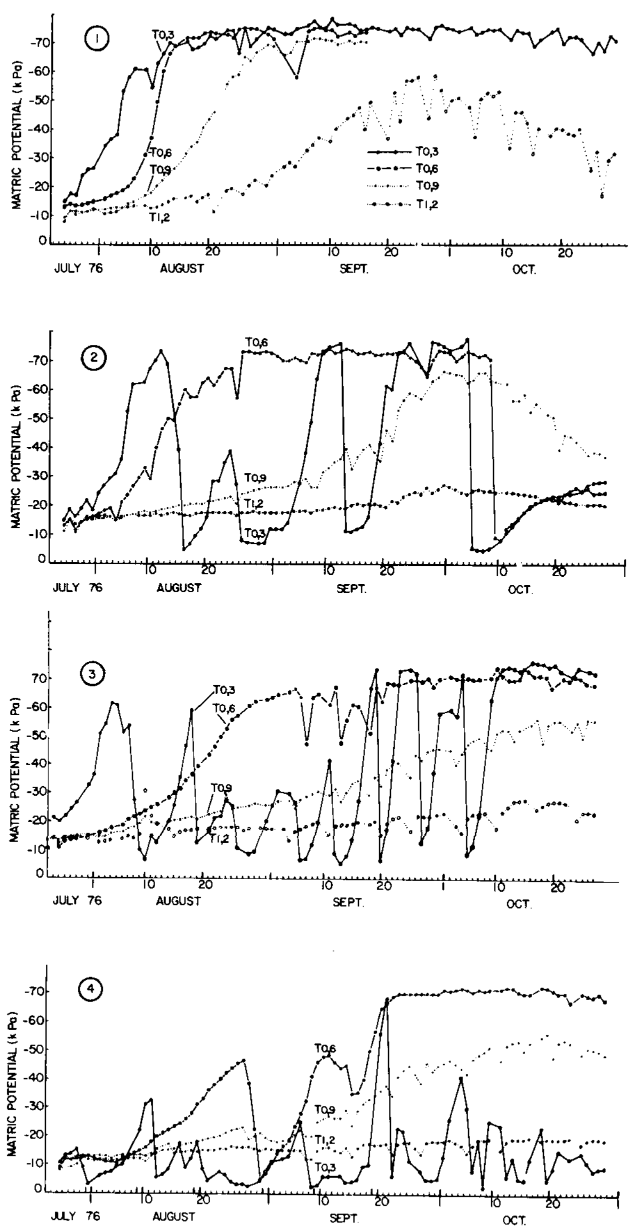

Figure 11

Tensiometer graphs depicting moisture withdrawal and replenishment for wheat on the Makatini soil at Groblersdal under 1) dry land farming, 2) drip irrigation at three critical plant stages, 3) "moist topsoil" drip irrigation management and 4) "wet topsoil" drip irrigation management

4.2.3 *Drip irrigation of wheat on Makatini soil*

Under the dry land wheat farming treatment at Groblersdal on the Makatini soil, in the absence of a high GWT, it was found that all the available moisture had been consumed to a depth of 0,6 m on August 14, and to a depth of 0,9 m on August 30.

For irrigation at three critical plant stages, over-irrigation was prevented under a management which consisted of three applications of 3 h, 3 h and 2 h on three consecutive days (Fig. 11.2). The highest soil moisture percentage line of 29% in Fig. 12.1 is lower than field capacity according to Fig. 4, which shows again that by means of tensiometer controlled irrigation over three days the moisture was replenished at the most to a depth of 0,6 m.

Where the 0—0,3 m soil layer was allowed to dry out to —70 kPa before the next irrigation ("moist topsoil" management), over-irrigation was prevented by means of irrigation durations of about 3 h and 2 h on two consecutive days (Fig.

