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SOIL WATER USE BY APPLE TREES

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A B S T R A C T

SOIL WATER USE BY APPLE TREES

The study investigated the soil water use of an unirrigated tree and an irrigated apple tree in Hawke's Bay, New Zealand in the middle of the summer of 1988/1989. A rainout shelter was used to eliminate any water inputs from both irrigation and rain to the unirrigated tree. The irrigated tree received water inputs from both irrigation and rain. The soil water content was measured by neutron probing and time domain reflectometry. The heat pulse technique was used to measure the sap-flow in the apple trunks. Both leaf water pressure potential and stomatal resistance were measured by the pressure chamber and porometer respectively. A measuring cylinder was used to monitor the apple growth during the study.

The results of the water use measurements were that

- the neutron probing and time domain reflectometry showed the soil water use was about 77 litres (4.3 mm) per day taken from 0 - 1900 mm depth around the irrigated tree. However soil water extraction around the unirrigated tree was only 19 litres (1 mm) per day at the beginning of the study, and no water extraction was measured from the top 1900 mm later in the study.
- the heat pulse technique showed that the unirrigated tree extracted slightly more soil water than the irrigated tree. The average sap-flow measured was 66 litres per day. Probably the unirrigated tree extracted much of its water from below 1900 mm depth, or from beyond the covered area.
- the amount of water use by the apple trees was similar to regional evaporation estimates obtained using the Priestley - Taylor formula, when 0.66 fractional canopy cover was assumed.

The water stress monitoring showed that the pressure chamber technique was a more sensitive way to monitor stress than was porometry.

The leaf water pressure potential values showed a significant difference between the irrigated and the unirrigated apple tree during the latter part of the study.

The readily available soil water storage capacity from 0 to 400 mm depth (the most active part of the root zone), from 0 - 1000 mm depth, and from 0 to 1900 mm, was about 36 mm, 89 mm and 170 mm respectively. When there was a lack of available soil water on the soil, the root system was forced to extract soil water from deep in soil profile.

The comparison of apple fruit growth showed that during the last days of the study, the apples on the unirrigated tree grew more slowly than those on the irrigated tree.

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CHAPTER I

THE WATER BALANCE OF APPLE TREES

1.1. INTRODUCTION

Fruit and vegetables are in the top six New Zealand exports, after meat, wool, butter, forest products, and aluminium and alloys. The value of fruit and vegetables is about 7 percent of the national export receipts. Apples are the second most important commodity in the fruit export sector after kiwifruit (HEDC, 1982). The national apple production is about 155 million tonnes/annum (Wong, 1987). Thus apples are an important New Zealand export commodity.

Apple orchards usually use irrigation systems to overcome soil water deficits during dry periods when evaporation is greater than rainfall, and so to obtain the maximum yield and fruit quality. Using an irrigation system involves defining when and how the optimal amount of water should be applied in an orchard. Otherwise the orchard will receive either over-irrigation or under-irrigation. Over-irrigation has several disadvantages, namely :

- higher irrigation expenses,
- nutrient leaching which can affect ground water quality and increase fertiliser cost,
- plant health problems due to water logging,
- decreased yield and fruit quality

On the other hand, under-irrigation causes plants to become unhealthy due to water stress and low soil nutrient availability. Thus it is important to investigate the amount of irrigation needed.

Irrigation is a water input, which is a component of the water balance. The understanding of the balance of the water inputs and outputs in an apple orchard is very important, because an unfavorable water balance can affect the apple tree development which can affect the export quantity and quality.

1.2. THE WATER BALANCE

Mass conservation can be used to explain the soil water balance (Hillel, 1982). In the root zone of an orchard over any time interval Δt , the change in storage equals the water inputs minus the outputs.

The inputs are rainfall (R) and irrigation (I), and the outputs are evaporation (E), drainage below the root zone (D) and surface runoff (S). In this thesis evaporation refers to all water vapour loss to the atmosphere, and so includes transpiration, evaporation from the soil and evaporation of intercepted water. So

$$\Delta W = R + I - E - D - S \quad (1.1)$$

where ΔW is the change in the water storage in the root zone, and all terms have dimensions of length, being equivalent depths of water.

1.2.1. WATER INPUTS

Water inputs in the orchard are rainfall and irrigation water. Rainfall and irrigation are treated as independent variables and must be measured (Scotter et al., 1979). When water inputs bring the soil to "field capacity", then the soil water deficit is assumed to be zero (Taylor and Ashcroft, 1972). Excess water input leads to water redistribution and drainage beyond the root zone. But drainage losses during summer will be small if the irrigation system is well managed.

In orchards infiltration with water ponded on the surface is rare. It usually only occurs during heavy rain and on less permeable soils. Most of the water falling on the land, as either rain or sprinkler irrigation, infiltrates as unsaturated flow (Philip, 1969).

1.2.2. WATER OUTPUTS

Given no surface runoff, the water outputs in the orchard are evaporation, and drainage water, which only occurs when there is excess water input. The understanding of evaporation is very important in agriculture and horticulture because evaporation is a major term in the soil water balance.

When the humidity in the atmosphere outside the leaf cuticle is lower than in the intercellular spaces within a leaf, there is molecular diffusion of vapour outwards through the stomata. The number and degree of opening of the stomata, and the humidity gradient control the rate of diffusion. The continual transpiration from leaves needs three physical conditions. Firstly, a supply of energy must be available to provide the quite large latent heat of vaporation. Secondly, there must be a lower vapour pressure in the surrounding air than at the evaporating surface. Thirdly, there must be a continuous supply of water. This is the rate limiting factor for transpiration in dry condition (Rose, 1966; Meidner and Sherif, 1976; Milburn, 1979).

Transpiration from plant leaves causes a water potential gradient between leaves and roots. The root water absorption and sap flow depend not only on the leaf water potential, but also on the soil water potential and hydraulic conductivity. On the other hand, the atmospheric environment largely determines the rate of evaporation from the leaves, because the opening of stomata depends on environmental variables such as the solar radiation received, and the humidity gradient between inside and outside the stomata. Thus, the whole soil-plant-atmosphere continuum affects the amount of water lost by evaporation (Philip, 1966). Often however the atmosphere has the dominant effect on the rate of evaporation as the process is usually energy limited.

When evaporation from bare soil can be ignored, such as in a region which is completely covered by vegetation, and soil water is always available, the root water extraction rate can be assumed to be equal to the evaporation rate. Then, provided adequate soil water is available, estimates of regional evaporation using climate data can be used to estimate root water extraction (Thornthwaite, 1948; Blaney and Criddle, 1950, Penman, 1948, Priestley and Taylor, 1972). The actual evaporation is usually measured only for research purposes.

1.3. THE STUDY

The aim of the study was to investigate the soil water use by two apple trees in Hawke's Bay.

One apple tree was covered by a rainout shelter over the soil surface to eliminate any water input from irrigation and rainfall, and to prevent any water output from soil and grass evaporation. Thus transpiration is the only water use around this unirrigated tree.

The other apple tree had no any cover. This tree received water inputs from both irrigation and rainfall. The water use consisted of transpiration and both soil and grass evaporations around the tree.

The water use of both trees was investigated by using

- neutron probing and time domain reflectometry to monitor spatial and temporal soil water content changes, reflecting the root water extraction,
- the heat pulse technique to measure the sap flow in the tree,
- meteorological data to estimate regional evaporation around the orchard.

The unirrigated tree was expected to come under water stress, while the irrigated tree was expected to remain unstressed. To detect the level of plant water stress, a porometer was used to measure the stomatal resistance and a pressure chamber was used to measure the leaf water pressure potential. Soil matric potential was measured with tensiometers. Finally, a measuring cylinder was used to monitor the apple fruit growth on the two apple trees.

CHAPTER II

SITE DETAILS AND METHODOLOGY

2.1. THE SITE

The research was carried out in the orchard of Mr. Van Howard, called the "RED APPLE", along Napier Road, Hastings, about 5 km from Havelock North.

The soil of the orchard was a permeable alluvial Twyford soil. The Karamu Stream runs adjacent to the orchard. Excessive water inputs, due to heavy rainfall or over-irrigation of the orchard, could cause leaching losses of plant nutrients to below root zone depth, and eventually pollute the stream. This would contribute to the serious weed and algal problems in the Karamu Stream. The difference in level between the orchard soil and the stream was about 4 m.

The irrigation system used on the orchard was a micro jet type. The water was drawn from a well. The micro jet emitters could irrigate to a radial distance of about 2 m, and were located between alternate trees along each row.

2.1.1. THE SOIL

The alluvial Twyford sandy loam in the orchard is a Recent soil formed through regular deposition of materials eroded from soils and rocks in the catchment drained by the Karamu stream. Because the soil materials were transported and deposited by the stream during its formation (Gibbs, 1980), the soil shows substantial variation within a distance of a few metres. Thus there is usually no well-defined soil profile.

The classification of the Twyword sandy loam in the NZ Genetic system is a Recent soil from greywacke alluvium, while in US Soil Taxonomy it is a Fluventic Udic Ustochrept, coarse loamy mixed mesic. The soil occurs near most of the streams and rivers of mid Hawke's Bay. The soil's bulk density is about 1.25 to 1.4 Mg/m³.

The Twyword soils range from well drained to excessively drained. A humus rich topsoil and a more stable structure can develop when the soil has not been flooded for an extended period.

The soil is a good soil for both agriculture and horticulture. To make the most of its potential productivity, the soil needs irrigation. On the other hand, irrigation with excess water can cause the accumulation of drainage water in lower areas (Pohlen et al., 1947).

2.1.2. THE ORCHARD

The apple trees (Malus sylvestris Var. Royal Gala) were planted about 18 years ago at a spacing of 5 m between rows and 3.6 m between trees in the rows. Figure 2.1. shows typical apple trees in the orchard during the fruiting period.

Grass strips between the rows were about 2.6 m wide, and bare soil strips were about 2.4 m in width in the tree rows. The grass was regularly mown to keep it short. Shelter trees, poplar, were planted along the orchard border.

2.1.3. ROOT DISTRIBUTION

Since the apple trees are mature (18 years old) the roots had fully explored the topsoil between them (K.A. Hughes, *pers. comm.*). Rogers and Head (1969) also found that the roots of mature apple trees had a uniform distribution horizontally.

Figure 2.2(a) shows the average root length density with depth averaged over all radii. The highest root density was found in the top 200 mm and the next highest between 200 and 400 mm depth. The



Figure 2.1. Apple trees in the orchard during the fruiting period.

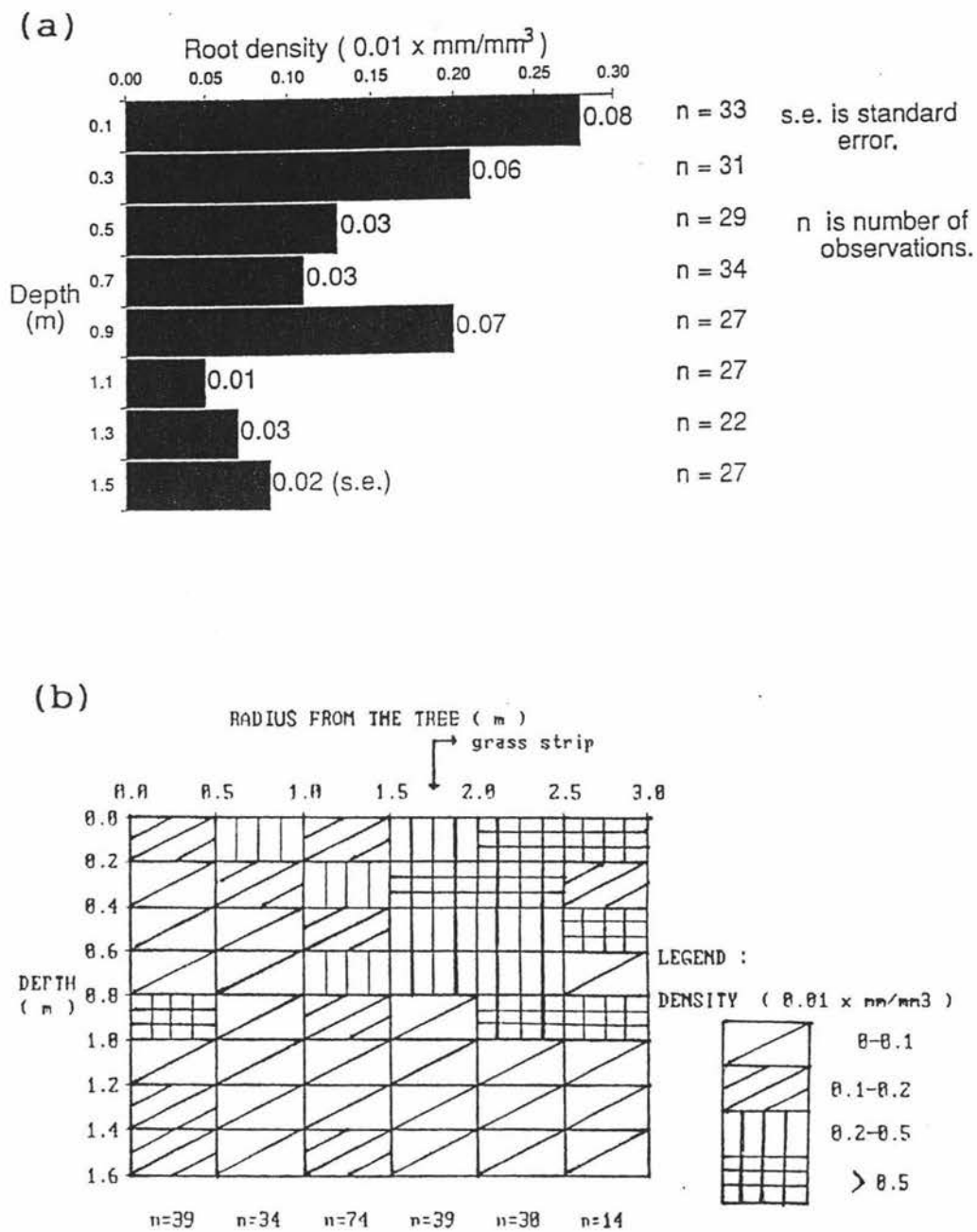


Figure 2.2. The average root length density measured with depth for all radii (a) and with depth in various radial classes (b) (K.A. Hughes, pers. comm.)

high density between 800 - 1000 mm depth is probably due to the existence of a finer soil layer at that depth. The soil water data in Figure 4.1. also suggest this. Measurements were only made to 1500 mm depth, and a reasonable density of roots was still seen at this depth. So there was apparently root growth below 1500 mm depth. Radially, 2.0 to 3.0 m radius from the tree showed the highest root density, probably due to overlapping roots from adjacent trees there (see Figure 2.2(b)).

2.1.4. THE CLIMATE AND WEATHER

The rainfall in Hawke's Bay is usually fairly low. Average monthly rainfall for Havelock North is shown on Figure 2.3., based on data from 1950 to 1980 at station no. D96689, Havelock North, 9 m above sea level. The average Penman Regional Evaporation data (E_r) for Napier are also shown. The distance between the Havelock North meteorological station and the experimental site is about 1 km, so that rainfall at the station will be similar to that at the site. The evaporation values show the regional evaporation around Havelock North.

Figure 2.3. explains the typical monthly water balance in Havelock North. Water surplus usual occurs from April to September. On the other hand, the region usually has a soil water shortage from October to March. The annual average rainfall is 798 mm and annual regional potential evaporation is 967 mm.

Table 2.1. shows the meteorological data, such as maximum and minimum temperatures ($^{\circ}\text{C}$), sunshine (hours/day), rainfall (mm), from the beginning to the end of observations. The regional evaporation estimate of Priestley and Taylor was calculated using procedures explained in Appendix A. For convenience in later discussion the days of intensive field study are numbered from 1 to 29 as shown in Table 2.1.

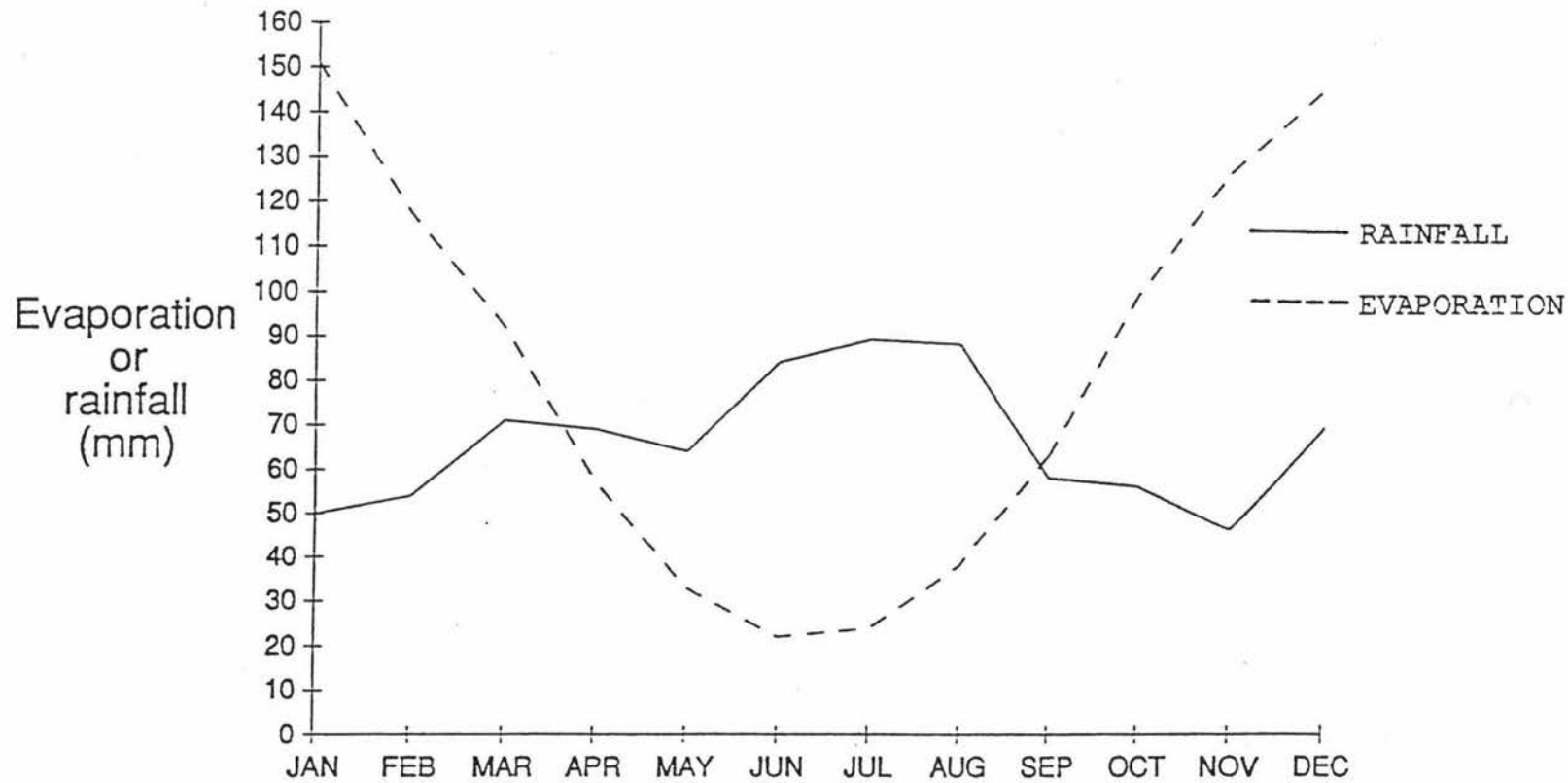


Figure 2.3. Average monthly rainfall (1959 to 1980) for Station D96689, Havelock North, 9 m above sea level, and average monthly Penman evaporation for Napier (NZ Met. Service, pers. comm.).

Table 2.1. Meteorological data for Havelock North
(Station no. D 9668A) from 13 December 1988
to 10 January 1989
(supplied by NZ Meteorological Service).

DAY:	DATE:	TEMP. MAX. (°C)	TEMP. MIN. (°C)	SUNSHINE (hours)	P & T* (mm)	RAINFALL (mm)
1	DEC 89, 13	24.3	16.2	2.0	2.7	-
2	14	25.0	8.2	10.2	5.5	-
3	15	17.4	15.1	0.0	1.8	-
4	16	20.3	8.4	10.3	5.3	-
5	17	22.7	5.5	13.6	6.4	-
6	18	29.7	8.5	11.5	6.2	-
7	19	22.0	9.6	6.0	3.9	-
8	20	22.5	16.6	7.8	4.9	-
9	21	25.0	15.3	9.5	5.6	-
10	22	26.1	16.1	3.2	3.3	-
11	23	21.0	14.5	9.1	5.2	-
12	24	21.5	13.5	13.6	6.8	-
13	25	22.9	9.9	13.0	6.5	-
14	26	23.2	13.7	14.1	7.1	-
15	27	23.5	15.9	14.0	7.2	-
16	28	24.4	12.3	3.3	3.1	0.8
17	29	21.2	18.3	0.0	2.0	14.0
18	30	22.3	17.9	0.4	2.1	8.3
19	31	23.4	17.6	2.4	2.9	10.4
20	JAN 90, 1	20.9	16.5	0.1	2.0	6.2
21	2	22.9	17.6	2.9	3.1	0.3
22	3	24.1	16.5	10.7	6.0	-
23	4	25.5	14.5	10.6	6.0	-
24	5	24.4	12.4	7.9	4.8	0.1
25	6	23.8	14.5	5.5	4.0	-
26	7	22.0	13.6	1.3	2.3	-
27	8	22.8	16.9	0.3	2.0	0.7
28	9	24.5	18.8	0.0	2.0	2.8
29	10	27.0	17.2	2.5	3.0	-
SUM :				185.8	123.7	43.6
MEAN :		23.3	14.2		4.3	

* Priestley and Taylor estimate of evaporation
(see Appendix A).

2.1.5. THE RAINOUT SHELTER

A rainout shelter was put in place around one tree to prevent all water inputs to this tree. Thus, the soil water extraction was assumed to be equal to the transpiration rate, as the shelter also prevented evaporation from the bare soil under the tree and the neighbouring grass strip.