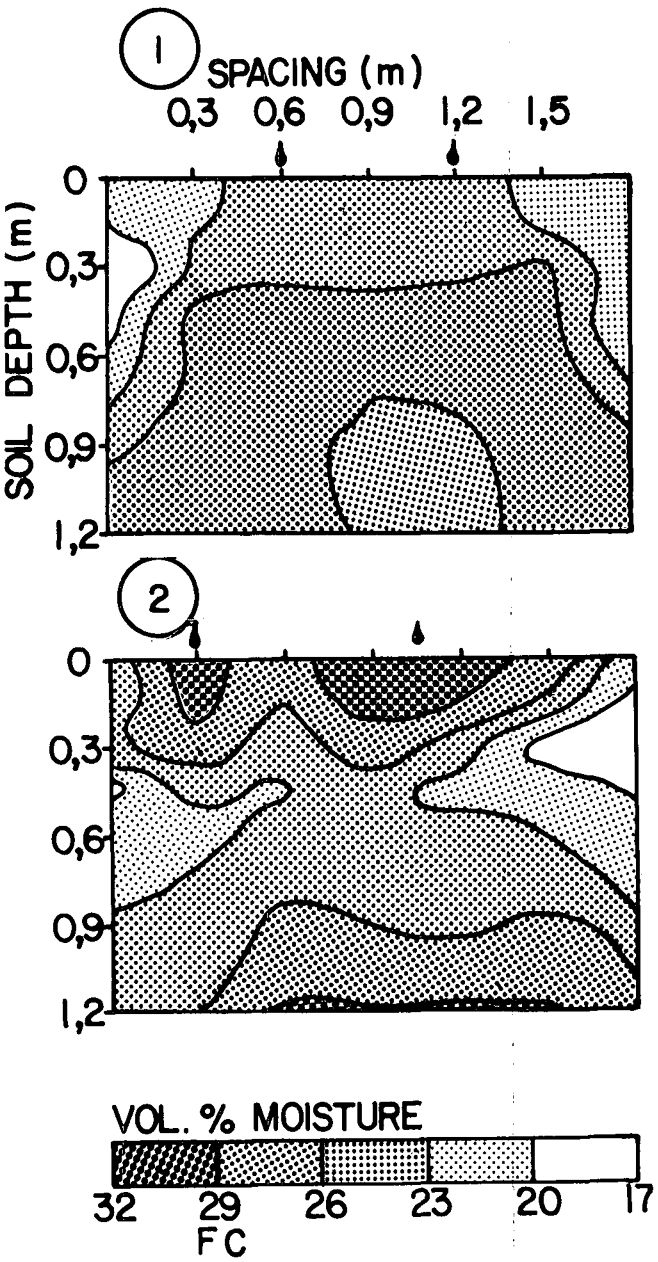

Figure 12
Soil moisture profiles below drippers on the Makatini soil at Groblersdal under 1) three applications on three consecutive days at a critical plant stage and 2) "wet topsoil" irrigation management

11.3). The duration of the irrigations, however, had to be somewhat longer or shorter depending on the evapotranspiration during different periods. Where the 0—0,3 m soil layer was allowed to dry out to a minimum of —20 kPa ("wet topsoil" management), over-irrigation was prevented by means of a daily irrigation of one to two hours (Fig. 11.4). The moisture profile in Fig. 12.2 proves the shallow rewetting of the topsoil under this daily drip irrigation. It was, however, difficult to always maintain a value of more than —20 kPa with a hand-operated drip system. The velocity of capillary moisture movement in the 0,9—1,2 m soil layer was calculated and it was found to be negligible. Under these tensiometer controlled medium to high frequency drip irrigations neither over-irrigation and drainage out of the root zone occurred, nor did upward capillary moisture movement into the bottom of the root zone take place. The total water usage (soil moisture + rain + irrigation) for the various treatments was as follows: dry land 172 mm (120 mm + 32 mm + 20 mm), three irrigations at three critical growth stages 452 mm (36 mm + 45 mm + 371 mm), "moist topsoil" management 476 mm (28 mm + 45 mm + 403 mm), and "wet topsoil" management 729 mm (30 mm + 45 mm + 654 mm).

Although over-irrigation was prevented, one has to be careful not to under-irrigate. This is the case when after every irrigation $T_{0,6}$ does not increase significantly from —60 kPa, in which case a dry hard layer may develop between 0,3 m and 0,6 m which will impede root proliferation.

4.2.4 *Microjet irrigation of wheat on Shorrocks soil*

Under the tensiometer controlled microjet irrigation of wheat it was also possible to replenish the moisture to a depth of approximately 0,45 m, while the moisture withdrawal from the subsoil continued to about 15 September, when the readily available moisture was consumed (Fig. 13).

The "moist topsoil" management consisted of three to six irrigations of half an hour's duration each every fourth day, the "very moist topsoil" management comprised three or two irrigations of half an hour each every third or fourth day, and the "wet topsoil" management comprised one or two irrigations daily of half an hour each. There were more irrigations on Fridays and on Mondays to compensate for non-irrigation on Saturdays and Sundays. It was shown again that during periods of a high evapotranspiration rate it is impossible to manually maintain $T_{0,3}$ between 0 and −20 kPa with a five day irrigation week (Fig. 13.3). Automation of the system would however eliminate the drawback of weekend non-irrigation.

Irrigation management was postponed during the rainy period of 27 Sept. — 4 October. During and immediately after that period the velocity of rain draining out between $T_{0,6}$ and $T_{0,9}$ was calculated to be 0 mm and 28 mm for the "moist topsoil" and the "wet topsoil" managements respectively. The total water usage (soil moisture + effective rainfall + irrigation) for the different treatments was as follows: dry land 235 mm (0 mm + 185 mm + 50 mm), "moist topsoil" management 421 mm (0 mm + 162 mm + 259 mm), "very moist topsoil" management 638 mm (0 mm + 162 mm + 476 mm), and the "wet topsoil" management, 760 mm (0 mm + 162 mm + 598 mm).

4.2.5 *Drip irrigation of soybeans on Shorrocks soil*

Finally, it is shown in Fig. 14 that under tensiometer controlled drip irrigation management of soybeans, the replenishment of moisture in the root zone only was successfully managed. Under dry land farming a total of 305 mm rain, on thirty separate days during the season, replenished the moisture in the 0—0,3 m layer, without any drainage to the subsoil (Fig. 14.1).

During periods of little or no rain the "moist topsoil" management comprised only one irrigation of one hour duration on thirteen separate days (Fig. 14.2), the "very moist topsoil" management comprised a daily 0,5—1 h irrigation (Fig. 14.3), and the "wet topsoil" management comprised a daily 1—2 h irrigation (Fig. 14.4). Under these types of management the total irrigation hours were 18 h, 31 h and 46 h respectively, while in all three cases the moisture in the topsoil only was replenished. Fig. 15.1 and Fig. 16 are examples of good "wet

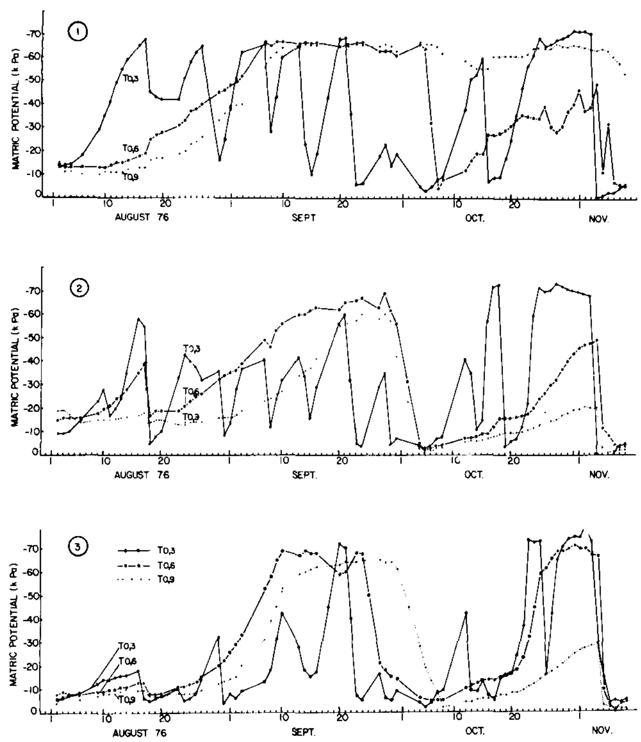

Figure 13
Tensiometer graphs depicting moisture withdrawal and replenishment for wheat on the Shorrocks soil at Pretoria under microjet irrigation: 1) "moist topsoil" irrigation management, 2) "very moist topsoil" irrigation management and 3) "wet topsoil" irrigation management

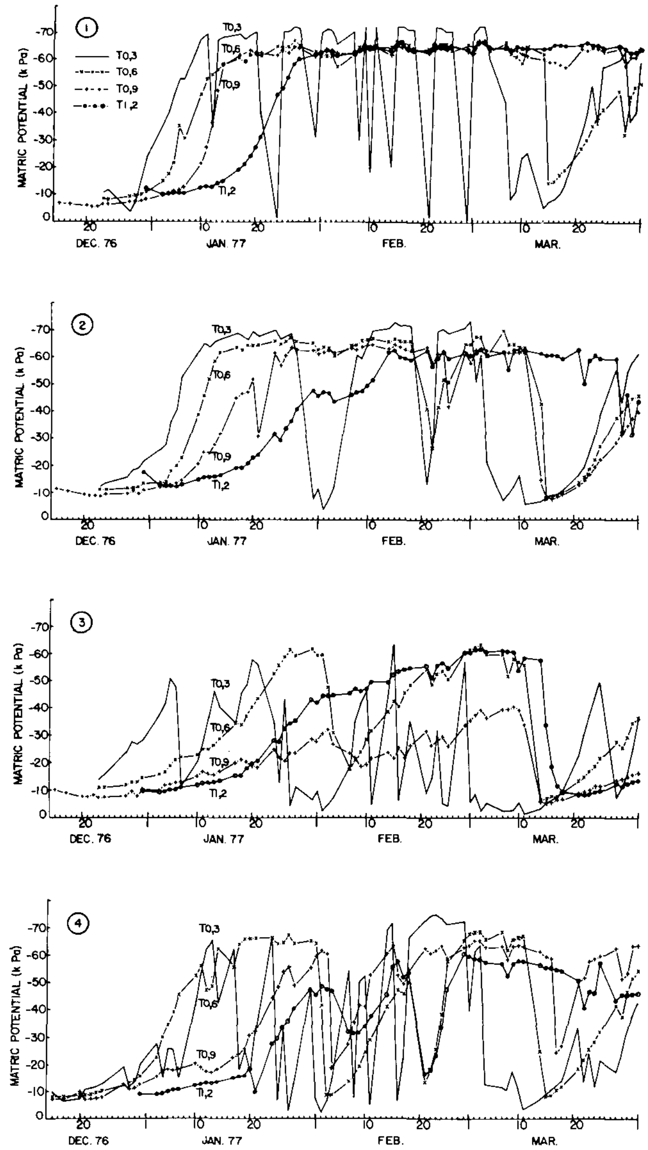

Figure 14
Tensiometer graphs depicting moisture withdrawal and replenishment for soybeans on the Shorrocks soil at Pretoria under 1) dry land farming, 2) "moist topsoil" drip irrigation management, 3) "very moist topsoil" drip irrigation management and 4) "wet topsoil" drip irrigation management

topsoil" management, while Fig. 15.2 is an example of over-irrigation in consequence of an increase in irrigation duration and frequency.

As a result of the "wet topsoil" management and the "very moist topsoil" management the moisture in the subsoil was replenished by the 61 mm rainfall during 29 Jan. — 1 Febr. This was not the case under the dry land and "moist topsoil" management. However, the 51 mm rainfall during 10—12 March which followed the 41 mm rainfall during 2—5 March, did replenish the moisture in the subsoil under all types of irrigation management. Under the "wet topsoil" and "very moist topsoil" management the moisture drained beneath 1,2 m, but not in case of the "moist topsoil" management and dry land farming.