The rainout shelter, which was also used in the summer of 1987/1988, has a steel frame, plastic "Lusterlite" roofing sheets, and a heavy plastic skirt. The steel frame, which was built by DSIR technicians, was about 6 m long and 2.5 m wide. The height was about 0.2 m at the centre and about 0.1 m at the edge. Inside the area covered by the shelter were tensiometer tubes, numerous TDR wave guides, neutron access tubes, and the heat pulse equipment. The roofing sheets were fixed on the steel frame and were opened when measurements were made. One roofing sheet had a hole as large as the trunk diameter to get the tree through the rainout shelter. The three pieces of heavy plastic skirt were attached on the edge of the steel frame and were joined to each other by zips. The grass covered by the skirt became yellowish due to a lack of solar radiation. Figure 2.4. show the rainout shelter when it was open for measurement. Figure 2.5. shows the effect the rainout shelter had on soil water content and so colour.

2.1.6. THE EXPERIMENTAL LAYOUT

The research concentrated on two individual apple trees, Tree U was the covered unirrigated tree and Tree I was an irrigated tree. Both irrigated and unirrigated trees were in the 4th row from the west corner of the orchard. The Trees I and U were the 6th and the 10th in that row (see Figure 2.6.). Subsequent references in this thesis to "irrigated" and "unirrigated" trees will always refer to Trees I and U respectively.



Figure 2.4. The rainout shelter around Tree U, open for measurements.



Figure 2.5. The difference between the soil within and outside the covered area around Tree U.

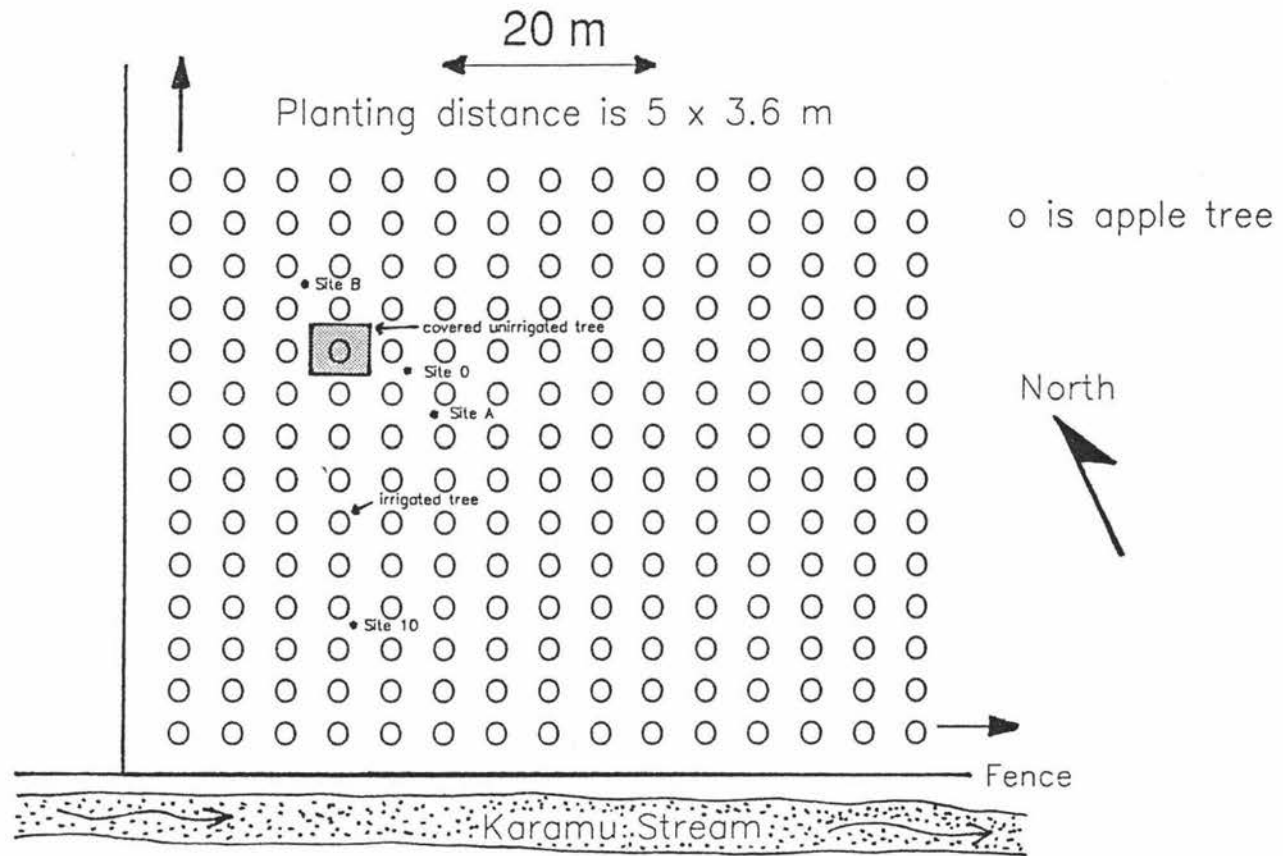


Figure 2.6. The layout of the experimental site in the apple orchard.

Around the irrigated tree there were 4 neutron probe access tubes (no. 1, 2, 3 and 4), 4 sets of TDR wave guides (no. 1, 2, 3 and 4), 3 tensiometer tubes (no. 1, 2 and 6) (Figure 2.7.). Each set of TDR wave guides consisted of 200, 400 and 600 mm depth wave guides. Around the unirrigated tree there were 5 neutron probe access tubes (no. 5 to 9), 11 sets of TDR wave guides (no. 5 to 15) and 6 tensiometer tubes (no. 3, 4, 5, 7, 8, and 9) (Figure 2.7.). In both trees the heat pulse technique equipment was installed to measure the plant sap flow.

2.2. MEASUREMENTS

The aim of the measurements was to explore the different behavior of the irrigated and unirrigated trees during the experiment.

The field experiment was carried out between 16 November 1988 and 10 January 1989. The rainout shelter was put over on 12 December 1988. The micro jet emitters around the unirrigated tree had been blocked several days before the rainout shelter was installed. The blocking caused a lower initial soil water content around the unirrigated tree. Typically an irrigation of about 24 mm was applied as a single application each week, with an application rate of about 2 mm/hour.

Irrigations were carried out on 15 December, immediately after fixing the rainout shelter, and on 29 December 1988. The other water input was rainfall. These water inputs either through rainfall or irrigation affected only the soil water storage around Tree I, the irrigated tree.

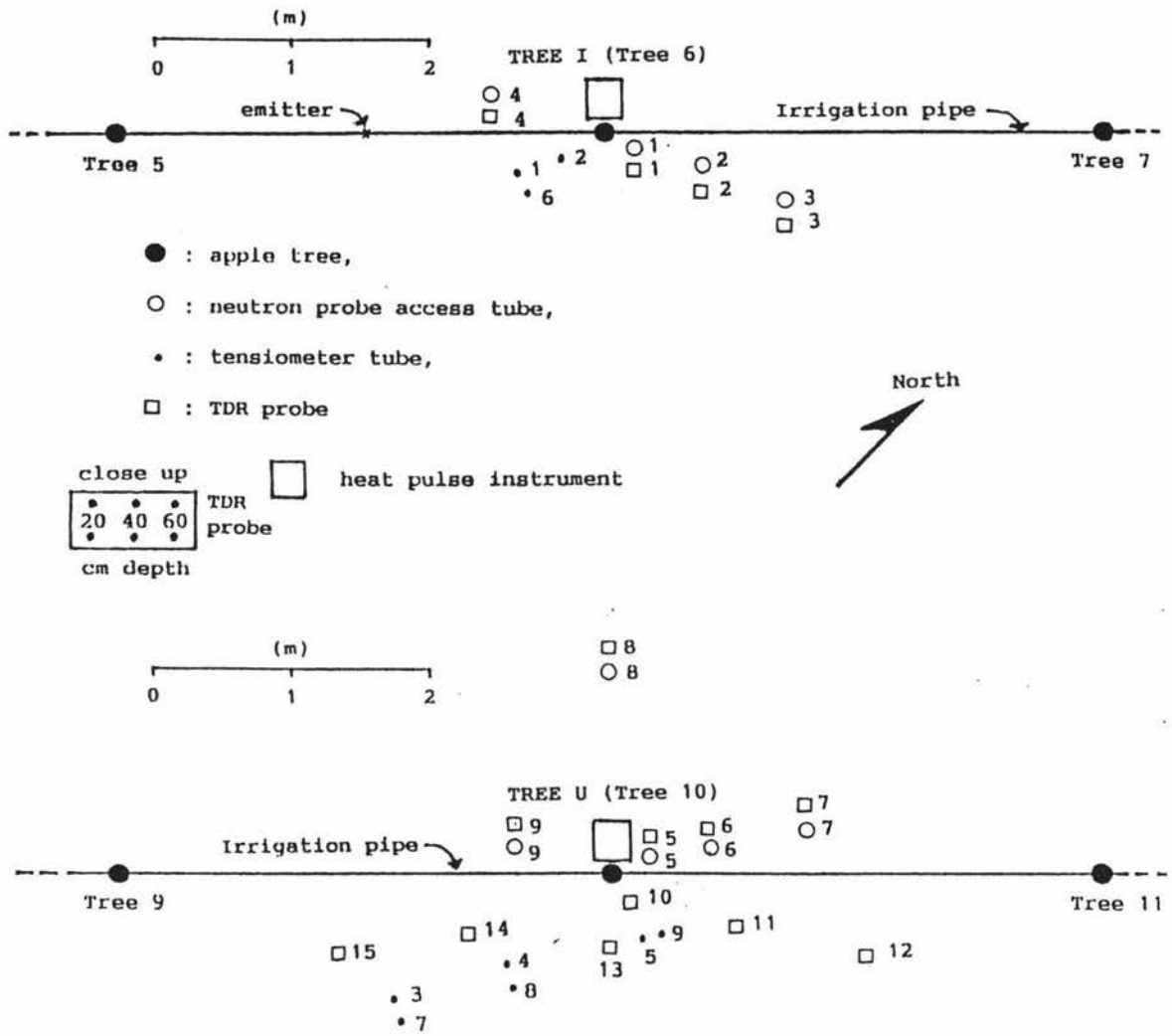


Figure 2.7. Layout around Tree I (above) and Tree U (bottom).

2.2.1. SOIL WATER CONTENT MEASUREMENT

The soil moisture content was measured using neutron probing and time domain reflectometry from 16 November 1988. The neutron probe instrument was used to measure the in situ volumetric soil water content and its change in time and space. In this study the probe was used to measure soil water content (m^3/m^3) at 400, 600, 800, 1000, 1200, 1400, 1500, 1600, and 1800 mm depth. Multiplying the soil water content (m^3/m^3) by the depth interval (m) gives the soil water storage in units of equivalent depth of water. The changes in soil water storage between 400 to 1800 mm depth could be monitored by repeated measurements of soil water content.

Since the research needed precise information about soil water content near the soil surface where the roots were densest, a portable IRAM-Time Domain Reflectometer was used. The neutron probe was not used to measure soil water content near the soil surface due to the escape of fast neutrons from the soil surface. Time Domain Reflectometer (TDR) measures the average volumetric soil water content (m^3/m^3) over the length of the guides, based on the dielectric constant of water in the soil. This allowed the water content of the top 400 mm of soil to be found. Thus the soil water storage from 0 to 1900 mm depth could be found when the TDR and neutron probe data were combined.

2.2.2. SOIL WATER PRESSURE POTENTIAL MEASUREMENT

Tensiometers were used to measure the soil water pressure potential (kPa). The tensiometers used during the research consisted of nine tensiometer tubes and one electronic pressure transducer. The tensiometer tubes consisted of PVC pipe with a thin ceramic cup on the bottom and a rubber septum on the top. The tensiometer tubes were filled with boiled water to avoid gas bubbles. Each tube was immersed into a prepared hole, and its ceramic cup adjusted to ensure a good contact with soil around the cup. The electronic pressure transducer had a hypodermic needle attached that could pierce the rubber septums to measure the pressure potential inside the tube.

2.2.3. SAP FLOW MEASUREMENT

Using heat as a tracer to measure the sap flow, the amount of plant water use can be found. This appears to offer a sensitive method for monitoring the dynamic water status of plants. This technique is called the heat pulse sap flow technique. The technique measured the sap flux density (m/day) directly in stems of intact apple trees with minimal interference. By multiplying the sap flux density (m/day) by the cross sectional area (m^2), the plant water use (m^3/day) can be calculated.

2.2.4. STOMATAL RESISTANCE MEASUREMENT

To monitor the level of plant stress, and to understand the diffusive resistance of leaves to water vapour, stomatal resistance was measured. A porometer, (made by DELTA-T DEVICES), was used to measure the stomatal resistance (s/cm)

2.2.5. LEAF WATER PRESSURE POTENTIAL MEASUREMENT

A portable pressure chamber was used to measure leaf water pressure potential (MPa). The pressure chamber technique has become the standard method to evaluate plant water status in the field.

2.2.6. APPLE FRUIT GROWTH MEASUREMENT

The plant under water stress may experience detrimental effects, especially reduced apple fruit growth. A special measuring cylinder was used to monitor apple fruit growth.

CHAPTER III

NEUTRON PROBE AND TIME DOMAIN REFLECTOMETER CALIBRATIONS AND TENSIO METER DESCRIPTION

3.1. NEUTRON PROBE

3.1.1. THEORY

The neutron scattering technique is quite popular for soil water studies, as the technique can be used to monitor the volumetric soil water content in the field without destructive sampling. The principle of the technique is that hydrogen nuclei in soil water are assumed the major soil component reducing the kinetic energy of fast neutrons, making them become slow neutrons in the thermal condition (Goodspeed, 1981). This occurs when the fast neutrons collide with the hydrogen nuclei in the soil. Energy transfer occurs in the collisions, so that the velocity of the fast neutrons decreases. After about 18 collisions, the fast neutrons become slow or thermalized neutrons (Visvalingam et al., 1972). The density of hydrogen nuclei counted is a reflection of the fraction of the soil volume consisting of water.

The measurement can be carried out by lowering the probe down into a 50 mm diameter aluminium access tube. The radioactive source emits fast neutron which pass into the soil. The detector, which is situated near the source in the probe, measures the intensity of the slow neutron 'cloud' in the sphere of influence. The scaler counts the thermalized neutrons detected. The count rate is proportional to the volumetric soil water content (Shirazi et al., 1976). The number of neutrons counted appears on the scaler screen after counting for a certain period of time. The period of time for counting can be adjusted to 15, 30, 45, 60 or 120 seconds. A 30 second period

counting time was used during the experiment. The count of slow neutrons, divided by the standard count, can be used to calculate the volumetric soil water content by using a calibration equation (Greacen, 1981). The standard count is a reading taken in the probe's shield. To reduce errors in measurements due to variations in electronic performance, radioactive decay, and due perhaps to temperature dependence in the electronics, the standard count has to be measured.

Although the technique has many advantages, it has one significant disadvantage. It is that the technique cannot be used to measure soil water content near the soil surface. The reason is that the radius of the sphere of influence, particularly in dry soil, is quite large. Consequently, if the probe is used to measure soil water less than about 200 or 300 mm deep, some fast neutrons escape through soil surface and so cannot be thermalized and counted by the detector. So the soil water content will be under-estimated. The soil water contents near the soil surface were very important in this research, as most of the active plant roots were near the soil surface. Thus, to measure the soil water content near the soil surface another instrument was used, namely the Time Domain Reflectometer, which will be discussed later.

3.1.2. METHODOLOGY AND CALIBRATION

The instrument used in the research consisted of a TROXLER 1255 neutron probe with a 100 mCi $^{241}\text{Am-Be}$ radioactive source, a detector placed near the source and a scaler. A calibration for this instrument was supplied, but it was decided to check its accuracy.

Calibration was carried out in the beginning of 1987/1988 summer. The Troxler 1265 was also used during the calibration. The volumetric soil water content measured by the Troxler 1255 (assuming the factory calibration), the Troxler 1265, and core sampling were compared at Site 0 and Site 10 (Figure 2.6.). The results of this comparison are shown in Figure 3.1(a) and (b), and indicate that although the Troxler 1255 and 1265 had similarly shaped profiles of soil water content with

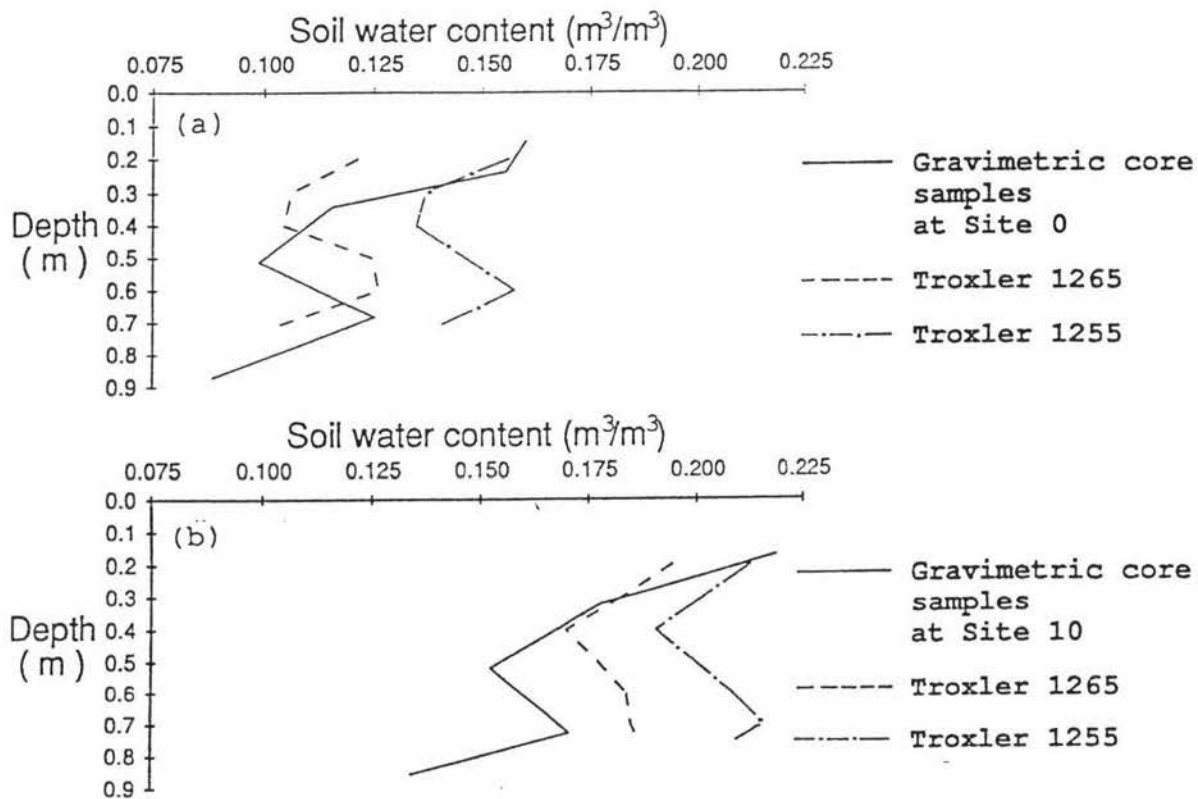


Figure 3.1(a). The soil water content profile at site 0, as measured gravimetrically on exhumed soil cores, and by neutron probing immediately afterwards.

Figure 3.1(b). The soil water content profile at site 10, as measured gravimetrically on exhumed soil cores, and by neutron probing immediately afterwards.

depth, the Troxler 1265 profile was closer to the core sampling values than the Troxler 1255. Thus, the Troxler 1265, which had been calibrated in the field by Clothier (1977), was used to establish a new calibration equation for the Troxler 1255 which was always used during the experiment.

A total of 299 contemporaneous measurements with both TROXLERs 1255 and 1265 probes were carried out. The calibration equation of the TROXLER 1255 derived from regression between soil water contents measured by TROXLER 1265 and count ratios measured by TROXLER 1255, as shown in Figure 3.2. is

$$\theta = 0.376 C_r - 0.0675 \quad (3.1)$$

where C_r is the count ratio of TROXLER 1255.

Figure 3.3. confirms that the new calibration equation of the Troxler 1255 was a lot better than the factory calibration, when compared to core data from Site A and Site B (Figure 2.6.).

3.2. TIME DOMAIN REFLECTOMETER (TDR)

3.2.1. THEORY

The Time Domain Reflectometer is a relatively new technique for measuring soil water content compared to the neutron probe. The instrument comprises a generator which releases an electrical pulse with a fast rise time step, a sampler which can transform a high-frequency signal into a lower frequency output, and an oscilloscope or other device showing the results of measurements. In the instrument used, the volumetric water content is displayed directly on an LCD screen.

The pulse generator creates an electromagnetic pulse which then is transmitted into the soil through a parallel rod transmission line (Topp et al., 1984; Baker et al., 1982). From the length of the

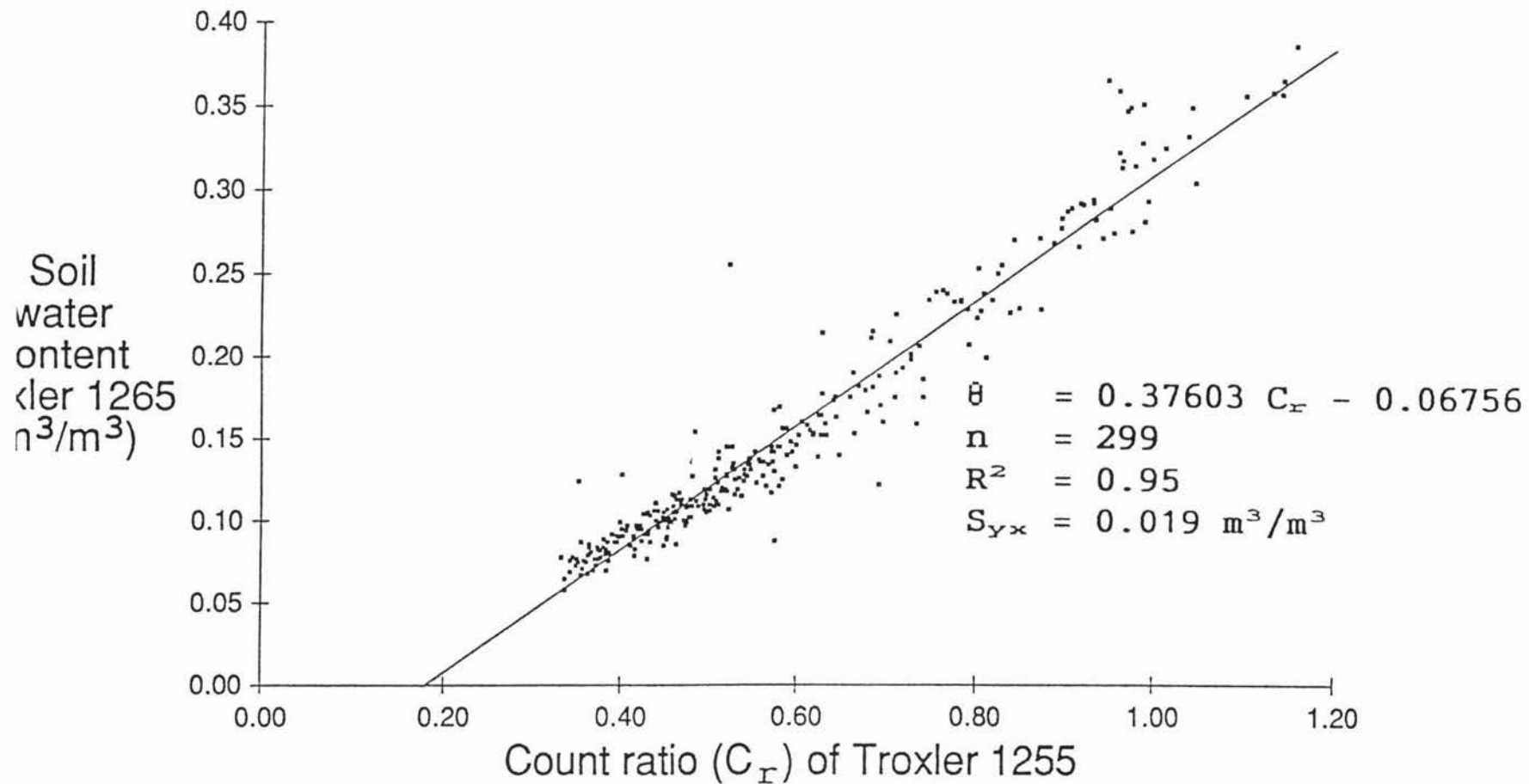


Figure 3.2. Comparison between the count ratio from the Troxler 1255 probe with the soil water content measured by the Troxler 1265.