The water usage (soil moisture + effective rainfall + irrigation) under the different treatments was as follows: dry land 377 mm (72 mm + 305 mm + 0 mm), "moist topsoil" management 528 mm (72 mm + 305 mm + 151 mm), "very moist topsoil" management 637 mm (72 mm + 305 mm + 260 mm), and "wet topsoil" management 768 mm (72 mm + 305 mm + 391 mm).

The last two sections give an indication of the method of applying irrigation water to the topsoil during a rain-free winter, as well as during a very rainy summer. Furthermore it shows that under the "moist topsoil" management (drying out to —70 kPa) less irrigation water was applied and rain was utilized more efficiently, than under the "very moist topsoil" management and the "wet topsoil" management of tensiometer controlled high frequency irrigation.

4.3 The use of tensiometers

Tensiometers are often regarded in irrigation practice and in the literature, as being cumbersome and unreliable respectively. In this study the following three disadvantages were confirmed:

i) There was a time lag between the moment of irrigation or moisture replenishment, and the moment of correct registration by the tensiometer of that specific moisture potential.

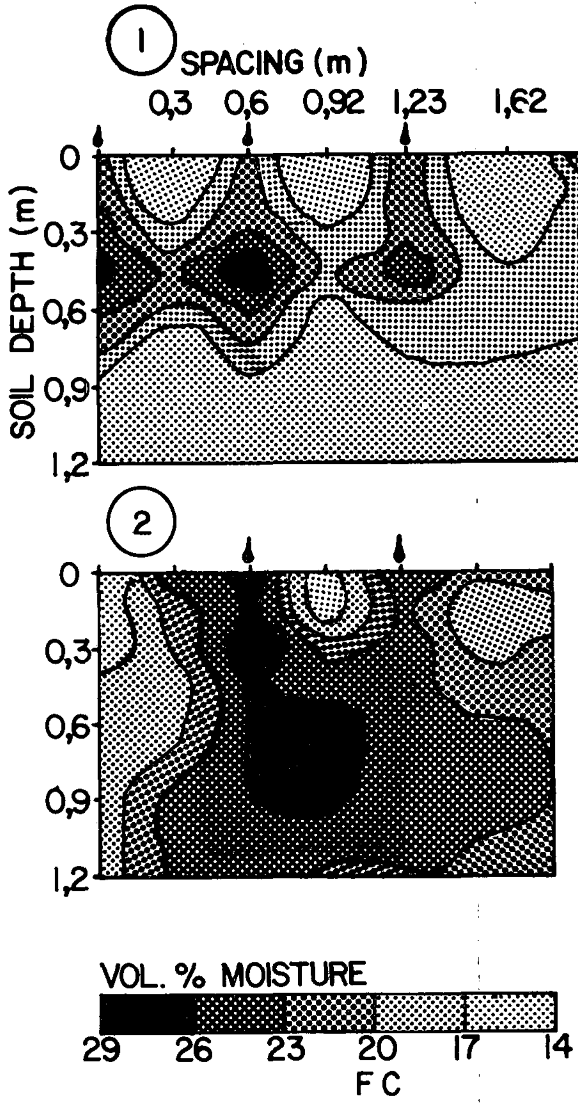

Figure 15
Soil moisture profiles below drippers on the Shorrocks soil at Pretoria under 1) good "wet topsoil" irrigation management and 2) bad irrigation management (over-irrigation)

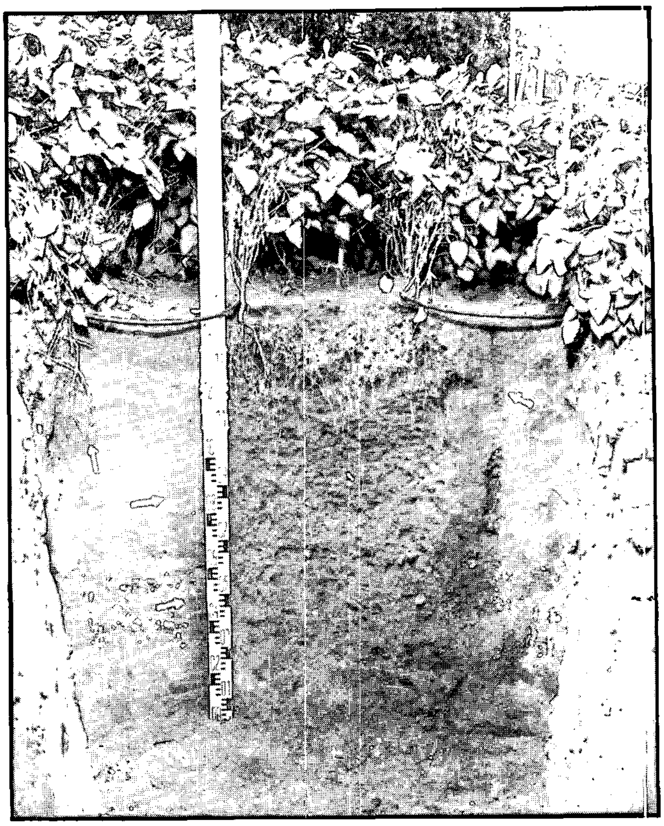

Figure 16
Soil moisture and root profile of soybeans on the Shorrocks soil at Pretoria

ii) There were variations between readings of tensiometers at the same soil depth of about 5 to 10 kPa. This was the result of either careless tensiometer installation or the textural heterogeneity of the soil, or both. The original set of tensiometers had to be supplemented by more tensiometers.

iii) The position of the $T_{0,3}$ at a distance of 0,3 m from a *dripper* had to be very carefully determined, otherwise wrong readings would result.