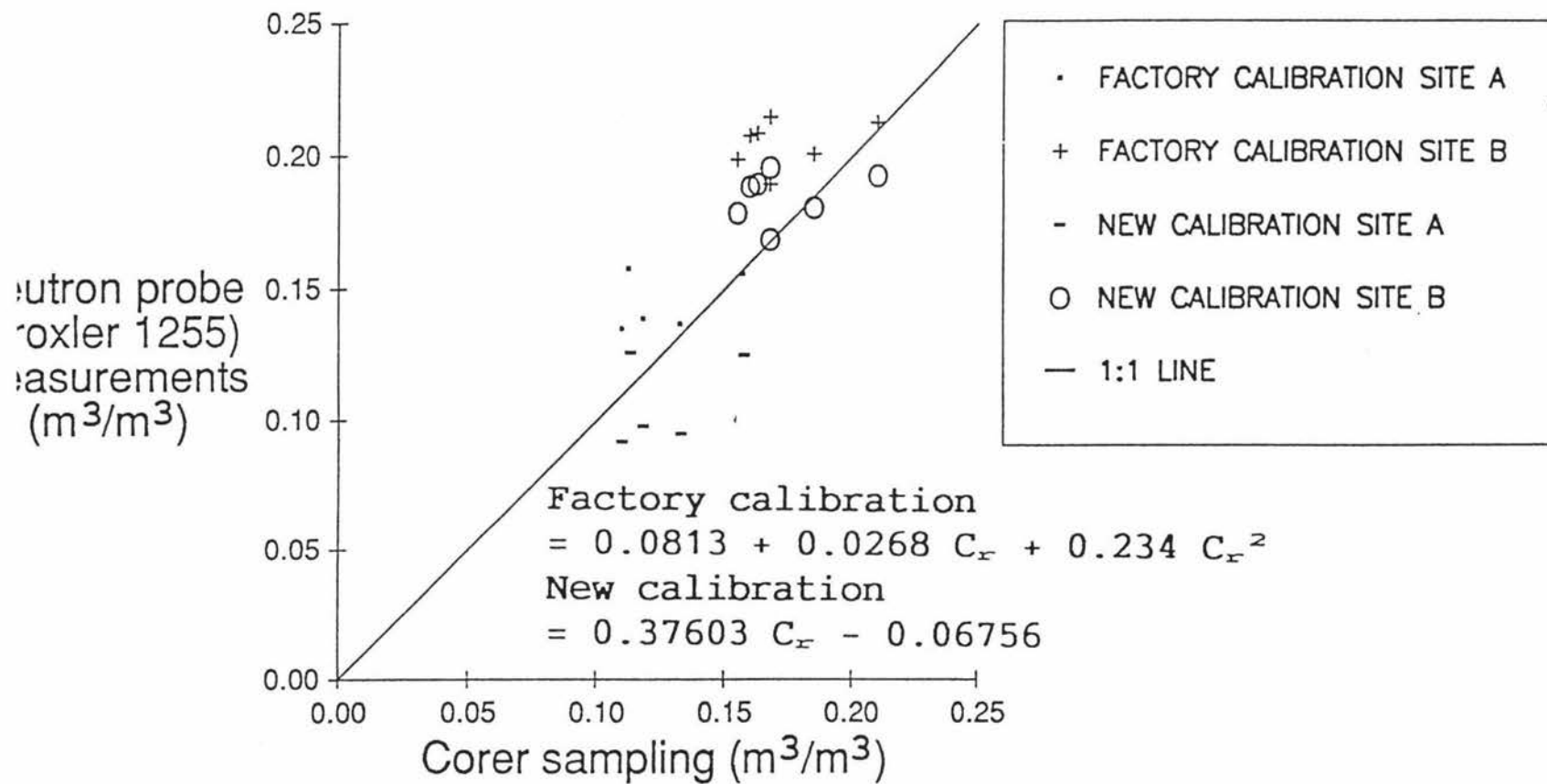


Figure 3.3. The factory and new calibration at Site A and Site B.

transmission line (L) and the signal travel time (t) determined by the TDR receiver, the velocity (v) of the pulse travelling in the soil can be found. The velocity is used to measure the dielectric constant of soil (Topp and Davis, 1982; Topp et al., 1983). Topp et al. (1980) showed that

$$v = C / K^{0.5} \quad (3.2)$$

where C is the speed of an electromagnetic wave in free space (3×10^8 m/s) and K is the apparent dielectric constant. As $v = 2L/t$, K may be found from substitution into Equation (3.2.) and rearrangement (Topp and Davis, 1985) as

$$K = (Ct / 2 L)^2 \quad (3.3)$$

The apparent dielectric constant (K) is strongly dependent on the volumetric water content of the soil.

The frequency ranges used are between 20 MHz and 1 GHz. Recently frequency ranges up to 3 GHz have been used for the new generation of TDR such as the TRASE-TDR.

The empirical relationship between dielectric constant (K) and volumetric water constant (θ) is

$$K = 3.03 + 9.3 \theta + 146.0 \theta^2 - 76.7 \theta^3 \quad (3.4)$$

As the aim of using the TDR is to measure the volumetric water content, to find θ Equation (3.4.) is solved to obtain (Topp, et al., 1980)

$$\theta = -5.3 \times 10^{-2} + 2.92 \times 10^{-2} K - 5.5 \times 10^{-4} K^2 + 4.3 \times 10^{-6} K^3 \quad (3.5)$$

Research carried out by Hoekstra and Delaney (1974) showed that the relationship between volumetric water content and the dielectric constant is relatively independent of soil type. Moreover, Topp et al. (1980) found that not only soil type but also soil density, soil

temperature and soluble salt content did not significantly affect the relationship between volumetric water content and dielectric constant as shown in Figure 3.4. However, it is prudent to check the calibration of any instrument before using it. This particularly applies to a new instrument which has just become commercially available, such as the TDR. So a calibration check was carried out.

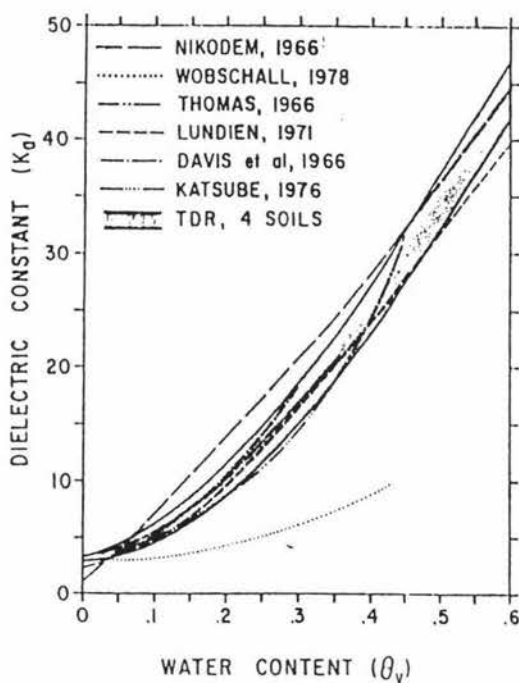


Figure 3.4. A comparison of results of the TDR experiments on four different soils possessing a wide range of textures with the results of other experiments which used a variety of techniques and soils (after Topp *et al.* 1980).

3.2.2. CALIBRATION METHOD

TDR calibrations were conducted in the Agricultural Physics Laboratory, Plant Physiology Division, DSIR, Palmerston North.

Disturbed coarse-textured C-horizon, and fine-textured A-horizon of the Manawatu fine sandy loam soil were packed into 10 litre buckets at a certain known bulk density. Measurements were made in five buckets, three containing the coarse textured soil and two containing the fine-textured soil. Therefore, we had five soil water contents. The layout of 3 parallel pairs of 10 and 20 cm rod transmission lines and five corer samplings sites in the buckets is shown in Figure 3.5. The volumetric soil water content of the soil was found from the gravimetric soil water content of the cores multiplied by the bulk density of the soil in the bucket.

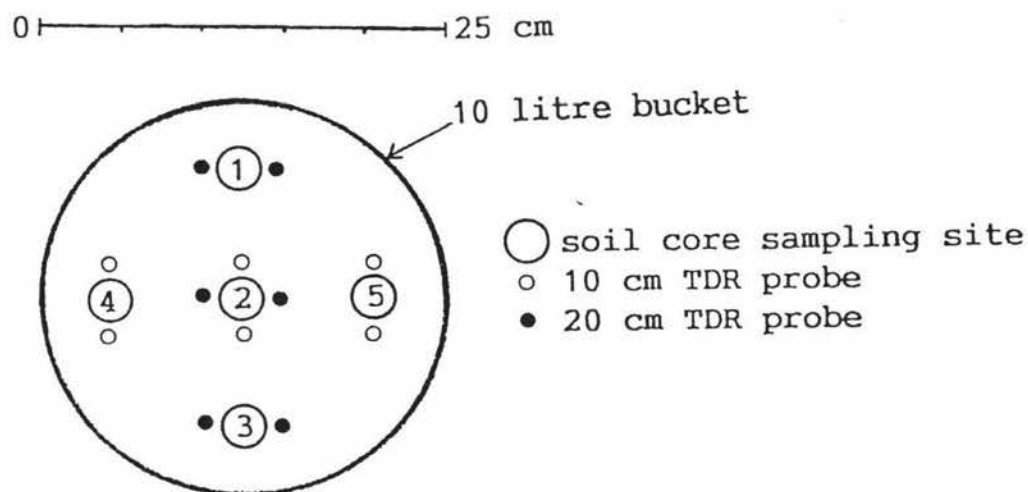


Figure 3.5. Laboratory TDR calibration sampling and measurement locations.

The TDR used in the research was the Model 600 IRAMS System (Serial Number 104968) which is owned by PPD-DSIR. However, TDR Number 105799 (DSIR) and 105999 (Department of Agronomy, Massey University) were also calibrated at the same time.

Measurements using both the 100 mm and 200 mm probes were made with each TDR in each bucket. Three replicates were taken of every measurement, then five soil cores were taken. Figure 3.6. shows the 3 TDRs used in the calibration experiments and one of the buckets.

3.2.3. CALIBRATION RESULTS AND DISCUSSION

The relationships between volumetric soil water contents as read on the TDRs (Y axis) and as found by corer sampling (X axis) are shown in Fig. 3.7. The linear regression equations from the data in Fig. 3.7. are listed in Table 3.1. All of the equations have a high correlation coefficient (R). Figure 3.7. indicates that replicate corer samplings have less variability than replicate TDR measurements. It also shows that the TDR measurements tended to over-estimate the soil water content.

Table 3.1. The relationships between volumetric soil water contents from TDR using factory calibration (Y) and gravimetric sampling (X)

TDR Number	L (mm)	Linear Regression Equation	R ² (%)
104968	100	Y = 1.20361 X - 0.01941	97.0
	200	Y = 1.23622 X - 0.01140	99.6
105799	100	Y = 1.15506 X - 0.01871	95.8
	200	Y = 1.19628 X - 0.02727	99.5
105999	100	Y = 1.51841 X - 0.07983	93.6
	200	Y = 1.17557 X - 0.00721	99.5



Figure 3.6. The three TDR instruments and a soil bucket as used in the calibration experiments.

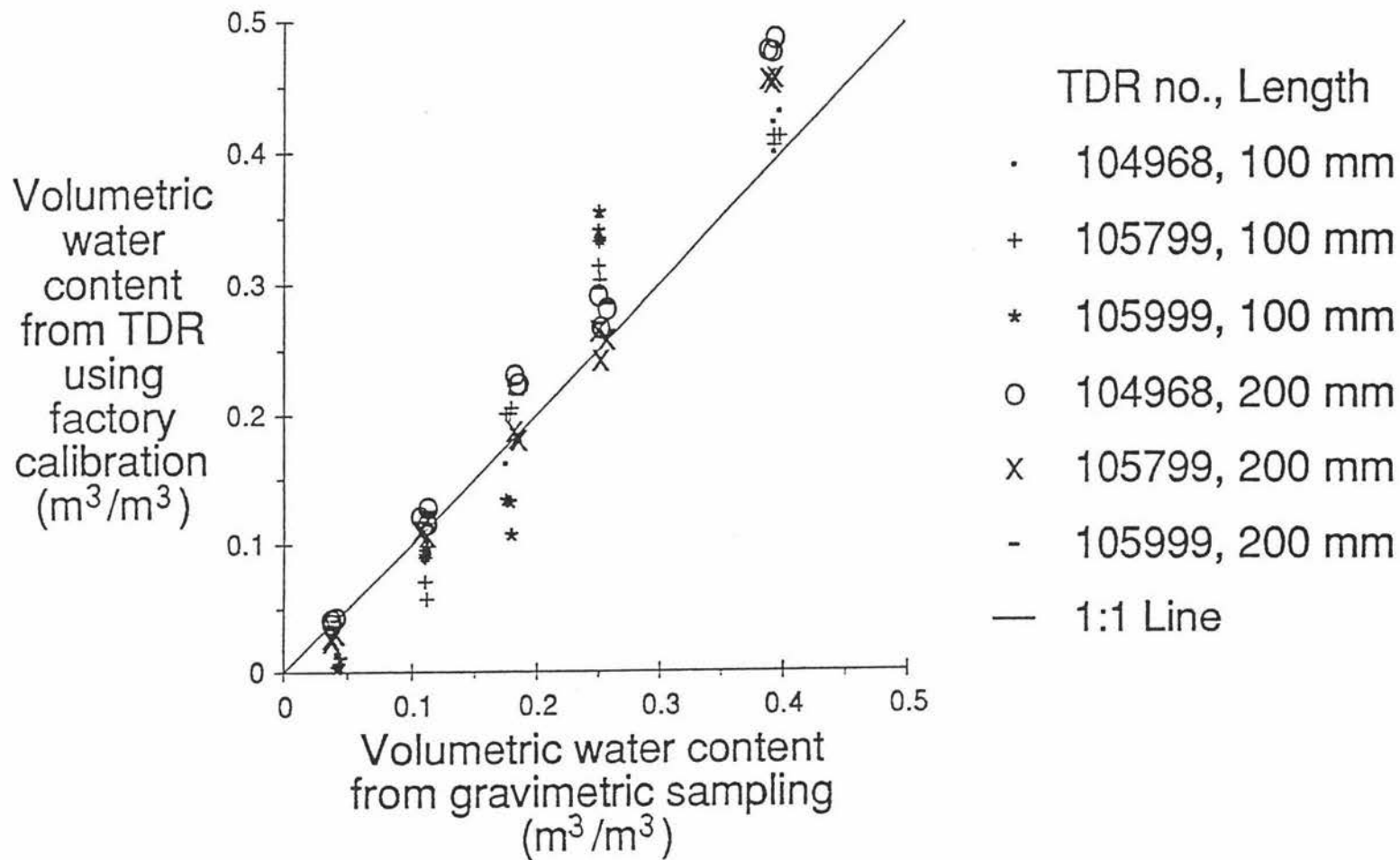


Figure 3.7. The relationships between TDR and corer sampling water content in the laboratory calibration.

This suggests that the factory calibration was not good, as the data differ significantly from the 1:1 line. Furthermore, the slopes of the regression equation for each instrument were different. Thus, the different TDR instruments have different errors in their factory calibration.

In this study only TDR No. 104968 was used in the field. Rahardjo (1988) also used this instrument in his experiment. He found the regression equation of his field data as

$$\theta_{\text{TDR}} = 1.062 \theta_{\text{core}} + 0.029 \quad (3.6)$$

n = numbers of observations = 13

$R^2 = 0.95$,

$S_{yx} = 0.026 \text{ m}^3/\text{m}^3$,

where θ_{TDR} is the soil water content measured by the TDR with 200 mm probes,

θ_{core} is the soil water content measured by corer sampling to 200 mm depth in the field,

R^2 is the correlation coefficient, and

S_{yx} is the standard error of the regression estimate.

A t-test of the data (Gomez and Gomez, 1984) showed there was no significant difference between laboratory and field calibration data for TDR No. 104968. Thus data from both the laboratory and field calibrations of TDR No.104968 were combined to create the final calibration equation used in the field study to be described.

The final equation found was (see Figure 3.8.)

$$\theta_{\text{TDR}} = 1.18397 \theta_{\text{field}} - 0.01387 \quad (3.7)$$

$R^2 = 0.98$

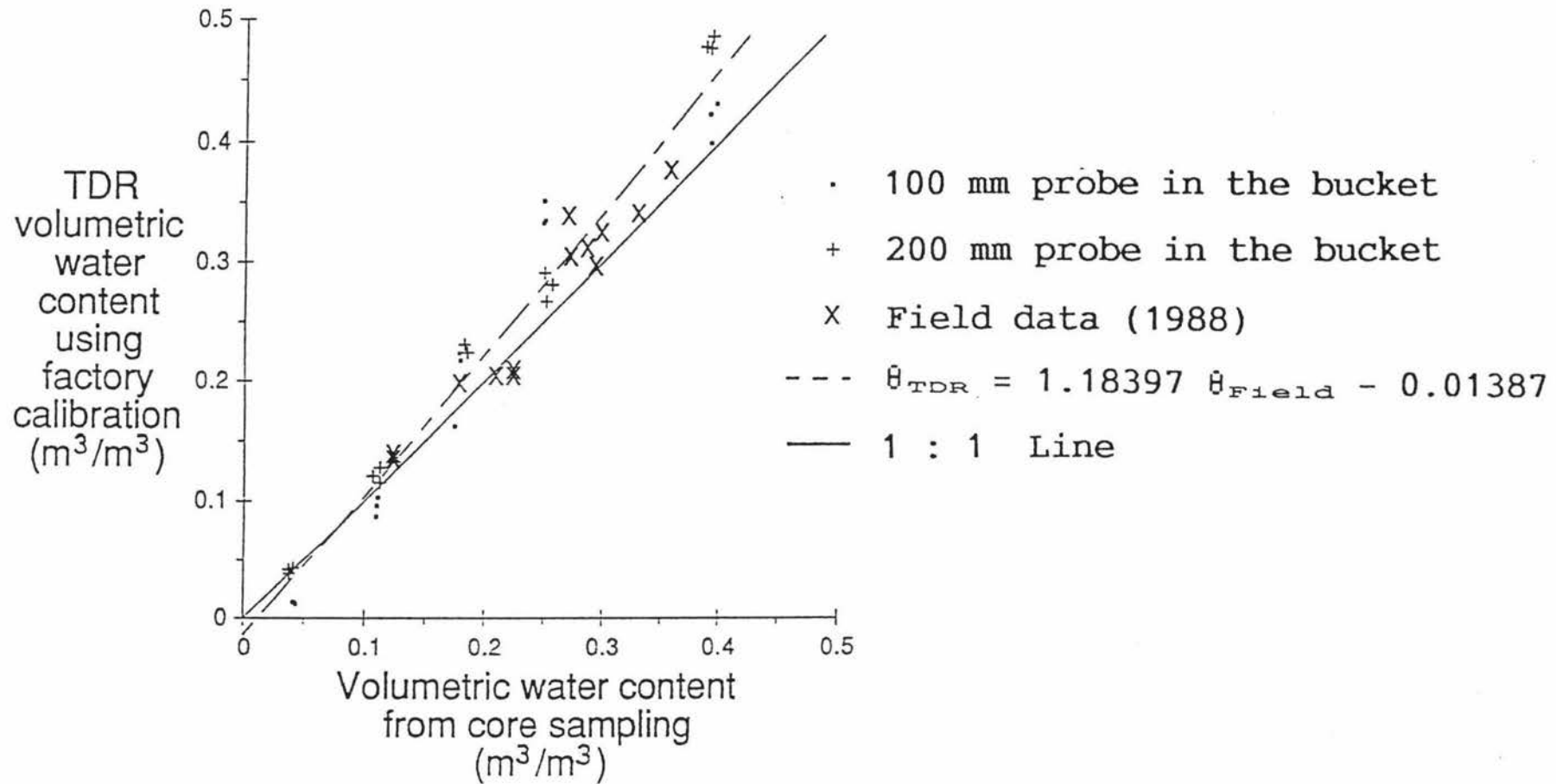


Figure 3.8. The laboratory and field calibration of TDR no: 104968, which was used in the experiment.

Thus, the corrected soil water content measured by TDR No. 104968 (θ_{field}) is

$$\theta_{\text{field}} = 0.844616 \theta_{\text{TDR}} + 0.01171 \quad (3.8)$$

3.2.4. APPLICATIONS

The applications of TDR in the research were, firstly to measure the soil water content near the soil surface from 0 to 400 mm depth, and secondly to measure the soil water change around both Tree I and Tree U from 0 to 200, 0 to 400 and 0 to 600 mm depths.

3.3. TENSIOMETER

The tensiometer is an instrument for measuring the matric potential of soil in the field (Hagan et al, 1967; Michael, 1981).

3.3.1. THEORY

The matric potential of soil water is a measure of how strongly the soil water is bound to the soil matrix, which influences how easy it is for plant roots to extract soil water.

The tensiometer consists of a porous cup, that is usually made by using ceramic material, connected through a tube to a pressure measuring device, with all parts filled with water (Hillel, 1980). The pressure difference between the tensiometer water and atmosphere pressure is measured. The pores of the cup must be small enough to stay water filled over the pressure range of interest (Kirkham and Powers, 1972).

From the formula

$$r = \frac{-2\gamma}{\phi} \quad (3.9)$$

where r is the pore radius (m),

γ is the surface tension between air and water =

$$7.34 \times 10^{-2} \text{ N/m}$$

ϕ is pressure in Pa or N/m^2 , relative to air pressure.

The diameter of pores used in tensiometer cups needs to be less than about 2.94×10^{-3} mm (DeLeenheer and DeBoot, 1966). The length of tube used depends on research requirements. The pressure difference can be monitored by a manometer using mercury or by a vacuum gauge. Older tensiometers consist of a porous cup, a tube and a vacuum gauge. But recent versions of the tensiometer have a separate pressure transducer. This can be a Bourdon type gauge or an electronic pressure transducer. The tensiometer tube then consists of a porous cup, PVC pipe and a septum (rubber stopper). The pressure transducer is connected to the tensiometer tube by inserting a hypodermic needle through the rubber septum. This septum reseals when the needle is withdrawn.

The tensiometer is reliable only over the range from about 0 to about - 85 kPa (Jensen, 1980; Hillel, 1971; Wither, et al., 1974, Michael, 1981, Curtis, et al., 1974). When the cup is in the soil where the soil water pressure potential is being measured, the water inside the cup will be attracted across the ceramic wall and tends to equilibrate with the soil water outside the cup. As the tensiometer system (in the tube) containing water is sealed completely, a negative pressure inside the system develops (Taylor and Ashcroff, 1972). It is very important to have good contact between the ceramic cup and the soil, so that the approach to equilibrium is not hindered by contact impedance. The time needed to achieve equilibrium will depend on the type of tensiometer, the soil and the soil water content. Old version tensiometers, which used a thicker ceramic cup with smaller pores

needed one day to reach equilibrium. Newer versions of the tensiometer, with thin ceramic cups with large pores, need less than one hour.

3.3.2. TENSIMETERS USED IN THIS STUDY

Tensiometers used in the research used an electronic pressure transducer. The electronic tensiometer, which is made by Irrigation Technology and Management, Wanganui, New Zealand, consisted of a separated electronic pressure transducer and of a PVC tube connected to a fragile porous cup. Water was poured into the tensiometer tube to about 20 mm from the top and then the filled tube was sealed by a wet rubber septum. One of the advantages of using the electronic tensiometer is that only one electronic pressure transducer is needed to measure many tensiometer tubes. By inserting a hypodermic needle connected to the transducer into the rubber vacuum stopper, the soil water pressure potential value appears on the small LCD screen of the transducer unit.

The tubes were installed in the soil at least 300 mm from a neutron probe access tube, otherwise the water in the tube could affect the neutron probing. There were two 300 mm depth tubes (TEN 1 and 2), and a 600 mm depth tube (TEN 6) around Tree I. Around Tree U were three 300 mm depth tubes (TEN 3, 4 and 5) and three 600 mm depth tubes (TEN 7, 8 and 9). All tensiometer tubes still had water in them on 26 Dec 1988. A correction of 3 kPa and 6 kPa was subtracted from the 300 mm and 600 mm depth readings respectively, to correct for the gravitation potential difference between the cup and the pressure transducer.

CHAPTER IV

SOIL WATER MEASUREMENTS

The soil water contents were measured at 0 - 400 mm using TDR, and at 400, 600, 800, 1000, 1200, 1400, 1500, 1600 and 1800 mm depths using a neutron probe.

4.1. SOIL WATER CONTENT PROFILES

The relationship between soil water content and depth gives the profile of soil water content at a particular site. Four profiles were investigated around Tree I (Sites 1 to 4), while around Tree U five profiles were measured at Sites 5 to 9. Data of Site 8 were not considered since the site had an unexpected leak. The soil around each tree had its own typical characteristic water content profile. Data for Sites 1 to 4, the profiles around Tree I, are shown in Figure 4.1. Data for Sites 5 to 9, around Tree U are shown in Figure 4.2.

Finer textured soil tends to contain more soil water than coarser textured soil, so bulges in the water contents profiles probably signify the presence of finer textured soil layers. The data in Figure 4.1. suggest that around Tree I there were two finer textured soil layers, one at about 1000 mm and the other at about 1600 mm depth at Sites 1,2 and 3, while there was just one finer textured soil layer at about 1500 mm at Site 4. In contrast Figure 4.2. shows that there was just one finer textured soil layer around Tree U, at about 1500 mm depth, at Sites 5,6 and 9, but two finer textured soil layers were found at Site 7, at about 1400 and 1800 mm depth. The different profiles in the two figures illustrate the variability that can occur over a distance of only about 15 m particularly in illuvial soils.

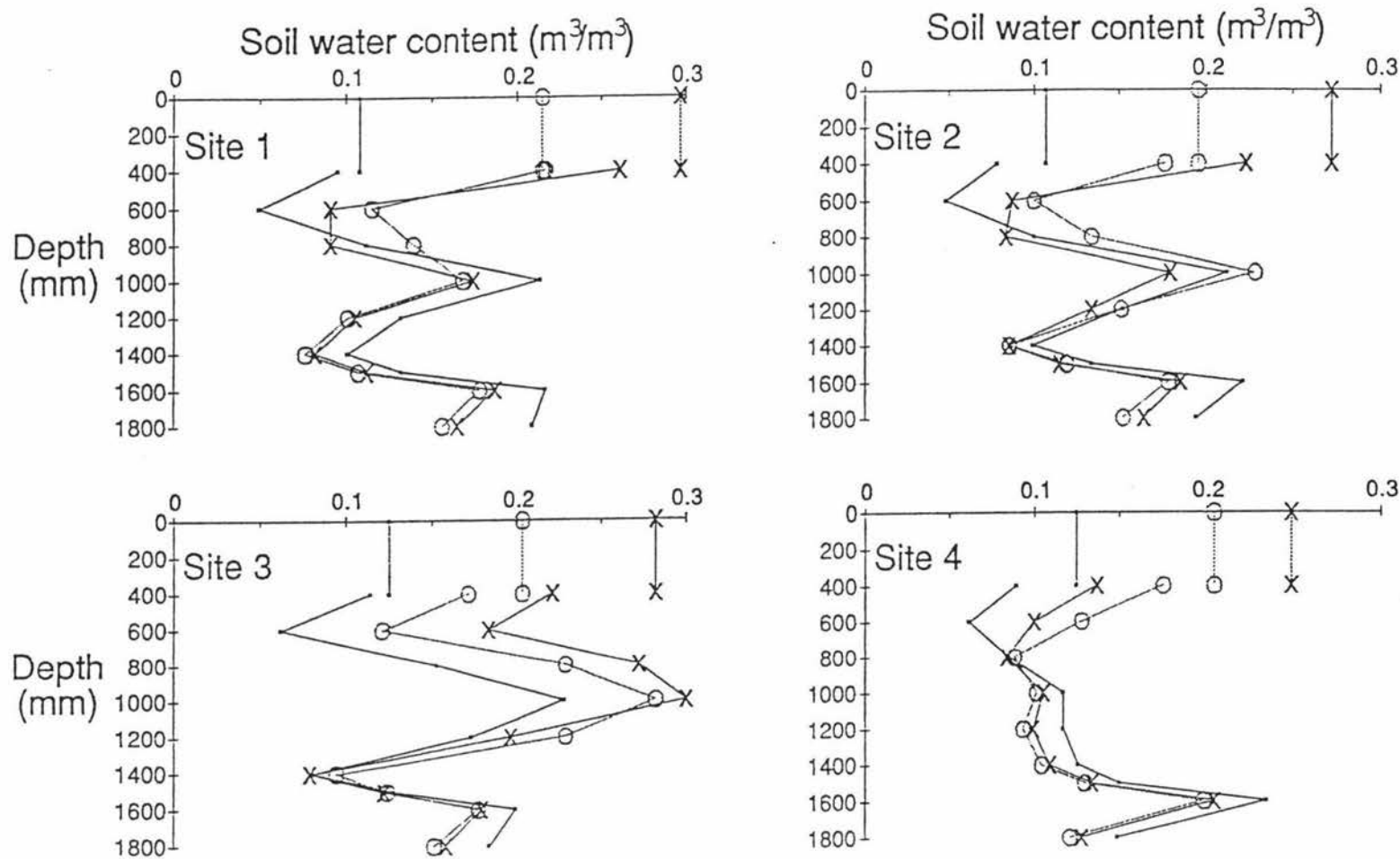


Figure 4.1. The volumetric soil water content profiles for Tree I measured on Day 1 (.), Day 18 (x) and Day 29 (o). For depth 0 - 400 mm TDR apparatus was used, while for depth 400 - 1800 mm a neutron probe was used.

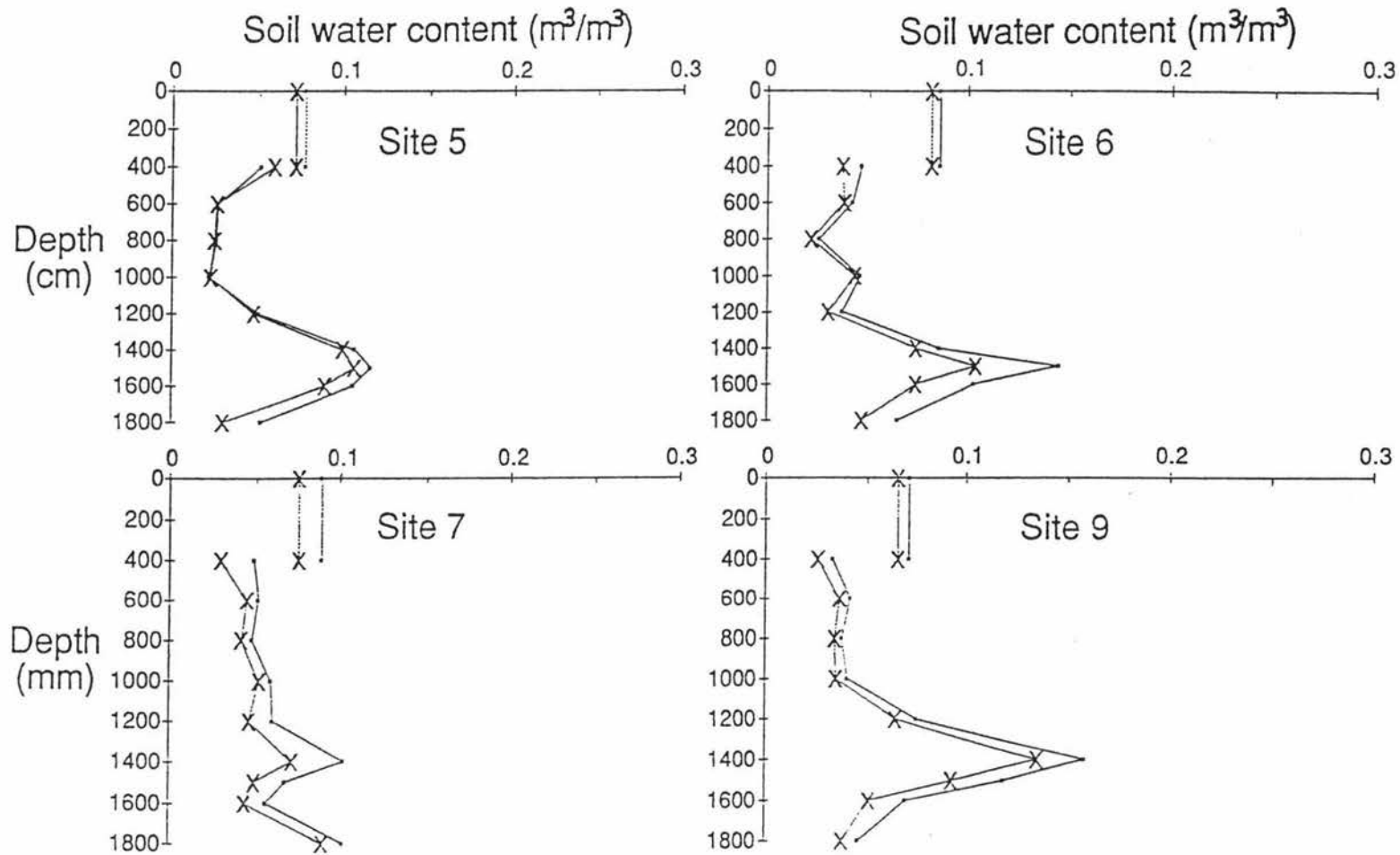


Figure 4.2. The volumetric soil water content profiles for Tree U measured between on Day 1 (.) and Day 29 (x). For depth 0 - 400 mm TDR apparatus was used, while for depth 400 - 1800 mm a neutron probe was used.

Throughout the study period, the soil around Tree I had a higher soil water content than that around Tree U. The uncovered Tree I received water inputs from irrigation water and rainfall, coupled with normal extraction by tree roots. Thus, the soil around Tree I showed soil water profile fluctuations which would be typical of other trees in the orchard. On the other hand Tree U, as a covered tree, did not have any water inputs during the study period, and the changes of soil water profile were caused only by root water extraction, as the soil was far too dry for any drainage to occur.

The soil water content in the top 400 mm of soil around Tree I ranged from about $0.11 \text{ m}^3/\text{m}^3$ on day 1 to $0.30 \text{ m}^3/\text{m}^3$ on day 18 after the second irrigation. Lower down in the profile the changes were less pronounced, but substantial changes in water content were measured down to 1900 mm depth. This suggests either that there were some active apple roots from 0 to 1900 mm depth, or that there was substantial drainage.

In contrast to Tree I, the range of soil water contents from 0 to 400 mm depth around Tree U was from about $0.08 \text{ m}^3/\text{m}^3$ on Day 1 to $0.06 \text{ m}^3/\text{m}^3$ on Day 29. The observed changes in soil water content occurred relatively uniformly from 0 to 1900 mm depth, indicating that active roots also existed from 0 to 1900 mm depth around Tree U.

4.2. SOIL WATER STORAGE

As the radius of the sphere of influence of the neutron probe is about 100 - 150 mm (Greacen, 1981), the neutron probe measurement at any depth can be used to estimate the soil water storage from 100 mm above to 100 mm below the probe depth.

Therefore the mathematical expression used to calculate soil water storage (W) from the surface to 1900 mm depth was

$$\begin{aligned}
 W = & 400 \theta_{\text{TDR},0-400} + 100 \theta_{\text{NP},400} + 200 \theta_{\text{NP},600} + \\
 & 200 \theta_{\text{NP},800} + 200 \theta_{\text{NP},1000} + 200 \theta_{\text{NP},1200} + \\
 & 150 \theta_{\text{NP},1400} + 100 \theta_{\text{NP},1500} + 150 \theta_{\text{NP},1600} + \\
 & 200 \theta_{\text{NP},1800}
 \end{aligned}
 \tag{4.1.}$$

where :

- W is soil water storage (mm),
- θ_{TDR} is volumetric soil water content measured by TDR,
- θ_{NP} is volumetric soil water content measured by neutron probing,

Changes in soil water storage allow the water balance to be monitored. Changes indicate the balance between water inputs from irrigation and rainfall and water outputs from soil water extraction and drainage (Hillel, 1980). Figure 4.3. shows the temporal changes in soil water storage from 0 to 1900 mm depth at the monitored sites.

Tree I received water inputs from both irrigation and rainfall. Irrigations were carried out on Days 3 and 17. The amount of each irrigation was about 24 mm of water applied at the rate of about 2 mm/hour. Rainfall data were obtained from a meteorological station near the research site and are shown in Table 2.1. The effects of wetting can be recognized in Figure 4.3. as significant increases in profile water storage. They were measured between Day 2 and Day 4, and between Day 16 and Day 21. The first wetting around Tree I was caused solely by the first irrigation on Day 3. There was no rainfall from Day 1 to Day 15 and just 0.8 mm rainfall on Day 16. The second wetting occurred because of both the second irrigation and several days of significant rainfall after the second irrigation. There were also small amounts of rainfall between Days 20 and 29 but not enough to balance the root extraction. On the other hand, the data for Tree U show no fluctuations in profile storage since there was no wetting of the covered tree.

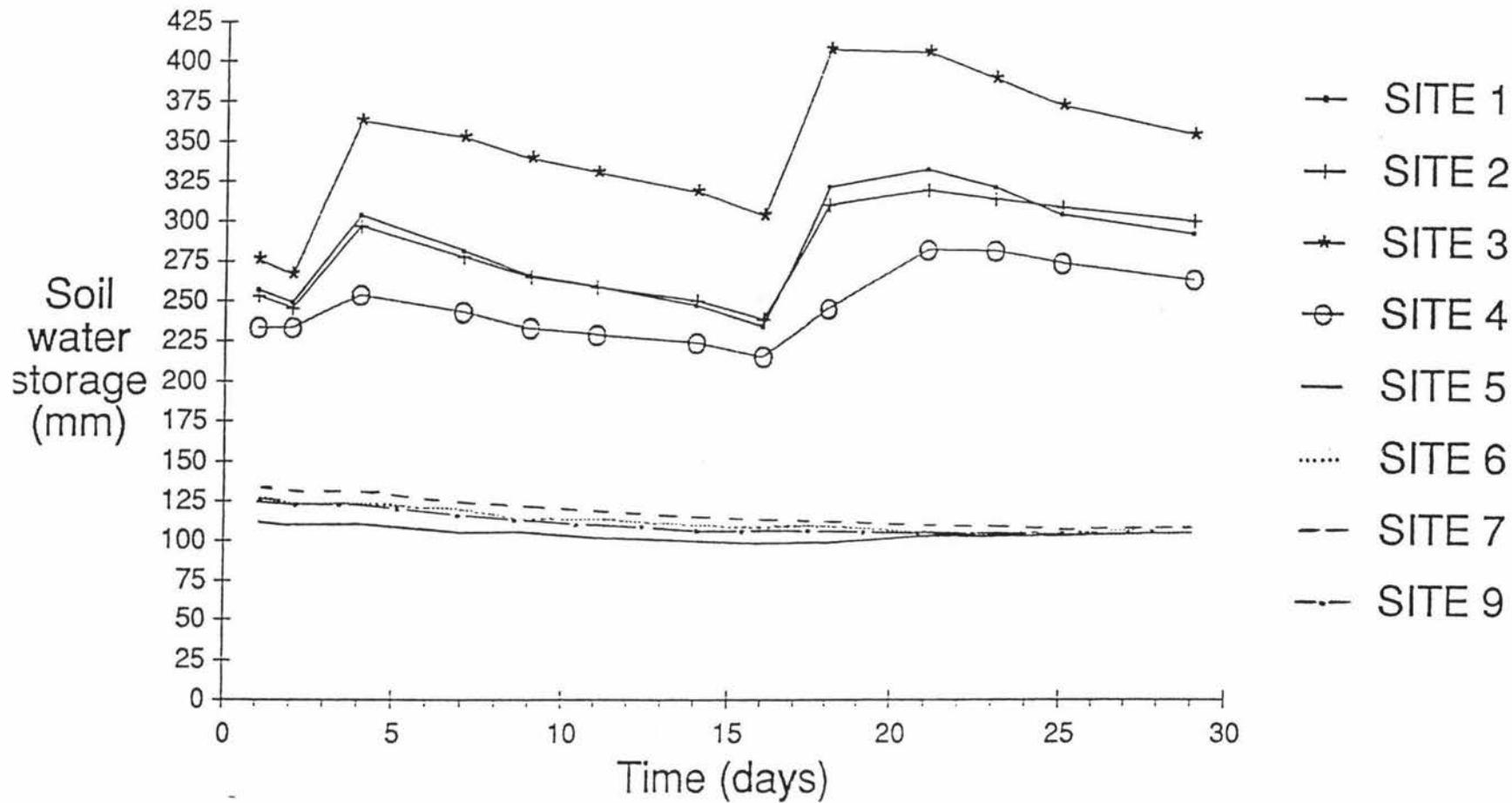


Figure 4.3. Soil water storage from 0 to 1.9 m depth with time for irrigated tree (sites 1 - 4) and unirrigated tree (sites 5 - 9), obtained by combining neutron probe and TDR data.

Figure 4.3. shows that the amount of wetting was different for Sites 1 - 4. Site 3 gained about 100 mm during each period of wetting. Whereas Site 4 gained only about 20 mm and 60 mm at the first and second wettings respectively. This indicates that there was significant variability in the amount of wetting, presumably due to sprinkler non-uniformity.

Because two significant periods of wetting occurred around Tree I, two periods of soil water extraction also can be recognized, one after each wetting period. The possible soil water extraction periods were from Days 4 to 16 and from Days 21 to 29. The soil water extraction can be estimated by the changes in profile soil water storage, providing there is no drainage. Drainage is negligible when the soil water content is below "field capacity". In case there had been significant drainage in the 3 days after irrigation or rainfall, the first and second periods of soil water extraction were taken from Day 7 to Day 16, and from Day 23 to Day 29 respectively. Figure 4.3. shows that during these periods the slope of soil water storage change, which indicates the amount of soil water extraction, was much higher around Tree I than around Tree U.

4.3. SOIL WATER CONTENT CHANGES

The amounts of soil water extraction from various depths, during the two extraction periods defined above, are shown in Figures 4.4. and 4.5. for Tree I and Tree U respectively.