However, several advantages were recorded:

i) Tensiometer readings showed qualitatively the depth of the percolating irrigation water front, thus indicating over-irrigation and under-irrigation.

ii) Tensiometer readings were quantitatively used to obtain the moisture retention curves of individual layers in the soil profile, and thereafter were used to calculate the volume of the moisture that drained away, the volume of capillary moisture that moved up and the volume of moisture that was used by the plants.

iii) The possible variation of the result of the calculation of over-irrigation was ± 30%, i.e. the calculation of the $K - \psi$ boundary curves of Fig. 5 resulted in a ± 30% variation from the average K-value. Although the variation of the result of the soil moisture calculation could be ± 9% (Fig. 4), the variation of the former values for the water usage and the following values for the ET-plant/E-pan ratio was only + 6%. This was so, because of the small difference in soil moisture from the day before irrigation to the day before the next irrigation, in comparison with the large volume of applied water under the medium frequency irrigation management during the same period.

iv) Finally, the accuracy of the tensiometer readings and calculations was improved by carefully de-airing, installing and servicing the mercury manometer tensiometers, by choosing two or three measurement positions for the control of the same management, and by using at every measurement position two or three tensiometers at the 0,3 m depth, two at the 0,6 m depth, and one for the 0,9 m and 1,2 m depths. In this way the management of sprinkler, microjet and drip irrigation system was very well controlled.

4.4 Water usage and crop yield

The water usages of ten years old Washington navel citrus trees during September and October 1974 and 1975, under different irrigation management, are summarised in Table 4. The water usage is obtained by measuring the moisture withdrawal beneath an area of 10 m^2 per tree. From the measurements it was clear that there was virtually no available moisture in the soil profile between the trees during the rainfree months of September and October. In Table 4 it is shown that the water usage of a navel orange tree under various irrigation managements was a maximum of about 41 *l*/d. Although as little as 26 *l* water per day per tree were used with four drippers per tree under the "wet topsoil" management, and no leaf wilting was observed, that figure is not fully reliable because of a lack of recorded yield. For periods of 25 to 38 days during September and October of 1974 and 1975 a ratio between evapotranspiration of the trees and evaporation from a Class A pan (plant/pan ratio) of 0,42 to 0,53 (for a water usage of 38–44 *l*/d per tree) and of 0,27 (for a water usage of 26 *l*/d per tree) was calculated from measurements. There was clean cultivation between the trees. In comparison herewith a ratio of 0,37 (Kp × Kc) was calculated by means of Table 19 (Kp is 0,67) and Table 28 (Kc is 0,55) from Doorenbos and Pruitt (1975), while Bredell (1977) used a ratio of 0,67. The latter found a higher crop production and a better quality of Valencias oranges with microjet than with drip irrigation. Unfortunately moisture movement into the subsoil was not measured.

The total dry mass of the top growth of soybean plants was about 56, 90, 85 and 133 g per plant, from dry land to the highest water usage. The yield of soybeans was about 2 400 kg/ha under dry land farming and about 3 200 kg/ha for the other three irrigation managements. For the fortnightly periods of January and February the following ratios were calculated, viz. 0,60; 0,60; 0,84 and 0,91 respectively, as averages for the "moist topsoil" and "very moist topsoil" irrigation management.

The water usages and companion wheat yields are plotted in Fig. 17. The water-yield curves show that the efficiency of water usage (yield per unit water) remained constant for the moisture withdrawal under all managements starting with dry land farming, *via* irrigation at the plant critical stages and commercial irrigation, to the nomogram irrigation. The latter gave the highest yield. In contrast, the *efficiency of water usage* under the "very moist topsoil" and "wet topsoil" management for Pretoria decreased, although the *efficiency of irrigation water application* remained the same during the rainfree winter for the three types of high frequency irrigation management, according to the previous section. The heavy uncontrolled aphis infection of the wheat on the Makatini soil at Groblersdal may account for the lower position of the appropriate curve.

For different periods in August, September and October 1976 the ET-plant/E-pan ratios were calculated. Every period

TABLE 4
TOTAL WATER USAGE OF A NAVEL ORANGE TREE AND ET-PLANT/E-PAN RATIOS FOR DIFFERENT TYPES OF IRRIGATION MANAGEMENT AND DIFFERENT PERIODS

Year	1974					1975		
Type of Irrigation	No Irrigation	"Wet Topsoil"		Commercial	"Very Wet"	"Wet"	"Very Wet"	"Wet"
					4 drippers	4 drippers	8 drippers	8 drippers
Period	19/9–29/9	29/9–23/10	23/10–20/11	20/9–28/10	22/9–24/10	19/9–25/10	29/9–24/10	29/9–23/10
Number of days	10	24	27	38	32	36	25	24
Rain (mm)	0	15	23	0	0	0	0	0
Rain (*l*, per 10 m^2)	0	150	230	0	0	0	0	0
Irrigation (*l*)	0	564	840	1 827	912	600	1 416	774
Total water supply (*l*)	0	714	1 070	1 827	912	600	1 416	774
Total water supply (*l*/day)	0	30	40	48	29	17	57	32
Drainage (*l*/day)	6	1	1	17	8	0	28	9
Plant available water supply (*l*/day)	−6	29	39	31	21	17	29	23
Soil moisture usage (*l*/day)	50	−2	3	10	17	8	4	18
Total water usage (*l*/day)	44	27	42	41	38	25	33	41
Class A-pan (mm/day)	9,3	10,5	8,0	9,0	9,0	9,0	9,0	9,0
Class A-pan (*l*/10 m^2)	93	105	80	90	90	90	90	90
PAN FACTOR (PLANT/ PAN RATIO)	0,47	0,26	0,53	0,45	0,42	0,28	0,37	0,45