Figure 4.4. shows that the top 200 mm of soil around Tree I had by far the greatest water content changes. This suggests that the most active roots of Tree I (which had frequent water inputs), were in the top 200 mm depth. From 200 to 400 mm depth showed moderate soil water content changes, and smaller soil water changes occurred below 400 mm. Extraction apparently occurred down to at least 1900 mm depth. Both extraction periods around Tree I show similar patterns of soil water extraction. If the availability of soil water is not a limiting factor, the root length density from 0 to 1600 mm will be

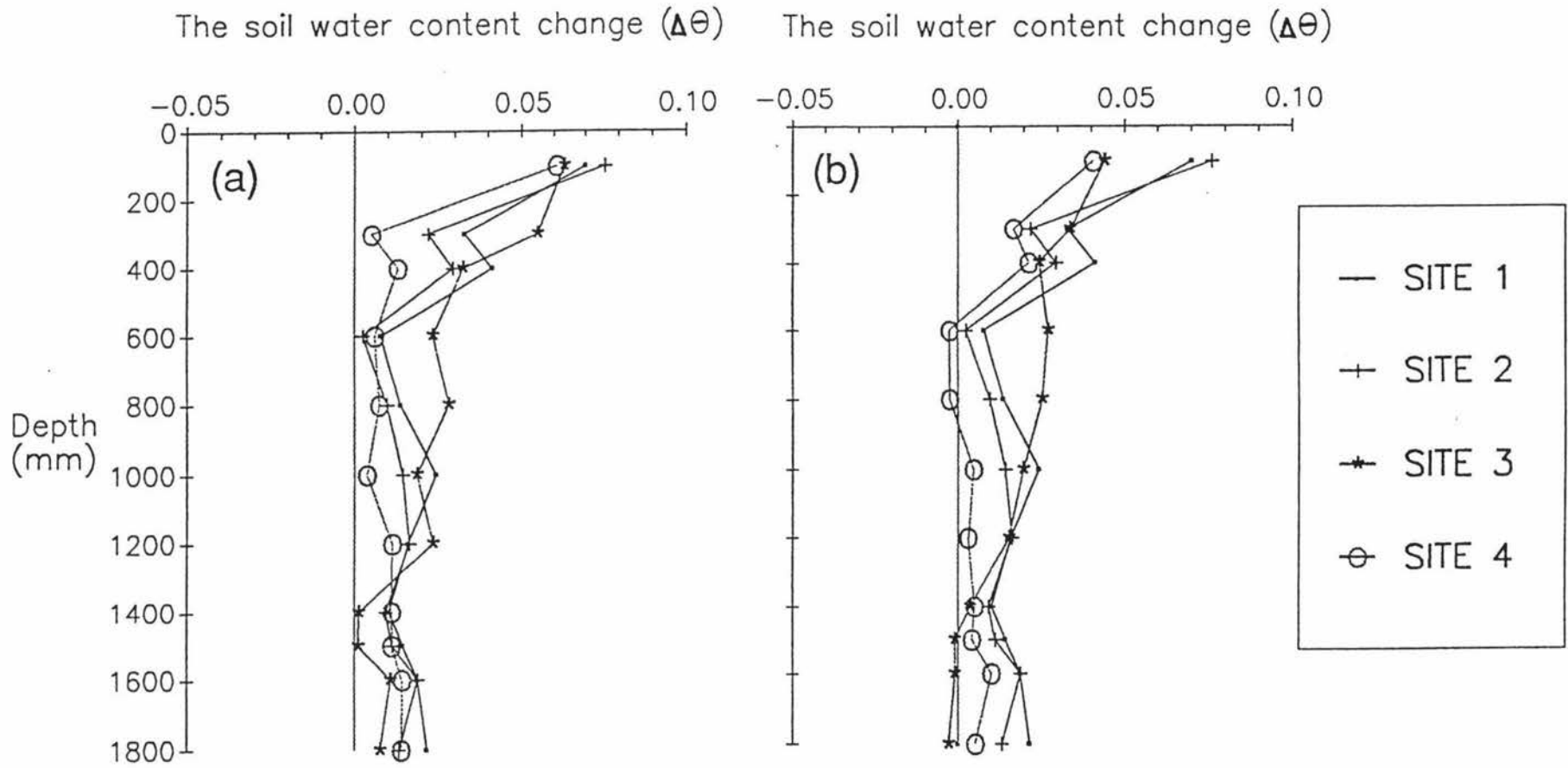


Figure 4.4. Change in soil water content profiles during two extraction periods for irrigated tree, (a) from Day 7 to Day 16 (9 days), (b) from Day 23 to Day 29 (6 days).

correlated with the soil water content changes with depth. The water use profile of Tree I (Figure 4.4.) is somewhat similar to the root density profile (Figure 2.2.). The top of 400 mm depth had the greatest root density, and the most soil water extraction of Tree I occurred over that depth.

Figure 4.5. shows the very different patterns of soil water extraction around Tree U. For this tree uptake depth was not correlated with root density. The extraction during the first period involved very small soil water content changes down to about 1300 mm depth, but somewhat greater soil water extraction between 1300 mm and 1700 mm depth. Thus Tree U, which had a much lower initial soil water content than Tree I (see Figures 4.1. and 4.2.) extracted soil water from the subsoil rather than the topsoil, exactly the opposite of how Tree I behaved. The second period of soil water extraction showed little or no soil water being extracted, as the soil water content changes were approximately zero from the soil surface down to 1900 mm depth. So if water was taken up by Tree U during the second period, it must have come from below 1900 mm depth, or from shallower roots growing beyond the covered area.

4.4. SOIL WATER USE

The amount of soil water use per unit land area at each of the measuring sites during the first and second periods can be calculated from the changes in soil water storage between days 7 to 16 and between days 23 and 29 respectively. Table 4.1. shows the soil water use (mm) during the two periods of extraction. Tree I extracted 40.9 ± 9.7 mm or an average of 4.5 ± 1.1 mm/day during the first period of soil water extraction and 24.1 ± 9.9 mm or an average of 4.0 ± 1.7 mm/day during the second period of soil water extraction. However Tree U extracted only 10.4 ± 0.5 mm or 1.2 ± 0.1 mm/day during the first period and -1.8 ± 2.2 mm or -0.3 ± 0.4 mm/day during the second period of the extraction.

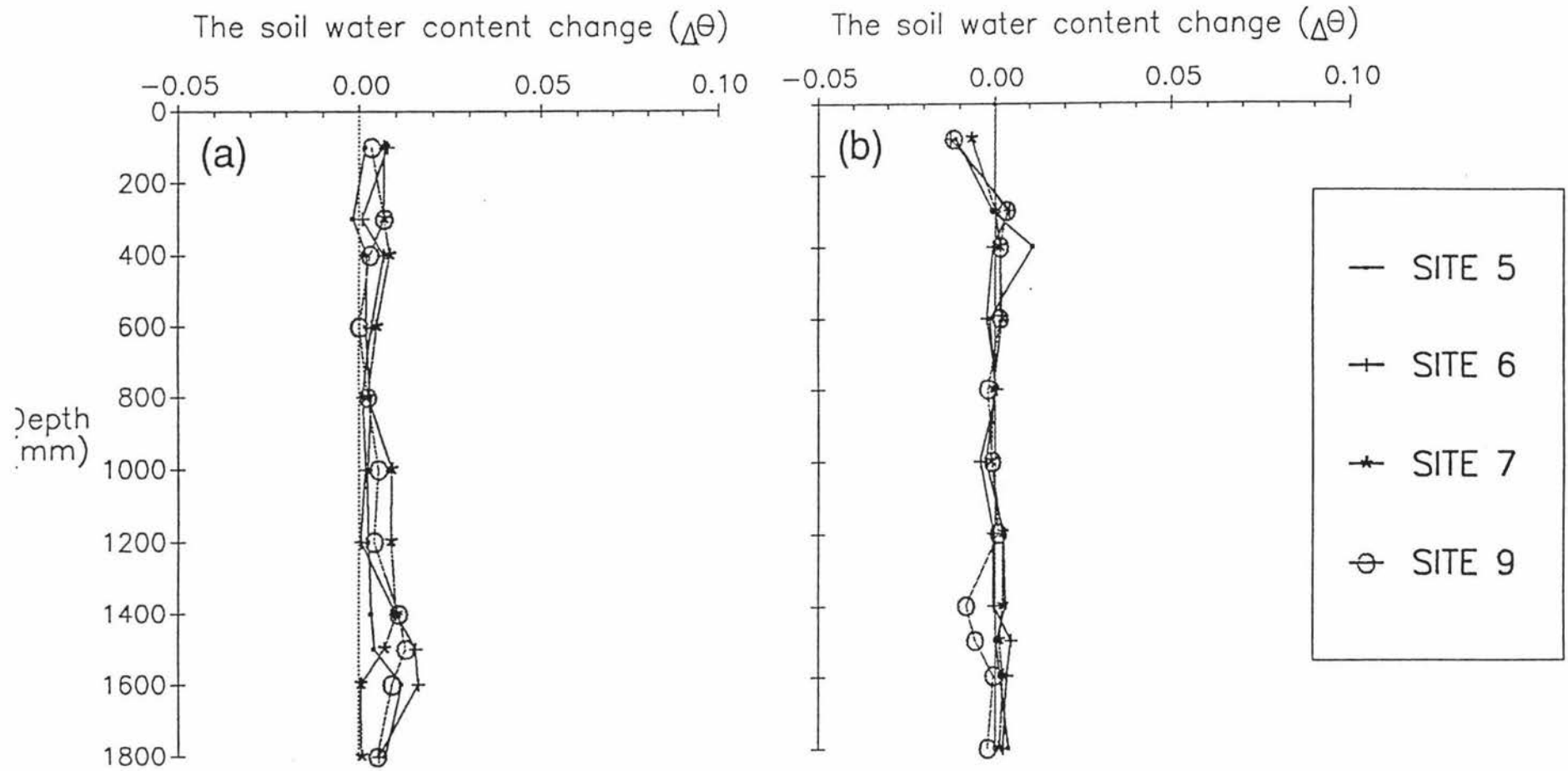


Figure 4.5. Change in soil water content profile during two extraction periods for unirrigated tree, (a) from Day 7 to Day 16 (9 days), (b) from Day 23 to Day 29 (6 days).

Rahardjo (1988) and Hughes *pers. comm.* (1988) found that the apple trees in the research orchard had a uniform horizontal root distribution between trees. Also the uptake from the four sites around each tree was similar (Table 4.1.). It seems reasonable therefore to assume that water use was uniform over the whole area around each tree. Thus, the soil water use per tree (litres) can be estimated by multiplying the average amount of soil water use per unit land area (mm) with the rooting area available to each tree (5.0 x 3.6 m). Table 4.2. shows the calculated soil water use. Tree I used 81.7 ± 19.4 litres per day and 72.4 ± 29.8 litres per day during the first and second periods of extraction respectively. There was no significant difference at the 5 percent level in the rate of soil water extractions between the first and second periods. As the soil around Tree I had a similar and adequate soil water status during both periods (Figure 4.3.) this would be expected, if weather conditions were similar. On the other hand, Tree U, the covered tree, had significantly different soil water extraction at the 1 percent level, both between the first and the second periods of extraction, and also from Tree I. During the first period, extraction by Tree U was only a quarter of that by Tree I. While there was apparently no soil water extraction from around Tree U in the second period but Tree U still survived. This is an interesting finding. One possibility is that Tree U had deep roots going below 1900 mm depth, which could extract enough soil water from below 1900 mm to maintain the plant water status and metabolism. Another possible reason is that long horizontal roots extracted soil water from beyond the cover area.

Thus, when there is adequate soil water in the topsoil, the apple tree will extract soil water from there, but when there is inadequate soil water in the topsoil, the apple tree will extract soil water from deeper in the soil, perhaps from more than 1900 mm deep in this soil.

Table 4.1. Soil water storage change per unit land area during extraction periods.

		Period I Days 7 to 16		Period II Days 23 to 29	
		Total (mm)	Average (mm/day)	Total (mm)	Average (mm/day)
Tree I	Site 1	47.3	5.3	29.4	4.9
	Site 2	39.2	4.4	13.9	2.3
	Site 3	49.1	5.5	35.3	5.9
	Site 4	27.9	3.1	17.9	3.0
Average for four sites :		40.9	4.5	24.1	4.0
Standard deviation :		9.7	1.1	9.9	1.7
Tree U	Site 5	6.3	0.7	0.0	0.0
	Site 6	10.2	1.1	-1.7	-0.3
	Site 7	10.9	1.2	0.4	0.1
	Site 9	9.9	1.1	-4.0	-0.7
Average for four sites :		9.3	1.0	-1.3	-0.2
Standard deviation :		2.1	0.2	2.0	0.3

Table 4.2. Soil water storage change per tree.

		Period I Days 7 to 16		Period II Days 23 to 29	
		Total (L)	Average (L/day)	Total (L)	Average (L/day)
TREE I					
Average for four sites :		735.4	81.7	434.2	72.4
Standard deviation :		174.3	19.4	178.6	29.8
TREE U					
Average for four sites :		168.2	18.7	-23.9	-4.0
Standard deviation :		37.3	4.1	35.5	5.9

4.5. SOIL WATER PRESSURE POTENTIAL

Figure 4.6. shows the soil water pressure potential around both Tree I and Tree U at 300 and 600 mm depths, measured by tensiometers with an electronic pressure transducer.

For Tree I the soil water pressure potential values, especially at 300 mm depth (Figure 4.6(a)), indicate wetting on Days 3 and 17, since the values on Days 4 and 18 were higher than the preceding values.

Figure 4.6(a) shows that soil water potential around Tree I at 300 mm depth was higher (less negative) than at 600 mm depth. This is in agreement with the soil water content measurement at 400 and 600 mm depths at Site 1, 2, 3 and 4 (Figure 4.1.) and would have been due to the irrigation and rainfall. Figure 4.6(b) does not show the complete soil water pressure potential from Days 1 to 25 because the soil became too dry for the tentiometers to function after Day 11. However, Figure 4.6(b) shows that the soil water content at 300 mm depth was drier than at 600 mm depth around Tree U. The data in Figure 4.2 also show that the soil water content at 400 mm depth was drier than at 600 mm depth at Site 6, 7 and 9, but not at Site 5, probably due to the variability of the illuvial soil at the experimental site. In summary, the tensiometer data indicate the topsoil around Tree I to be adequately watered during the study period, but the topsoil around Tree U to be at potentials suggesting plant water stress.

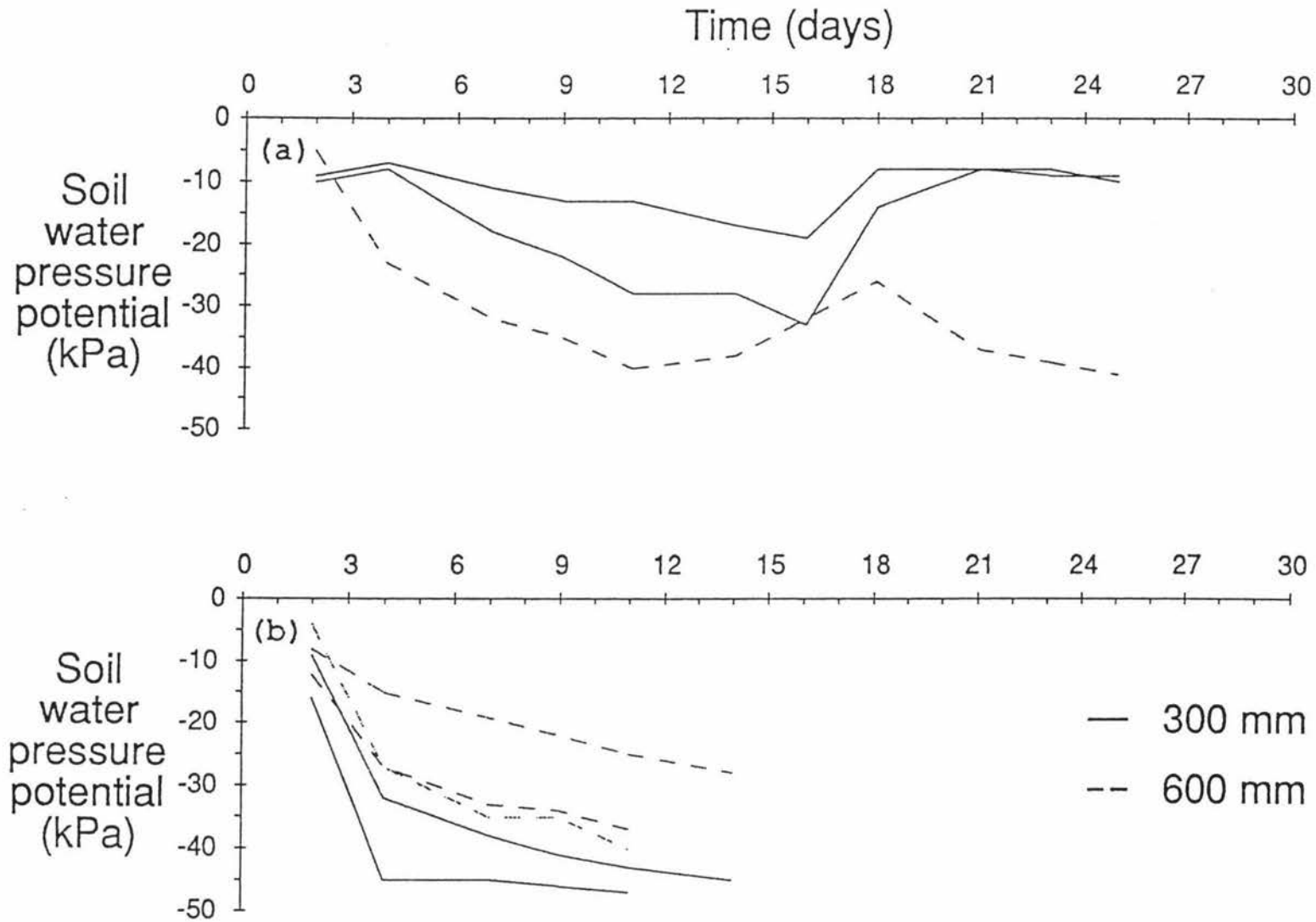


Figure 4.6. Soil water pressure potential measured by electronic tensiometer around Tree I (a) and around Tree U (b).

CHAPTER V

THE ABOVE GROUND MEASUREMENTS

5.1. HEAT PULSE TECHNIQUE

The direct measurement of sap-flow in the stem of intact plants is an advanced and useful technique in soil water management. Using heat as a tracer for the sap-flow, which is equal to the amount of plant water use, offers a sensitive technique for monitoring the dynamic water status of plants (Swanson and Whitfield, 1981; Green and Clothier, 1988). The name of the technique is the heat-pulse sap-flow technique and it has been studied since 1932 when it was first suggested by Huber.

5.1.1. SAP-FLOW

Xylem is the system of "pipelines" within the plant stem or trunk. It serves the plant as a vascular water transport system (Huber, 1956; Milburn, 1979). The darker coloured core in the centre of a tree stem is the heartwood. This is not only dead, but also the oldest part of the tree stem. Heartwood cannot transport sap (Zimmermann, 1983). The outer wood is cambium and phloem. Cambium produces both xylem and phloem cells, while phloem functions to distribute the results of photosynthesis (Zimmermann and Brown, 1977). However, neither cambium nor phloem transport sap from roots to leaves. Thus sap flow only occurs in the xylem. Transpiration through stomata creates a potential difference between the leaves and roots, causing a decrease in the sapwood capillary potential (Siau, 1984). This induces sap-flow in the sapwood.

The average sap flux density is proportional to the sap velocity, but also depends on the density and moisture content of the wood. The volumetric flow rate can be found by multiplying the average sap flux density and the cross-sectional area of the xylem annulus through which flow occurs.

5.1.2. THE TECHNIQUE

The key to the technique is heat transport in the sapwood. A pulse of heat is released by a heater and detected by nearby temperature sensors. The time delay (t_0) between releasing and receiving the heat pulse can be used to compute the heat pulse velocity. The heat pulse velocity can then be related to the sap velocity. The velocity of the heat pulse is not the same as the sap velocity because heat is absorbed by the wood as well as the sap.

Huber (1932) used a small heated wire loop, which was embedded under the bark of the stem, to release the heat pulse. As this technique could not detect heat pulse velocities below 1 m/h, Huber and Schmidt (1937) developed the compensation heat pulse technique where a heater is inserted radially into the stem.

Heat enters the sap flow mainly by thermal conduction through the vessel walls (Huber, 1932; Huber and Schmidt, 1937; Marshall, 1958). When the sap velocity is very slow, most of heat is transferred away from the heater by conduction rather than convection (Closs, 1958). However, when the sap moves at greater speeds, the rate of movement of the heat pulse will depend more on convection and less on conduction (Marshall, 1958).

In the compensation heat pulse technique, a heater probe and two temperature sensors are used, one fixed at distance X_u upstream and the other a distance X_d downstream from the heater probe. The sensors and the heater are inserted radially into the stem. The heat pulse velocity upstream is faster than downstream, but the upstream heat pulse decays more quickly than the downstream pulse, as seen in Figure 5.1(a).

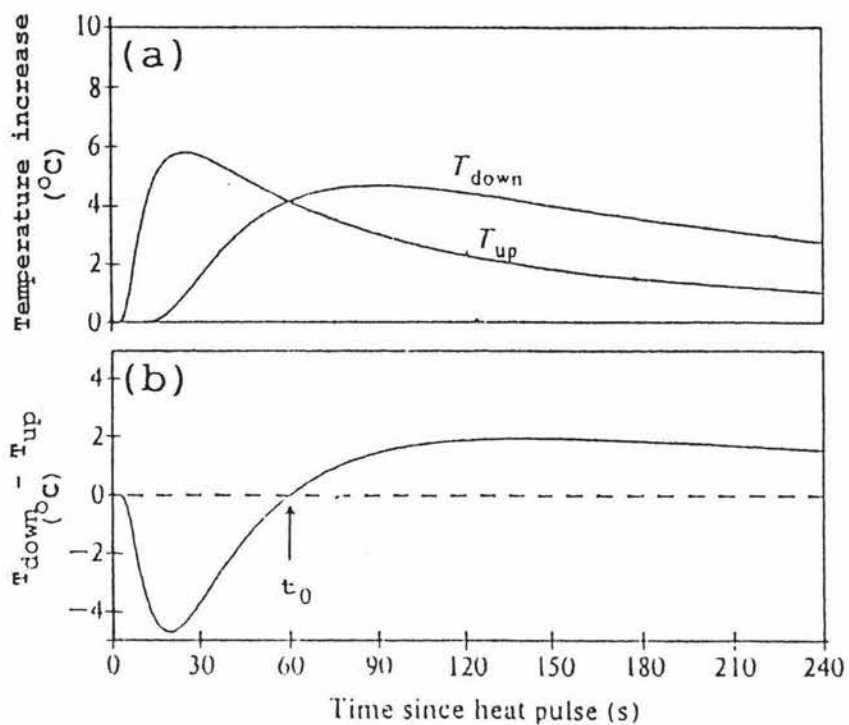


Figure 5.1(a). The typical relationship between temperature and time for heat pulses upstream ($X_U = 5$ mm) and downstream ($X_D = 10$ mm).

Figure 5.1(b). The typical difference between downstream and upstream temperature. t_0 is the time delay until the upstream and downstream temperatures are equal (after Swanson, 1962).

Swanson (1962) defined the heat pulse velocity (V) as

$$V = \frac{X_u + X_d}{2 t_0} \quad (5.1)$$

where t_0 is the time delay after pulse initiation when the temperatures at points X_u and X_d become equal. Figure 5.1(b) shows a typical time delay.

The heat pulse velocity (V), calculated using equation (5.1), needs to be corrected to take account of the fact that the tissue in which the sap flows has been partly blocked by both heater and temperature probe insertion (Cohen *et al.*, 1981). The probes are finite in size and have thermal properties different from the surrounding wood (Swanson and Whitfield, 1981). To calculate the corrected heat pulse velocity (V'), Green and Clothier (1988), who developed the heat pulse apparatus used in this research, used a numerical solution developed by Swanson (1983).

The sap flux density (J) in a homogeneous stem can be calculated from V' and the properties of the wood as (Marshall, 1958)

$$J = \frac{\rho_T}{\rho_W} \left(M_T + \frac{C_T}{C_W} \right) V' \quad (5.2)$$

where $\rho_T = \frac{\text{oven dried weight of wood}}{\text{green volume}}$

= the density of wood in kg m^{-3}

ρ_W = the density of water (sap) in kg m^{-3}

$M_T = \frac{\text{green mass} - \text{oven dried mass}}{\text{oven dried mass}}$

= the moisture content of wood in kg kg^{-1}

$$C_T = \text{the specific heat of oven dry wood} \\ = 1.39 \times 10^3 \text{ J kg}^{-1} \text{ K}^{-1}$$

$$C_W = \text{the specific heat of water (sap)} \\ = 4.21 \times 10^3 \text{ J kg}^{-1} \text{ K}^{-1}$$

Finally, by integrating the sap flux density over the sap-wood cross-sectional area, the volumetric flow rate (Q) is found as

$$Q = \int_H^R 2\pi r J(r) dr \quad (5.3)$$

where $J(r)$ is the sap flux density at radial distance (r) in a stem with xylem between radii H (heartwood) and R (cambium) (see Figure 5.2a.).

5.1.3. INSTRUMENTATION

Each set of heat pulse probes used in the research consisted of two temperature sensors, controlled by a heat pulse circuit, and a heater which was controlled by a heater circuit. Tree I and Tree U each had three sets of the heat pulse probes installed in them and these were monitored by a Campbell CR21X data logger powered by a 12 Volt lead-acid battery.

The heater probes were made from insulated nichrome resistance wire (10 ohm/m) mounted inside a stainless steel tube of 1.8 mm outside diameter and 60 mm long. At one end the nichrome wire was soldered to the steel tube, while at the other end copper leads were soldered to both the stainless steel tube and the nichrome wire. The heater was connected in series with a 60 W, 0.4 Ohm power-resistor. Each heater was turned on for 1.5 seconds every measurement.

Each temperature sensing probe consisted of four micro-bead thermistors spaced at intervals of 5 mm inside a length of teflon tubing, which was 1.85 mm in outside diameter and filled with epoxy

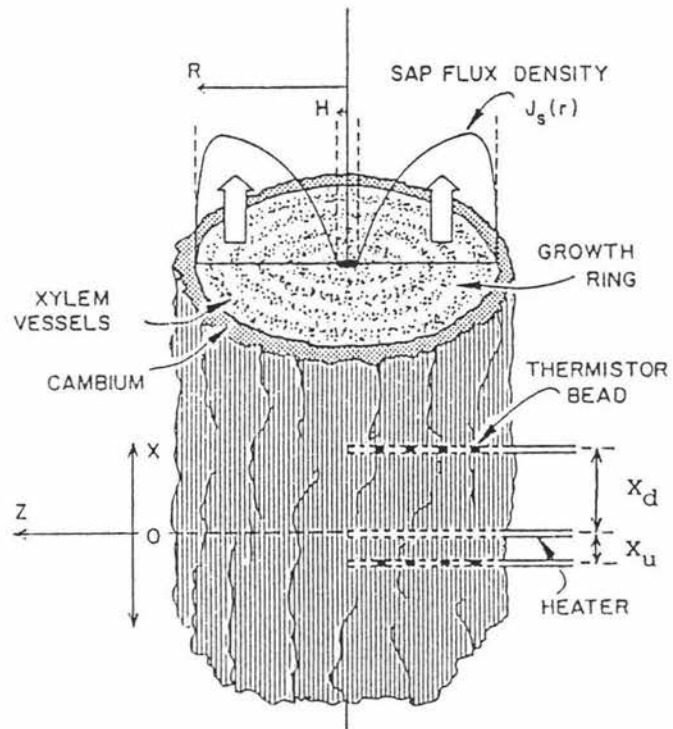


Figure 5.2(a). A diagram showing the position of heater probe and thermistor beads used to monitor the heat pulse velocity.

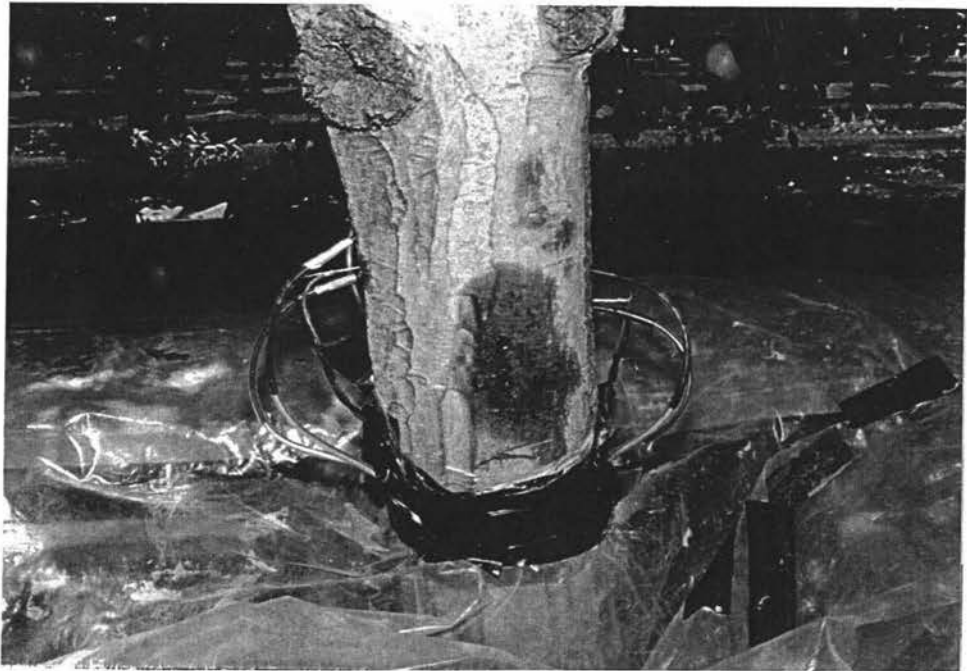


Figure 5.2(b). Two of three sets of heater probes and thermistor beads in the trunk of Tree U.

resin. The leads from each thermistor were electrically insulated from each other. The sensor was very flexible and easily inserted and removed from the apple tree trunk (Green and Nicholson, 1987). Figure 5.2(a) shows the position of a set of heat pulse probes and Figure 5.2(b) shows two of the three sets of heat pulse probes installed in the trunk of Tree U.

The Campbell CR21X data logger had programs to translate the analogue temperature inputs to digital outputs of the sap flow velocity from the three heat pulse probe sets (see Figure 5.3(a)). The sap velocities were measured every 30 minutes.

As the memory of the data loggers was limited, to record all data audio cassette recorders were used to store the output from the data loggers in the field. The data were stored on normal audio cassette tape (see Figure 5.3(a)). To capture the sap flow velocity data from the cassette tape, a Tape Reader Cassette Interface (made by Campbell Scientific Inc., Logan, Utah, USA) was used. The tape reader was connected to a computer. Figure 5.3(b) shows the cassette recorder, tape reader and computer. The calculations were carried out using MINITAB computer software at Plant Physiology Division, DSIR, Palmerston North. When the computer had read the values of the sap flow velocities, firstly the data were checked to remove inconsistent values. Then the average of the three sap flow velocities was calculated. By multiplying the cross-sectional area of the xylem annulus with the average sap flow velocity, the rate of sap flow was found.

5.1.4. RESULTS

The measured water use of Trees I and U from Day 2 (14 December 1988) to Day 24 (5 January 1989) is shown in Figure 5.4. The figure shows that Tree U consistently used slightly more water than Tree I. This was not expected, as Tree U was not irrigated. A possible reason is that the canopy of Tree U might have been slightly larger than that of Tree I. The daily pattern of water use by Trees I and U was similar. Usually there was no sap flow at night, the exception to

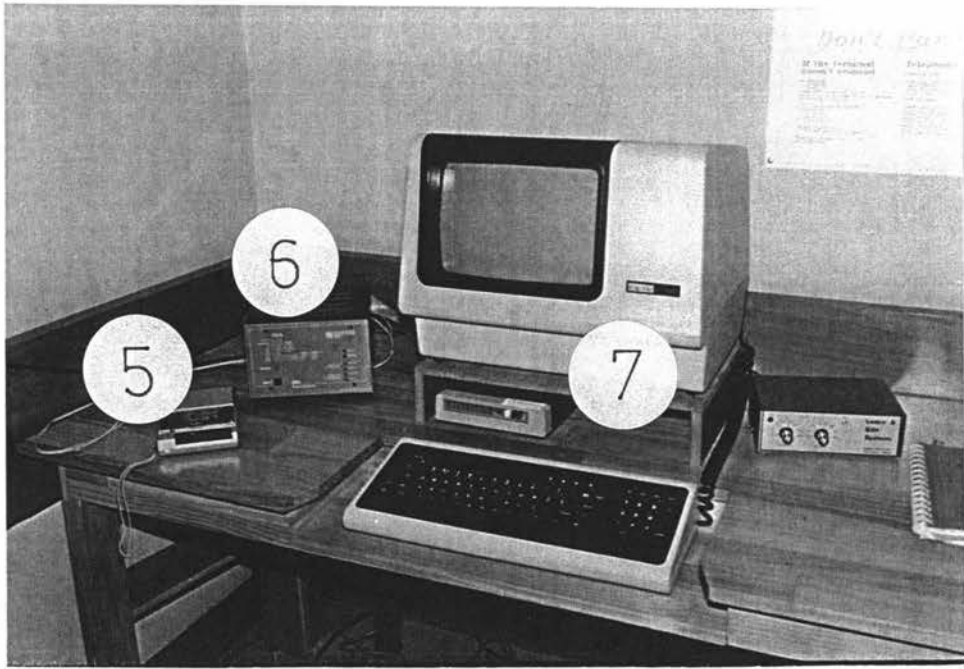
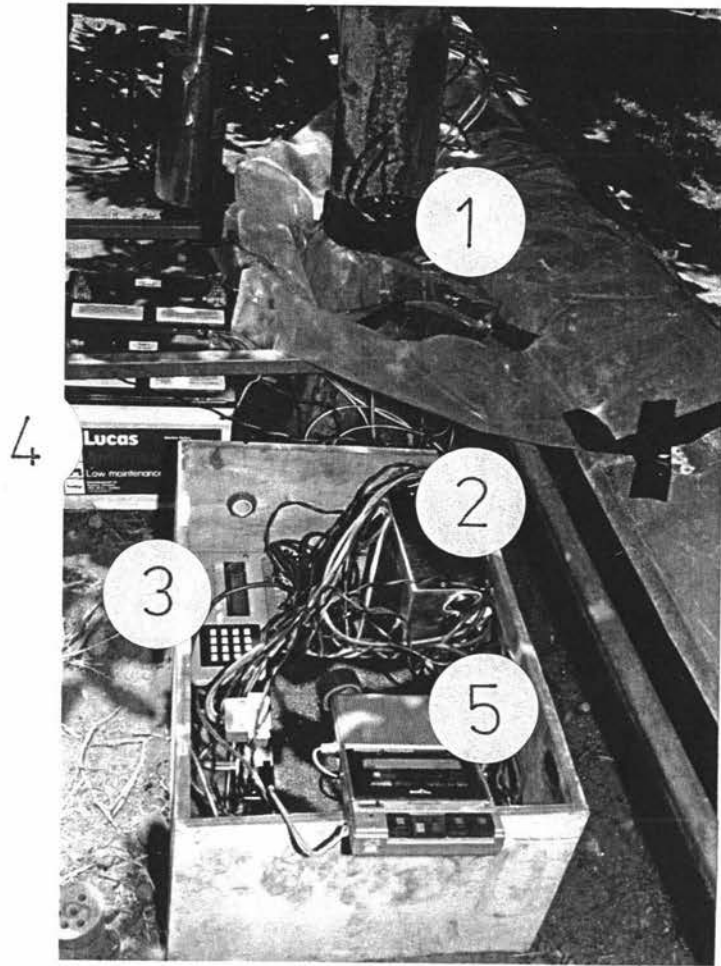


Figure 5.3(a). The heat pulse instruments in Tree U, consisting of 3 sets of thermistor beads and heaters (1) which were controlled by heat pulse and heater circuits (2) and connected to a Campbell CR21X data logger (3) powered by a 12 Volts lead-acid battery (4) and connected to an audio cassette recorder (5).

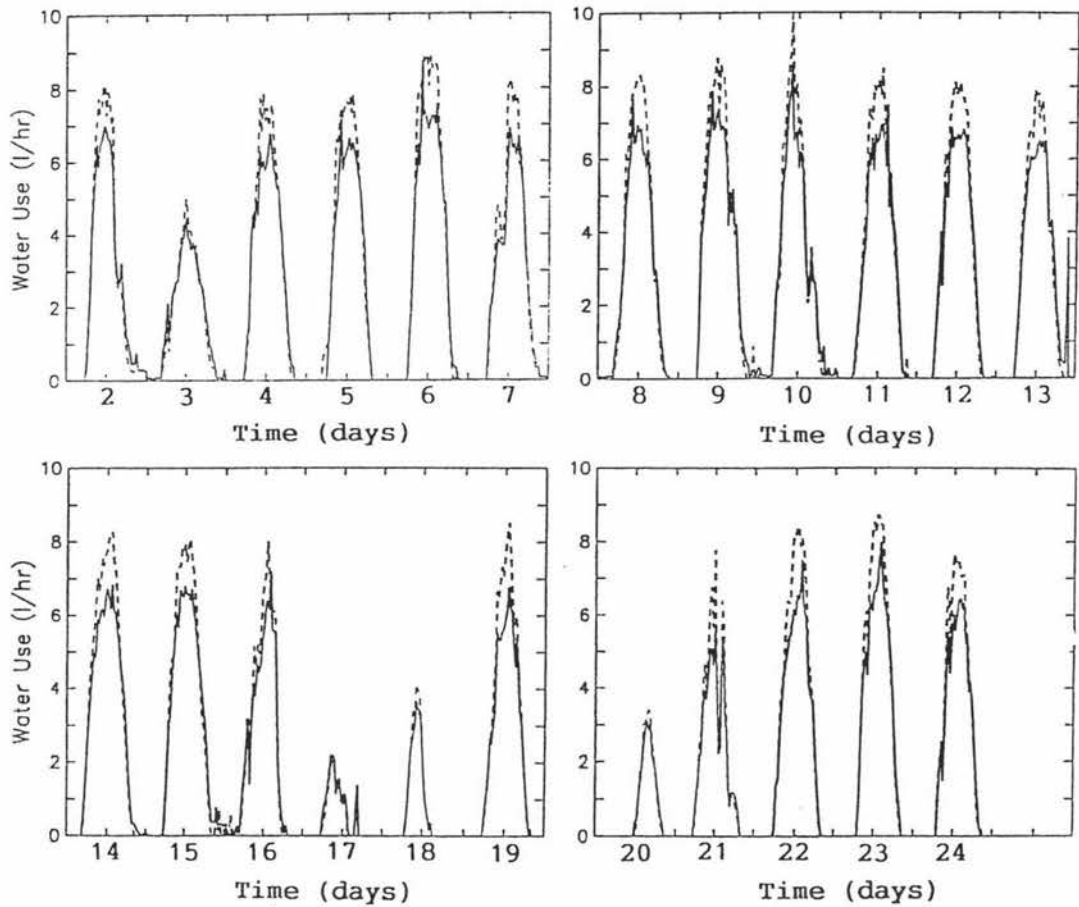


Figure 5.4. The pattern of daily water use (litres/hour) from Day 2 to Day 24 as measured by the heat pulse technique for Tree I (—) and Tree U (-----).

this being Days 2, 3, 9, 10, 14, and 15. Why water was lost on some nights but not others calls for some explanation. Stomata, which are small pores connecting the internal air spaces of a leaf to the outside air, usually are closed during the night and open during the day, depending on the available energy from sunshine (Jarvis and Mansfield, 1981). But in some dicotyledons, such as apple, stomata can remain open on windy nights with a low humidity (Sharpe, 1973, Muchow et al., 1980; Turner et al., 1980; Judd et al., 1986), leading to nocturnal transpiration (Green et al., 1989).

Figure 5.5. shows the average daily water use of Trees I and U. Day 3 (December 15) was a cloudy day without rain, and so had a lower water use than most other days. However, cloudy days with rain (Days 17, 18 and 20) had even lower water use values than Day 3. On cloudy days with rain, evaporation of the rain itself, and the presence intercepted water on the leaves, would lead to a high humidity and a small saturation deficit. Thus the stomata would not fully open and even if they did, little transpiration would occur due to the small vapour pressure deficit. The average water use from Day 7 to Day 16 for Tree I was 63.0 litres/day and for Tree U was 68.5 litres/day.

5.2. STOMATAL RESISTANCES

5.2.1. STOMATA

In dicotyledon plants, such as apple, stomata are located on the bottom of leaves. The opening or closing of stomata will depend on the expansion and contraction of the two guard cells at the entrance of each stomate (Bidwell, 1974).

If the rate of water loss from the plant through the stomata exceeds the rate of water uptake from the soil, the plant will suffer a water deficit. Higher plants can use different mechanisms to cope

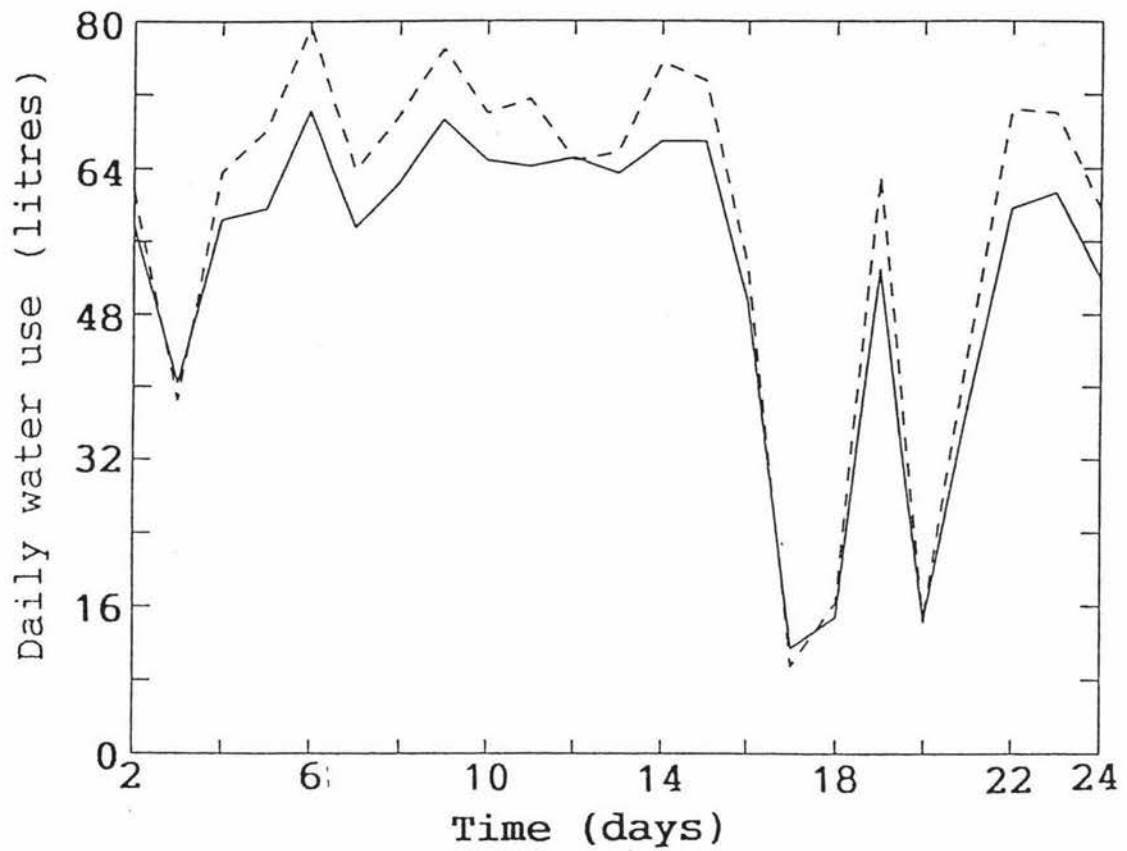


Figure 5.5. Daily water use measured by the heat pulse technique from Day 2 to 24 for Tree I (—) and Tree U (-----).

with stress, such as slowing down transpirational water loss through stomata control, using water stored in a certain organ, or by developing deeper root systems to extract soil water (Speer et al., 1988). The transpiration rate reflects in part the stomatal response to environmental conditions. Small reductions in epidermal turgor can result in increasing stomatal resistance (Davies et al., 1981). As water stress develops in the plant, the degree of water deficit affects the stomatal response to photon flux density, temperature, carbon dioxide and vapour pressure deficit, giving a certain maximum stomatal opening which is lower than that when stress is absent. As the stress increases, the maximum degree of stomatal opening on any day will be less (Hall et al., 1976). Thus when there is enough water in both soil and plant, the guard cells surrounding stomata will open fully in sunlight, as the guard cells are turgid. On the other hand, when both soil and plant have less water, the turgor of the guard cells will decrease, and the stomata will reduce their opening period, or even stay closed all day. The closure of stomata is related to the amount of the growth regulator abscisic acid (ABA) (Wright, 1969 and 1977). During water stress, ABA is transported from mesophyll to the guard cells. The more ABA in the guard cells, the less the stomata open (Jones and Mansfield, 1972; Loveys, 1977). The degree of stomatal opening affects CO₂ uptake, which will affect not only photosynthesis but also metabolism in general. Furthermore plant growth, which depends on photosynthesis, will be affected.