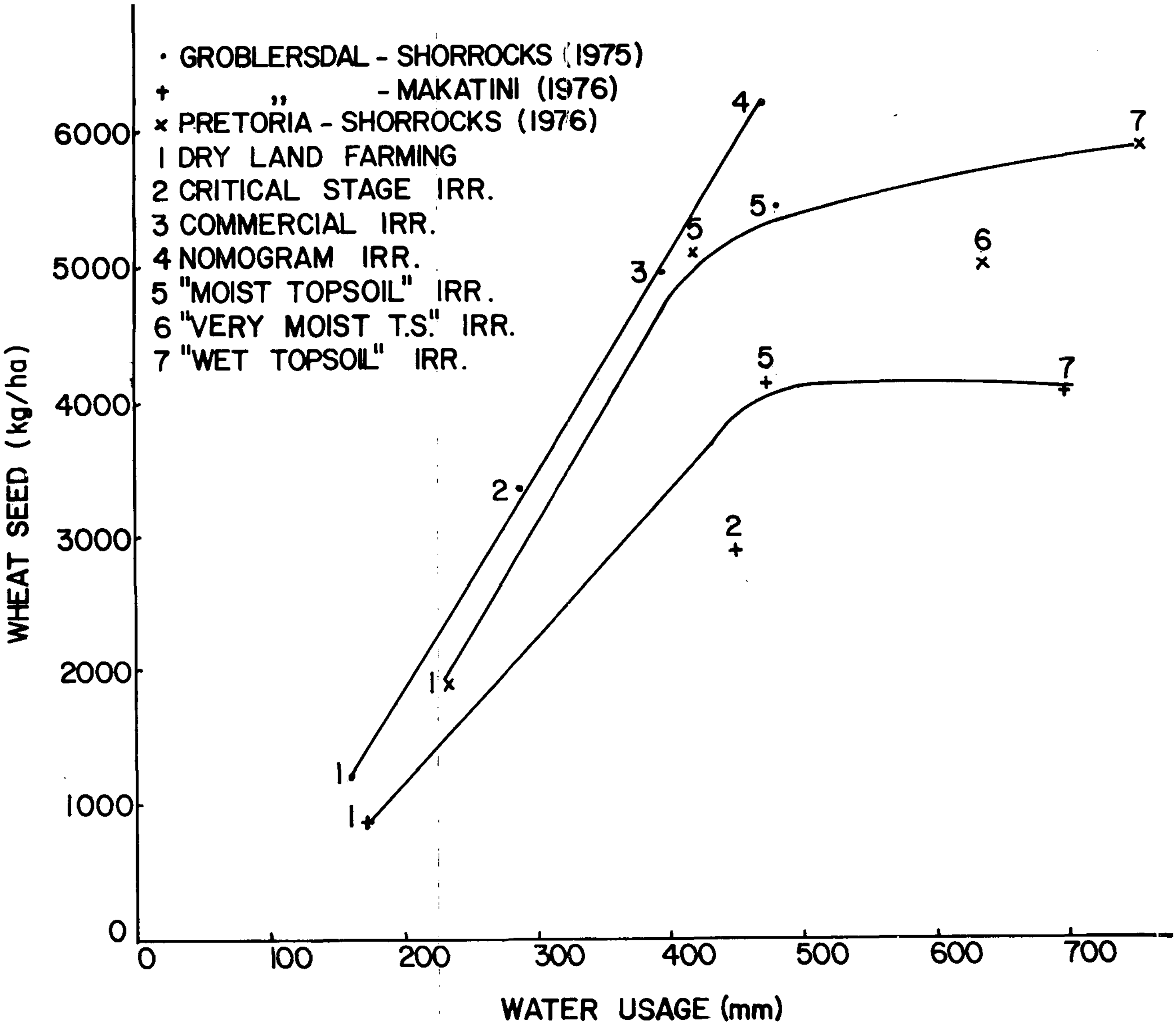

Figure 17
Water usage and Inia-wheat seed yield for three different soils and seven different types of irrigation managements

started on the day when $T_{0,3}$ was lower than −70 kPa and the crop was irrigated, and ended when $T_{0,3}$ was again lower than −70 kPa, just before the next irrigation. In this way there were 15−21 days per period to 20 September and 43 days for the last period at the end of the growing season at Groblersdal. The periods for the Pretoria season comprised 9−13 days each. Fig. 18.1 and 18.2 give a picture of scattered points and various lines. The scattering is partly a result of the different types of irrigation management (from dry land to "wet topsoil"), by which different numbers of irrigation per season and different quantities of water per irrigation were applied. The base curve (lower-limit curve) of all those points which represent four or more irrigations per season is the line through the 0,6 ratio level declining to a ratio of 0,45 at the end of the season. For both the Groblersdal and Pretoria area two separate lines are drawn: one representing the ratios under normal or "moist" water supply with a drip system and the other representing "wet topsoil" management with a drip system, i.e. luxury water consumption. A third line for the highest ratios is obtained from the results of the microjet system near Pretoria.