When the humidity in the atmosphere outside the leaf cuticle is lower than in the intercellular spaces within a leaf, there is molecular diffusion of water vapour outwards through the stomata. The number and openness of the stomata, and the humidity difference, will affect the rate of diffusion. The porometer is an instrument to measure the diffusive resistance of leaves to water vapour (Stiles, 1970; Montheith and Bull, 1970; Squire and Black, 1981). The stomatal resistance measured may be related to the transpiration rate from the leaves, and may detect whether the plant is under stress or not. High values of stomatal resistance indicate that the plant is under stress, as the opening of stomata is smaller due to their lower turgor. On the other hand, low stomatal resistances suggest a normal transpiration rate, as the stomata are fully open.

5.2.2. THE POROMETER

The porometer used was Automatic Porometer Mk3 made by DELTA - T DEVICES, England (see Figure 5.6(a)). The clamp is attached to a cup, containing a relative humidity (RH) sensor and two thermistors, which are used to measure leaf and cup temperature. The leaf measured is held in the clamp with the cup facing the bottom of the leaf, as the stomata are there. A small electric diaphragm pump is used to blow dry air into the cup. The source of dry air is a drying chamber containing silica gel. When the RH in the cup has been lowered 5 percent below the ambient level, the pump switches off. Water vapour then diffused through the stomata, increasing the RH in the cup. The device measures the time taken for the RH in the cup to rise from 5 percent below to 5 percent above the ambient value, and a number of counts which is proportional to this time appears on the small LCD screen after each pumping cycle. The frequency of the oscillator used in the counting device is 200 Hz. The measurement is repeated until the response time is constant. The leaf stomatal resistance values can be found by comparing this time with similar times measured using perforated plates with known diffusion resistances in the apparatus instead of leaves.

The sequences of events involved when the porometer was used were as follows. Firstly, the temperature and RH of the air were measured. The RH value switch was then set to the appropriate value. Secondly, the moulded polypropylene calibration plate, which was covered with blotting paper wet with distilled water, was clipped by the clamp. The plate has six sets of holes of varying size. The diffusion time associated with a certain hole size appeared on the right LCD screen of the device. By plotting the diffusion time and corrected resistance readings, a calibration graph was made, as shown in Figure 5.7. This was done before and after every measurement. Thirdly, several randomly selected leaves from Trees I and U were clipped by the clamp and their diffusion times measured (see Figure 5.6(b)). The value of the temperature difference between the cup and leaf could be read on the left LCD screen of the device.

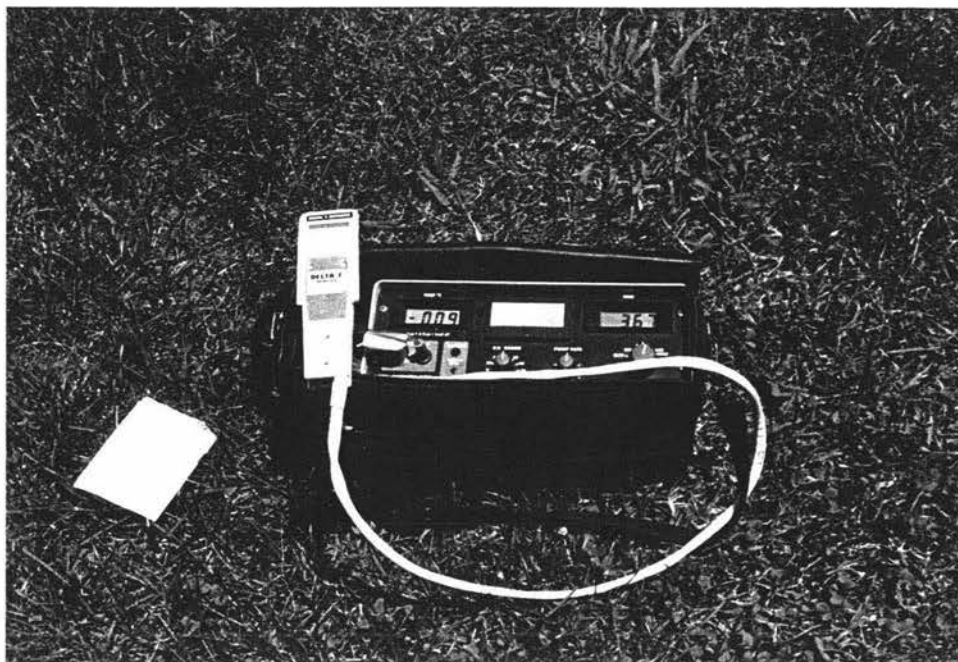


Figure 5.6(a). The Delta-T Device Porometer.



Figure 5.6(b). Using the porometer to measure the stomatal resistance of the bottom of a leaf.

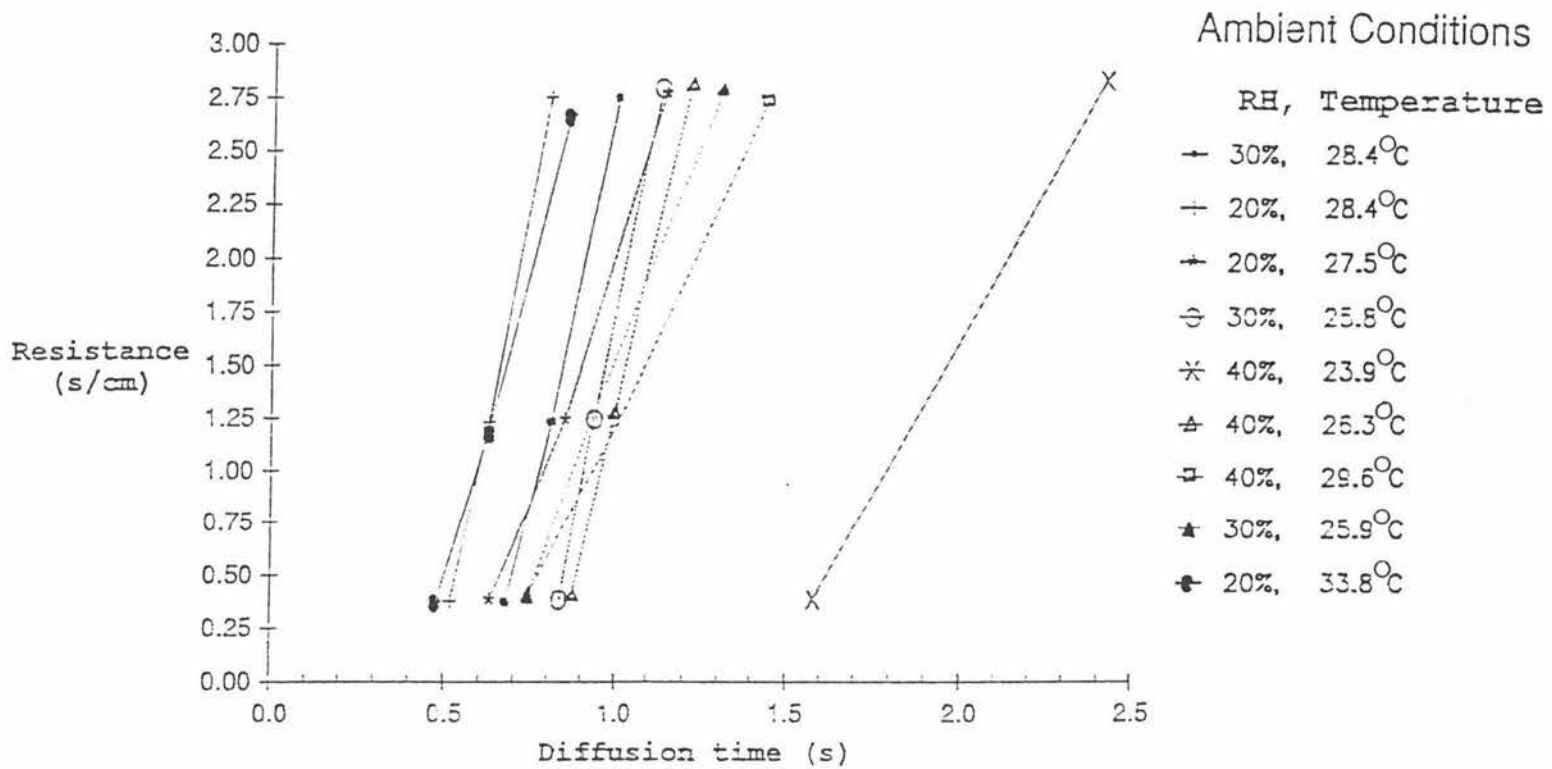


Figure 5.7. The correlation between diffusion time (s) and plate resistance (s/cm) for porometer calibrations under various relative humidity and temperature conditions.

The factory calibration was carried out at a temperature of 20°C, so for measurement at temperatures other than 20°C, a correction of the known resistance of the plate was needed. This was made using Table 5.1. The correction was calculated by interpolating between air temperature and index values. The index calculated was then multiplied to the standard known resistance of the plate.

During most of the measurements and calibrations, there was a small temperature difference (dT) between the cup and the leaf. When the leaf temperature was higher than the cup temperature, more water vapour would be driven into the cup, and this would decrease the diffusion time. So, the measured diffusion time needed to be corrected to take account of this also. The corrected diffusion time (t') was calculated by

$$t' = t + c_0 t dT \quad (5.4)$$

where t is diffusion time measured in the field

(1 count = 1/200 second),

c₀ is coefficient of the temperature difference between cup and leaf or plate at a certain RH range in %/°C (see Table 5.1),

dT is temperature difference (cup - leaf) measured in °C

5.2.3. RESULTS

Figure 5.7. shows some typical calibration graphs found during the investigation. The hole sizes used were holes number 4, 5 and 6. Most of the calibrations had similar slopes, but different intercepts, due to the different RH and temperature at each calibration.

Based on the calibration graph and the diffusion time measured, values for the stomatal resistance of the apple leaves from Days 9 to 29 for both Trees I and U were found and are shown in Figure 5.8. The t-test values for the data indicated that there were significant

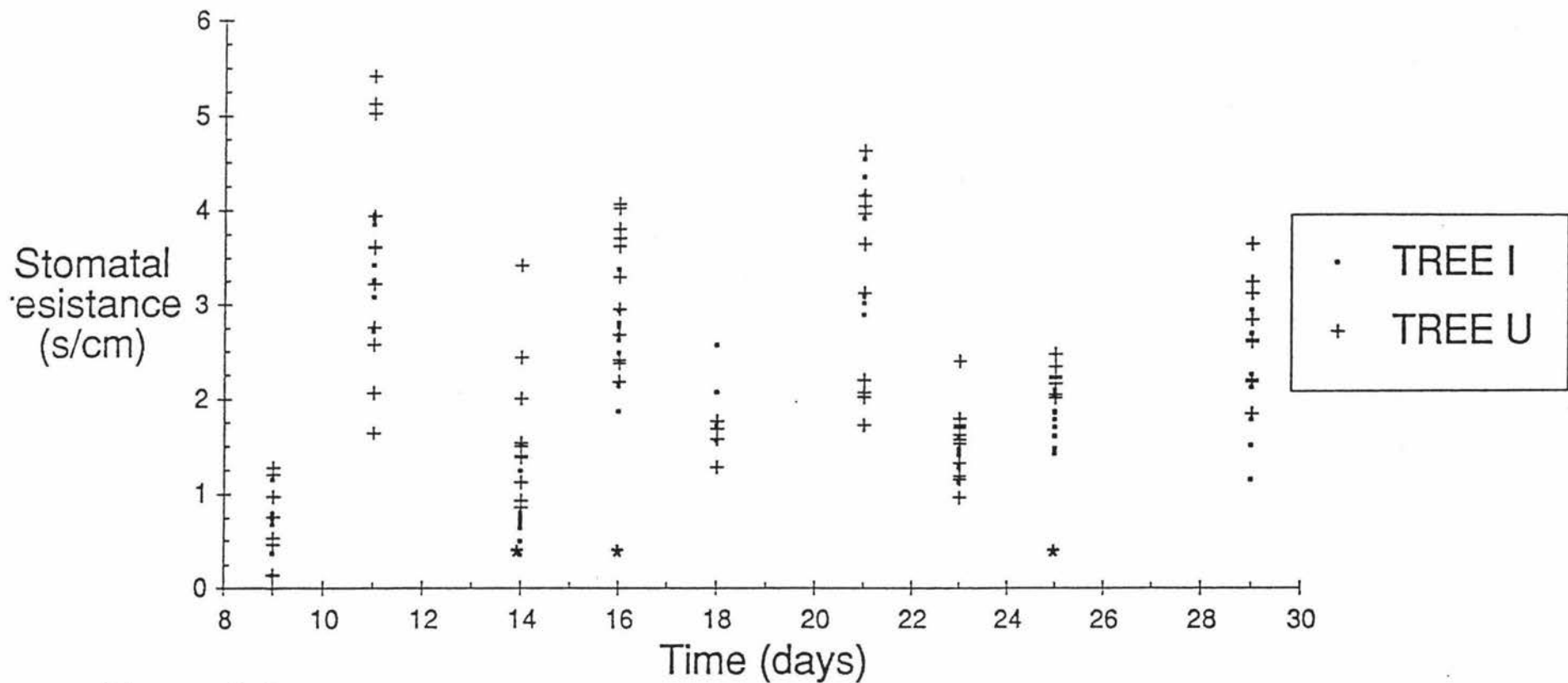


Figure 5.8. Stomatal resistance of apple leaves from Trees I and U. Days 14, 16 and 25 showed a significant difference (indicated with *) in the stomatal resistance values between Trees I and U.

Table 5.1. The diffusion resistance and time corrections.

Group of holes	1	2	3	4	5	6
Resistance (s/cm)	22.5	10.9	6.5	2.9	1.3	0.4
Temperature (°C)	0	10	20	30	40	50
Multiply plate resistance by	1.12	1.06	1.00	0.99	0.88	0.81
RH range (%)	20	30	40	50	60	70
c _o (%/°C)	7.5	8.5	10	12	15	20

from : operating manual.

differences in stomatal resistance between Trees I and U only on Days 14, 16 and 25 (see Table 5.2). On most days there were no significant differences between Trees I and U.

The stomata resistances tend to be small on days without rain, such as on Days 9, 14, 23 and 25, with lower relative humidity (50 - 75 %) and with sunshine, with most values between 0.65 and 1.75 s/cm. On the other hand, Days 16, 18 and 21, which were wet or cloudy, and had high humidity (> 80 %) and short sunshine duration (< 4 hours/day), had greater values of stomatal resistance with most values between 2.64 and 3.63 s/cm. When the stomatal resistance of Trees I and U were significantly different, the average value for Tree U was between 0.4 to 0.9 s/cm higher than for Tree I.

Swietlik et al., (1983) reported that a stomatal resistance value of about 4 s/cm indicated the beginning of water-stress in apple seedlings in Beltsville, USA, while values of about 3 s/cm showed the trees were in normal condition. Chapman (1970) stated that fruiting apple trees have lower stomatal resistance, because during the

fruiting period the trees need more energy and so transpire more. Erf and Proctor (1987) found that typical values of completely defruited (0 fruit/tree), left unthinned (483 fruits/tree) and thinned (370 fruits/tree) eleven-year-old apple trees were 3.57, 3.03 and 2.78 s/cm respectively during the fruiting period in Guelph, Canada. At the end of fruiting values dropped to about 1.3 s/cm.

Based on the above data for apple trees, our values for stomatal resistance seem to be lower during the fruiting period on sunny days.

Table 5.2. Averages and standard deviations of stomatal resistance (s/cm) values and t-test parameters.

Day	Tree I	Tree U	t-test value	t(0.05) (n_1+n_2-2)	t(0.01) (n_1+n_2-2)
9	0.65 ± 0.35	0.69 ± 0.44	0.18	2.18	3.06
11	3.37 ± 0.50	3.55 ± 1.26	0.38	2.11	2.90
14	0.72 ± 0.24	1.62 ± 0.76	3.40	2.10	2.88 **
16	2.64 ± 0.41	3.20 ± 0.70	2.20	2.09	2.86 *
18	1.98 ± 0.45	1.58 ± 0.21	1.63	2.45	3.71
21	3.63 ± 0.68	3.06 ± 1.07	1.33	2.11	2.90
23	1.35 ± 0.17	1.55 ± 0.39	1.32	2.11	2.90
25	1.75 ± 0.23	2.19 ± 0.15	4.95	2.11	2.90 **
29	2.07 ± 0.64	2.70 ± 0.58	2.10	2.15	2.98

* : significant difference at 0.05 level
 ** : significant difference at 0.01 level

5.3. LEAF WATER POTENTIAL

5.3.1. WATER POTENTIAL

The balance between water loss through transpiration, and water uptake via roots, controls the plant water status which is usually related to the plant water deficit (Boyer, 1969). Quality and yield can be affected by even a small plant water deficit which puts the plant under a certain stress.

Transpiration from leaves induces a plant water potential difference between roots and leaves, and so the movement of liquid water through the plant (Jarvis and Marison, 1981). The decrease in leaf water potential during the day is related to the increase in transpiration of woody plants under normal well-watered conditions (Jarvis, 1975). Under these conditions, the potential difference between roots and soil is nearly zero. In the evening, the transpiration rate decreases, leading to an increase in leaf water potential. When the transpiration ceases or is very small during the night, the leaf water potential returns slowly to its initial pre-dawn value. Thus a plant has a certain pattern of diurnal change in leaf water potential due to transpiration during the day (Klepper, 1968). But when the soil water supply is not sufficient to maintain plant water uptake, the average plant water potential will decrease, and the diurnal leaf water potential pattern changes to a lower position, showing the degree of stress (Waring and Cleary, 1967). However if appropriate soil water inputs from rain and irrigation occur, the diurnal pattern almost immediately returns to the normal pattern described above.

Scholander et al., (1964; 1965) described a simple technique to estimate the degree of plant water stress by using a pressure chamber to balance the internal plant water potential.

The balancing pressure can be written as follows :

$$\varphi_x = P + \varphi_s \quad (5.5)$$

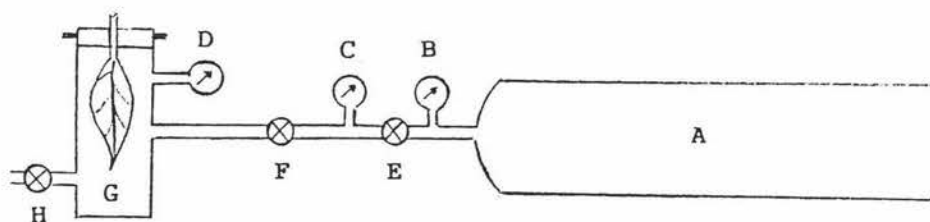
where φ_x is xylem water potential,
 P is hydrostatic pressure of the xylem sap which is equal in magnitude to the pressure in the chamber,
 φ_s is osmotic pressure (Boyer, 1967; Ritchie and Hinckley, 1971)

Since the magnitude of osmotic pressure is small, it is normally not lower than -0.3 MPa (Scholander et al., 1966; Boyer, 1967 and 1968), and the pressure chamber does not estimate φ_s (Boyer, 1968), the value of φ_x is assumed equal to P (Barrs et al., 1970; Boyer and Ghorashy, 1971; Duniway, 1971; West and Goff, 1971). Thus the pressure chamber can be used to estimate the leaf water potential, which is often used as an indicator of the degree of plant water deficit or stress (Ritchie, 1975).

5.3.2. THE PRESSURE CHAMBER

The pressure chamber used in the research was similar to the portable pressure chamber introduced by Waring and Cleary (1967) and Tobiessen (1969). Figure 5.9. shows the components of the pressure chamber apparatus, and Figure 5.10. shows the portable pressure chamber used in the research.

The general mechanism of how the pressure chamber works is as follows. When water is in a blind-ended capillary with wettable walls, such as the xylem vessels in a severed fresh leaf, not only is there a pressure difference across the curved interface, but also the water column is broken and water withdraws into the petiole a short distance. Water inside the leaf is at a lower pressure than the air. To measure the original pressure before the leaf was severed, the leaf is placed in a chamber with the cut petiole end protruding through a rubber gland. Then a certain pressure of nitrogen gas is applied in the chamber, and water is forced from the mesophyll to refill the xylem (Duniway, 1971).



- A : Nitrogen gas tank,
 B, C, D : Pressure gauges,
 E, F : Control valves,
 G : Leaf chamber,
 H : Bleed-off valve

Figure 5.9. Diagram of the pressure chamber apparatus.



Figure 5.10. The pressure chamber apparatus used in the research.

The minimum pressure needed for the exudation of water (xylem sap) from the cut end of the petiole is assumed equal in magnitude to the internal pressure potential of the leaf before it was severed.

The procedure used was as follows. Each apple leaf was cut and put in a small transparent plastic bag to avoid water loss due to evaporation (Gandar and Tanner, 1976). The cut end of the leaf was quickly inserted through a rubber gland into the chamber top less than one minute after its removal from the tree. The top was affixed to the chamber body. Then the chamber was pressurized by nitrogen until we could see exudation of xylem sap from the leaf. The pressure was then recorded. Finally, the bleed-off valve was opened.

5.3.3. RESULTS

The pressure chamber used was a portable one. The leaf water potentials were measured every few days from Day 9 to Day 29. Several samples were taken every measurement from both Trees I and U. Fully unshaded leaves were selected for measurement. The range of values measured was from -0.70 MPa to -1.90 MPa. The average values for Trees I and U when they were significantly different were -1.3 and -1.7 MPa respectively. Based on the t-test values of the leaf water potential means, there were significant differences between Trees I and U on Days 11, 14, 21, 23, 25 and 29 (see Table 5.3.). This indicates that on most days there were differences in leaf water potential between Trees I and U, as shown in Figure 5.11. Environmental conditions strongly affect the leaf water pressure potential values. Some workers argue as to whether pre-dawn or mid-day leaf water pressure potential is a better indicator of the level of stress, since leaf water pressure potential will be lower with increasing transpiration. The difference between pre-dawn and midday values becomes greater as apple trees experience water stress (Powell, 1976). Powell (1976) found that the difference in water pressure potential in an apple tree between droughted and irrigated conditions in Bristol, UK, on a sunny day was about 0.3 MPa, with typical potential values of about -1.0 MPa.