The 0,6 ratio line can be used as a base for irrigation scheduling. However, a sequence of 0,75; 0,77; 0,90; 1,05; 0,70 and 0,45 (Aug. − Oct.) according to the normal line will provide more available soil moisture during the season and a higher yield when soil fertility is not limiting. The position of the tops of all the drip-curves above a ratio of 1,0 can possibly be explained by the fact that each irrigation treatment area was only about 14 m², in which the height of the wheat was above that in the adjacent dry land area. This could have caused a higher water consumption than would have been the case in the centre of a large area of similarly irrigated wheat. However, there was no difference between the ratios of a 14 m² and a 50 m² area in the 1977 trials.

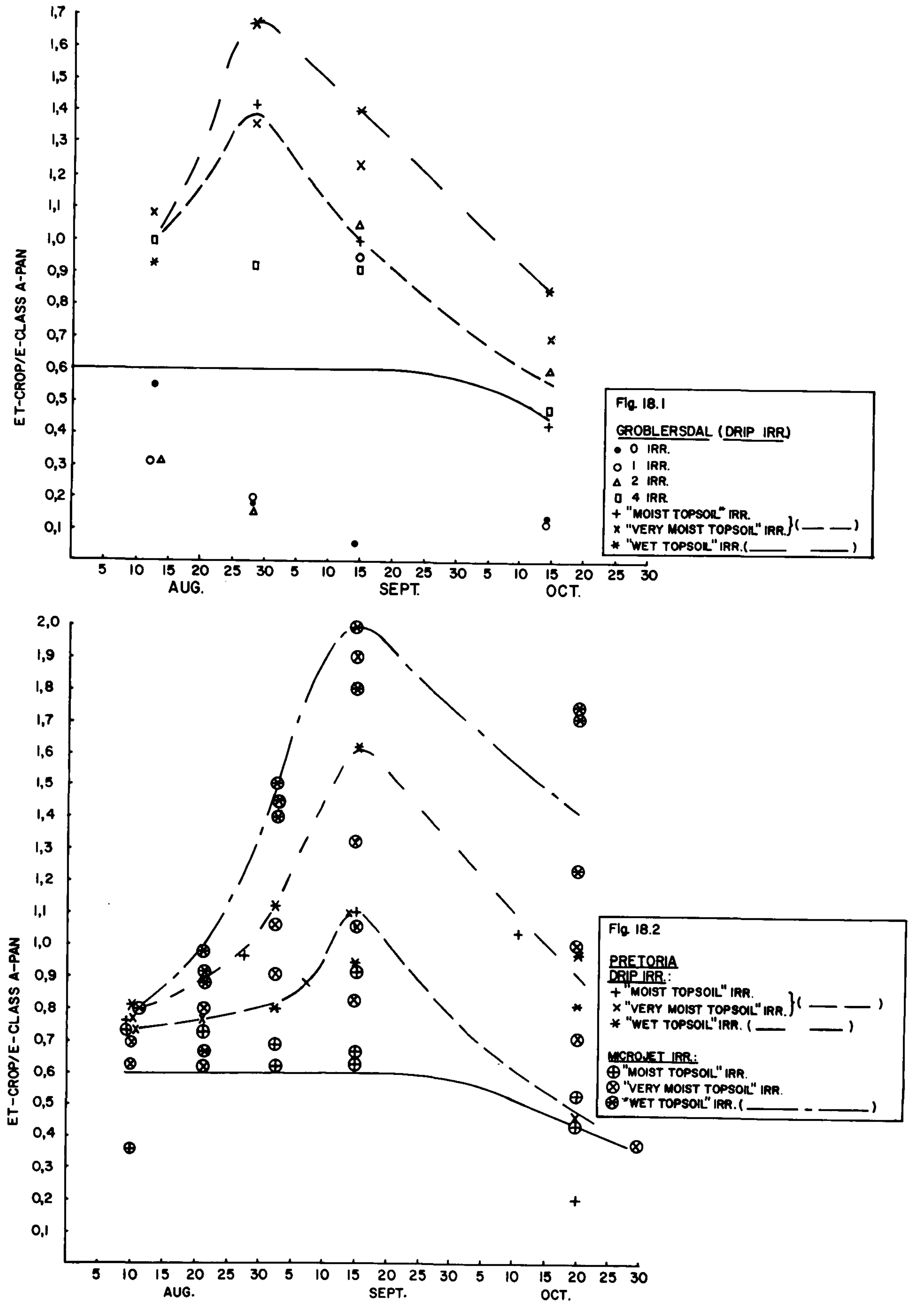

Figure 18

ET-crop/E-Class A pan ratios for wheat and for different types of irrigation management during a part of the growing season at Groblersdal and Pretoria

5. Conclusions

The purpose of this irrigation research was to find an improved type of irrigation management to prevent over-irrigation and under-irrigation in order to decrease the long term danger of salinisation of irrigated soil, and to obtain the highest yield per unit water during short term water scarcity.

5.1 Correct irrigation management

This goal was achieved by means of tensiometer controlled medium frequency irrigation, and the use of both the moisture retention curve and the $K - \psi$ curve. Under medium frequency irrigation, that is irrigation four times a day with an irrigation duration of 0,5 h each (drip irrigation of navel orange trees), or 3 h and 2 h on two consecutive days per week (drip irrigation of wheat) less water per irrigation was applied. The volume of irrigation water, which had to replenish the used soil moisture, was calculated beforehand by means of the tensiometer reading and the moisture retention curves. Finally, the real depth of water penetration and the velocity of moisture movement was checked and calculated by means of the readings of $T_{0,3}$ (tensiometer at 0,3 m depth below the soil surface), $T_{0,6}$, $T_{0,9}$ and $T_{1,2}$ and the $K - \psi$ curves.

For correct irrigation the following criteria were found to apply:

(i) The $T_{0,3}$-reading should drop to about -70 kPa and may even stay there for about three days before the next irrigation is applied to the wheat crop (this is "moist topsoil" management). For the navel orange trees, the $T_{0,3}$-reading can be allowed to drop to about -25 kPa by manipulating the frequency and duration of the several irrigations per day (this was 'wet topsoil" management).

(ii) The $T_{0,6}$-reading should be allowed to drop to about -60 kPa during the first two months of the season, and is not allowed to increase more than to about -25 kPa after every irrigation. When after irrigation the $T_{0,6}$-reading is still at -60 kPa, this means that no soil moisture is replenished at that depth and a hard soil layer may develop which prevents root proliferation, this is under-irrigation. When the $T_{0,6}$-reading increases to -10 kPa, a lot of irrigation water has moved beneath a depth of 0,6 m into the subsoil, this is over-irrigation.

(iii) The $T_{0,9}$-reading should be allowed to drop beyond -25 kPa to about -60 kPa. This and the $T_{0,6}$ kPa reading means that the moisture of the subsoil is used by the crop, while the velocity of irrigation water movement at that small reading beneath a depth of 0,6 m is so low that this and some rainfall can be stored in the 0,6—0,9 m soil layer without much drainage to the subsoil.

In principle topsoil irrigation management encourages salinisation. *Therefore this type of irrigation management is only recommendable in regions where there is enough rainfall to leach the salts out of the top of the soil profile.* During the years of these investigations salt accumulation was not observed, although this was only confirmed by measurements at Zebediela.

5.2 The use of tensiometers

Tensiometers can be used qualitatively to indicate the depth of irrigation water penetration. They can also be used quantitatively to plot the moisture retention curve and to calculate the volume of water draining away, the volume of capillary water moving up and the volume of moisture used by the plant. Reliable tensiometer readings for the above criteria and calculations can be obtained by carefully de-airing, installing and servicing mercury manometer tensiometers, and by using two or three tensiometers at a depth of 0,3 m, two at a depth of 0,6 m and one at depths of 0,9 m and 1,2 m, all of them on one position, and this set of tensiometers repeated on two or three positions per irrigation management.

5.3 Water usage (watersaving) and crop yield

5.3.1 ***Drip irrigation of navel orange trees.*** It was possible to decrease the 30% over-irrigation, under the Zebediela commercial management during July, August and September, to a 0—5% over-irrigation by means of tensiometer controlled "wet topsoil" management. Instead of four drippers per tree, eight drippers per tree were necessary, and instead of 67 *l* water per tree per day, only 41 *l* water per day were applied. This saving is significant when water is scarce. However, to move away from over-irrigation may easily lead to under-irrigation, e.g. where drippers are exposed to the sun, and during the critical flowering stage.

5.3.2 ***Sprinkler irrigation of wheat.*** It was possible to save 78 mm water per unit area during the growing season by means of tensiometer controlled sprinkler irrigation on a soil with a high ground water table at Groblersdal. Irrigation frequency increased in the following sequence: plant critical stage irrigation, commercial irrigation and nomogram irrigation. In the same order more water was used (up to 471 mm), but the Inia-wheat yield increased proportionally to 6 100 kg seed per ha.

5.3.3 ***Drip irrigation and microjet irrigation of wheat.*** Under the "moist topsoil" dripper management and microjet management the water usage was 476 mm and 421 mm, and the seed yield 4 000 kg/ha and 5 000 kg/ha respectively. In contrast, under the "wet topsoil" dripper and microjet management 729 mm and 760 mm water were used and yields of 4 000 kg/ha and 5 700 kg/ha obtained respectively, this was luxury water consumption. These figures for drip and microjet irrigation might be used as well for flood and sprinkler irrigation respectively.

5.3.4 ***Drip irrigation of soybeans (SSS. 3).*** Under the "moist topsoil" and "very moist topsoil" management an average seed yield of 3 200 kg/ha was obtainable from a water consumption of 528—637 mm.

5.4 ET-plant/E-Class A pan Ratio

For the correct drip irrigations, such as "wet topsoil" management for navel orange trees, the "moist topsoil" management for wheat — 1976 and the "very moist topsoil" management for soybeans, the following ratios can be used:

Ten year old Navel orange trees at Zebediela: during July, August and September, ratios of 0,42—0,53.

Wheat: a fortnightly sequence of 0,75; 0,77; 0,90; 1,05; 0,70 and 0,45 with the highest ratio on Aug. 27 at Groblersdal and on Sept. 15 at Pretoria.

Soybeans: during January and February a fortnightly sequence of 0,60; 0,60; 0,84 and 0,91.

The ratios found may be used for irrigation planning, but for daily irrigation management they should always be used in combination with tensiometers or soil augers, because the ratios depend on the length of the irrigation cycles.

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*Students of the Hogere en Middelbare Bosbouw en Cultuurtechnische School at Arnhem and the Hogere Tropische School at Deventer, the Netherlands.

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