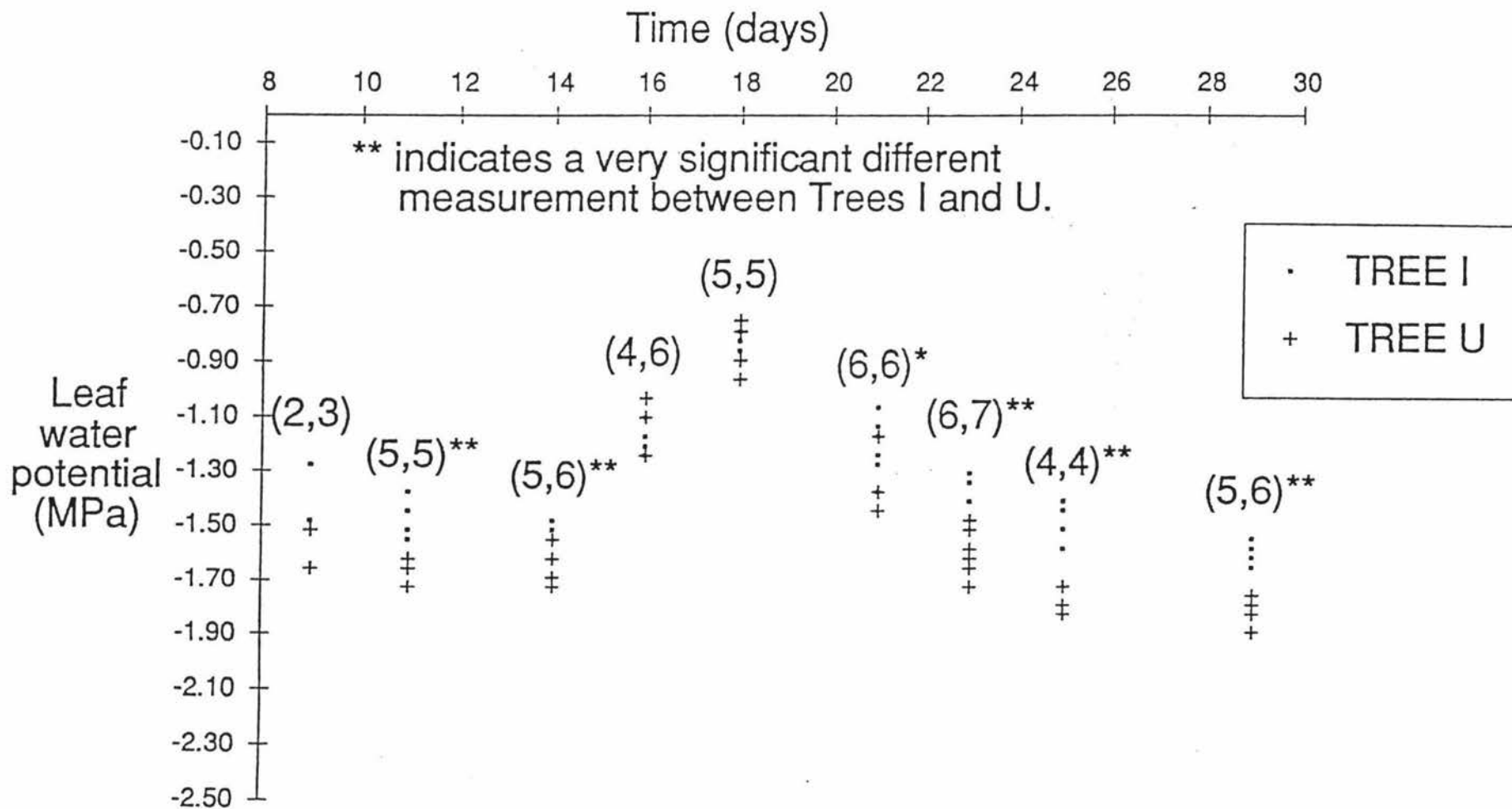


Figure 5.11. Leaf water potential measured by pressure chamber apparatus on Days 8 to 30. The first and second numbers in the parentheses show the number of leaf samples of Trees I and U respectively being measured.

Table 5.3. Average leaf water pressure potential (MPa)

Day	Tree I	Tree U	t-test	t(0.05) (n ₁ +n ₂ -2)	t(0.01) (n ₁ +n ₂ -2)
9	-1.38 ± 0.15	-1.56 ± 0.08	1.89	3.182	5.841
11	-1.47 ± 0.07	-1.68 ± 0.04	5.67	2.306	3.355 **
14	-1.50 ± 0.02	-1.64 ± 0.08	4.09	2.262	3.250 **
16	-1.18 ± 0.06	-1.16 ± 0.09	0.39	2.306	3.355
18	-0.82 ± 0.03	-0.86 ± 0.08	1.04	2.306	3.355
21	-1.21 ± 0.11	-1.36 ± 0.09	2.43	2.228	3.169 *
23	-1.37 ± 0.05	-1.62 ± 0.09	5.72	2.201	3.106 **
25	-1.49 ± 0.08	-1.78 ± 0.04	6.67	2.447	3.707 **
29	-1.60 ± 0.04	-1.80 ± 0.06	6.73	2.262	3.250 **

* : significant difference at 0.05 level

** : significant difference at 0.01 level.

Stomata closure occurred completely at a value of about -2.5 MPa. However West and Gaff (1967) found that stomata of apple will remain closed due to stress at values of about -1.8 to -2.2 MPa. Irving and Drost (1987) reported that the midday water potential in apple trees at Levin, NZ during the summer fruiting period ranged from -1.3 to -1.8 MPa in unstressed trees, but -1.7 to -2.3 MPa in stressed trees. Erf and Proctor (1987) recorded that unstressed fruiting apple tree in Guelph, Canada had typical values of about -1.6 MPa, increasing to about -1.0 MPa at the end of season after fruiting.

Our data are similar to values found by Irving and Drost (1987) in NZ and Erf and Proctor (1987) in Canada, but lower than the values found by Powell (1976) in UK. However, the difference between the unstressed and stressed trees is similar to that found by Powell (1976).

5.4. APPLE FRUIT VOLUME

5.4.1. MEASURING CYLINDER TECHNIQUE

The technique used to measure the volume of an apple fruit was based on the measurement of the displaced water volume by the apple in a measuring cylinder. The measuring cylinder consisted of a main cylinder, a scaled small cylinder, a rectangular base and a spirit level. The scaled small cylinder was connected in parallel to the main cylinder as shown in Figure 5.12. Firstly, the cross-sectional areas of both cylinders were determined. Secondly, the cylinders were filled with a certain amount of water and the height of the water was recorded. Thirdly, the apple fruit was sunk in the water of the main cylinder and the new water level was recorded from the scaled small cylinder. Finally, the apple fruit volume could be calculated by multiplying sum of the cross sectional areas with the difference in water level after and before the fruit was placed in the measuring cylinder. To ensure vertical positioning of the cylinder, a spirit level was fixed on the rectangular base of the cylinder and its air bubble was maintained in the centre during fruit measurement.

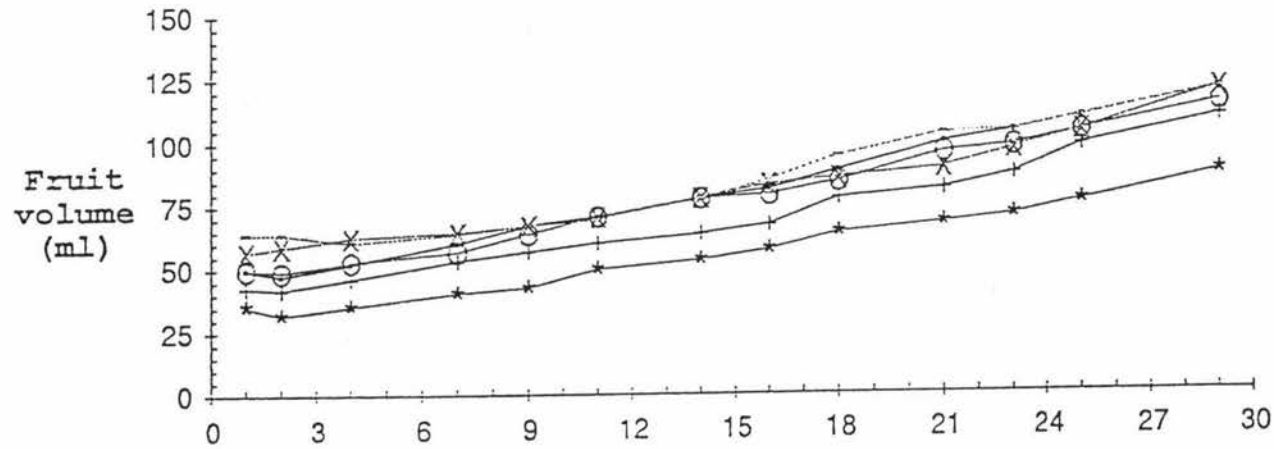
5.4.2. APPLE FRUIT GROWTH

The apple fruit growth was monitored by measuring the volume of selected fruit from Day 1 to Day 29. Six apple fruits were chosen from each of Trees I and U. During the research period, one of the selected apple fruits from Tree I and two apple fruit from Tree U dropped off, so new fruits had to be selected.

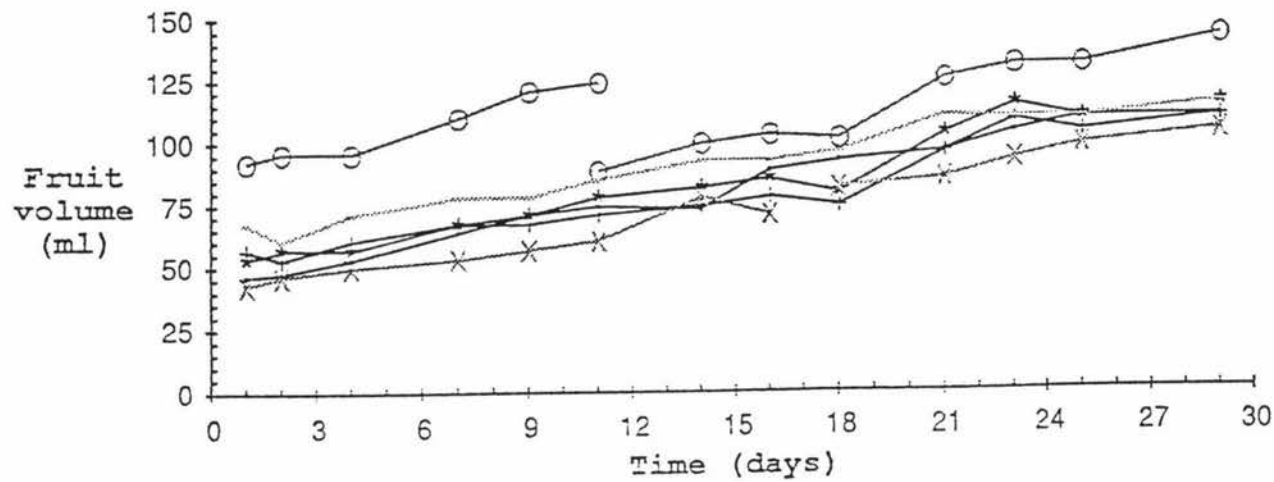
Figure 5.13. shows the individual apple fruit volumes on both Trees I and U from Day 1 to Day 29. Figure 5.14. shows the average apple volume on Trees I and U. The difference in growth rates between apples on Trees I and U from Day 1 to Day 9 (the first nine days) was not significant. But from Day 21 to Day 29 (the last nine days) there was a difference, significant at the one percent level, as shown in Table 5.4. The reason for investigating the apple growth during the first and last



Figure 5.12. The measuring cylinder used to monitor apple growth.



- Tree I, Fruit 1
- + Tree I, Fruit 2
- * Tree I, Fruit 3
- ⊖ Tree I, Fruit 4
- × Tree I, Fruit 5
- Tree I, Fruit 6a
- Tree I, Fruit 6b



- Tree U, Fruit 1
- + Tree U, Fruit 2
- * Tree U, Fruit 3
- ⊖ Tree U, Fruit 4a
- ⊖ Tree U, Fruit 4b
- × Tree U, Fruit 5a
- × Tree U, Fruit 5b
- ⋯ Tree U, Fruit 6

Figure 5.13. The relationship between apple fruit volume (ml) and time (days) for Tree I (above) and Tree U (below).

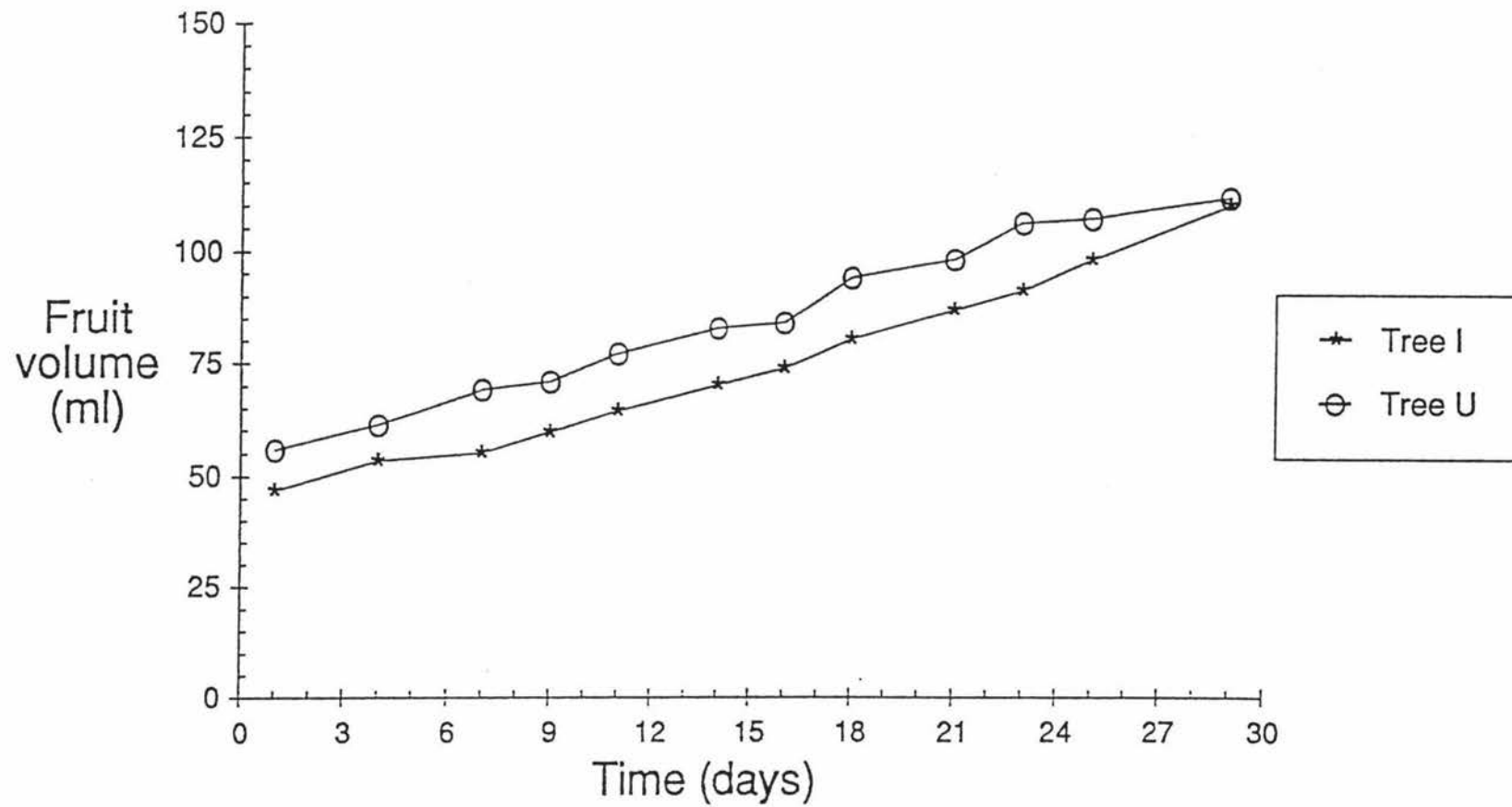


Figure 5.14. The average apple fruit volume with time.

nine day periods was that during these periods none of the fruit being measured dropped off. One fruit from Tree I dropped off after Day 11, while two fruits from Tree U dropped off after Days 11 and 16.

During the first nine days of the study period, the fruit growth rate of the apples on Tree U was not significantly different to those on Tree I. This means that fruits on Tree U (unirrigated) were still growing as well as Tree I (irrigated), which received water freely. But Tree U did show the effects of 'stress' during the last nine days of the research period, when the fruit growth rate on Tree U was much lower than Tree I (see Figure 5.14 and Table 5.4).

Table 5.4. The average of apple fruit growth rates (ml/day) of both Trees I and U.

Fruit Number	Days 1 to 9		Days 21 to 29	
	Tree I	Tree U	Tree I	Tree U
1	2.22	3.11	2.58	1.66
2	1.78	1.31	3.43	1.66
3	0.89	2.22	2.42	1.45
4	1.78	3.55	2.34	2.05
5	1.33	1.78	3.79	2.31
6	0.49	1.33	2.13	0.56
Average	: 1.41	2.22	2.78**	1.61**
St. dev.	: 0.65	0.94	0.67	0.60

** significant difference at the one percent level.

The effects of stress on fruit growth have been reported by several workers. Powell (1974) found that withholding irrigation and rain for 3 months had significant effects on apple fruit development, both in the season of the study and in the following year. However, Irving and Drost (1987) reported that apple trees under stress during summer in Levin, NZ showed no difference in fruit size, but quality was reduced by fruit cracking.

Our data showed that the apple tree under stress, with no water from rain or irrigation for almost one month, had slower fruit growth in the 4th week of the treatment. Unfortunately, we have no data on fruit quality, except its volume.

CHAPTER VI

DISCUSSION, CONCLUSIONS, AND PRACTICAL IMPLICATIONS

6.1. INTRODUCTION

In this chapter the significance of the results reported in the preceding chapters are discussed; and soil, plant and weather data are compared. The results reported here are also compared with results obtained at the same site a year earlier.

6.2. EXPERIMENT DURING SUMMER 1987/1988

The same trees, Tree I (irrigated) and Tree U (unirrigated), were used for experiments during the summer of 1987/1988. An irrigation of 425 litres of water was applied to Tree U over an area of 3.0 x 3.5 m on 9 November 1987, the start of the measurement period. This meant that the soil under Tree U was much wetter than during the 1988/1989 experiment. The projected fractional canopy area, measured by detecting the transmission of light through the apple tree canopy, was 0.55. The size of apple fruit was still small, as the experiment was carried out earlier in the fruiting period.

Water use, measured by neutron probing and time domain reflectometry around Tree U from 9 November 1987 to 1 December 1987 was 777 (\pm 112) litres, or on average 35 (\pm 5) litres per day. While water use measured by the heat pulse technique was 25 litres per day, almost within the error band of the neutron probe measurements. The soil water pressure potential values remained high (above - 14 kPa), indicating no water stress, due to the big soil water reservoir supplying the 777 litres of soil water extracted during the period of

the experiment (Rahardjo, 1988). These daily water use values are lower than those reported above for 1988/89, and the reasons for this will be discussed later.

6.3. SOIL DATA

During 1988/1989 tensiometer measurements showed that the matric potential around Tree I at 300 mm depth was higher (less negative) than at 600 mm depth. On the other hand, around Tree U the data showed that the soil at 300 mm depth was drier than at 600 mm depth. This finding agreed with the TDR measurements which indicated that the initial soil water content in the top 400 mm around Tree I was wetter than around Tree U.

Just before each extraction period, Tree I received water inputs. The input preceding the second extraction period was much higher than that preceding the first period. The second water input included about 24 mm of irrigation water on Day 17, and 0.8, 14, 8.3, 10.4, 6.2 and 0.3 mm of rainfall on Days 16, 17, 18, 19, 20 and 21 respectively, while the first water input consisted only of about 24 mm of irrigation on Day 3.

Soil water use measured by neutron probing and time domain reflectometry near Tree I (over 0 - 1900 mm depth) from Day 1 (19 December 1988) to Day 16 (28 December 1988), the first period of extraction, was 81.7 ± 19.4 litres/day, while from Day 21 (2 January 1989) to Day 29 (10 January 1989), the second period of extraction, was 72.6 ± 29.8 litres/day. On the other hand, water use by Tree U measured during the first period of extraction was only 18.7 ± 4.1 litres/day and during the second period of extraction was -4.0 ± 5.9 litres/day.

The soil water extraction from Tree I over 0 - 1900 mm depth during the first period of extraction (81.7 ± 19.4 litres) was higher than for the second period of extraction (72.6 ± 29.8 litres). But, if we calculate soil water extraction from 0 to 1100 mm and from 1100 to 1900 mm depth separately for Tree I, we find for the first period

that 74 percent and 26 percent of soil water was extracted from 0 - 1100 mm depth and 1100 - 1900 mm depth respectively. However, during the second period 92 percent of the water came from 0 - 1100 mm depth and only 8 percent from 1100 - 1900 mm depth. This means that when there was more available water in the soil, such as during the second period of extraction, the root system preferred to extract soil water from the top metre of soil. In contrast in the first extraction period, Tree U extracted only 42 percent of its soil water from 0 - 1100 mm depth and 58 percent from 1100 - 1900 mm depth. This means that, because of a lack of soil water availability in the topsoil, the root system was forced to extract soil water from deep in the soil profile (see Figure 6.1.).

6.4. PLANT DATA

Water use was monitored using the heat pulse technique from Day 2 to Day 24. Measurements of both stomatal resistance and leaf water potential were carried out from Day 9 to Day 29, while apple volume was measured from Day 1 to Day 29.

The heat pulse technique data showed an unexpected result, in that the unirrigated tree had a slightly higher water use than the irrigated tree especially near midday on sunny days (Figure 5.4.). However, the patterns of daily water use for Trees I and U were similar. The heat pulse technique also indicated the existence of nocturnal sap flow on some nights. Windy conditions and high saturation deficits due to the low humidity on some nights apparently induced stomata to stay open, allowing diffusion of water vapour which caused the nocturnal sap flow. On cloudy days with rain there was less sap flow than on a cloudy day without rain. The higher air humidity due to the evaporation from rain and interception would induce smaller saturation deficits at the leaf surface, and so little transpiration. Finally, the average daily water use of Trees I and U measured by the heat pulse technique were 63.0 ± 5.6 and 68.5 ± 6.8 litres/day respectively during the first period of extraction.

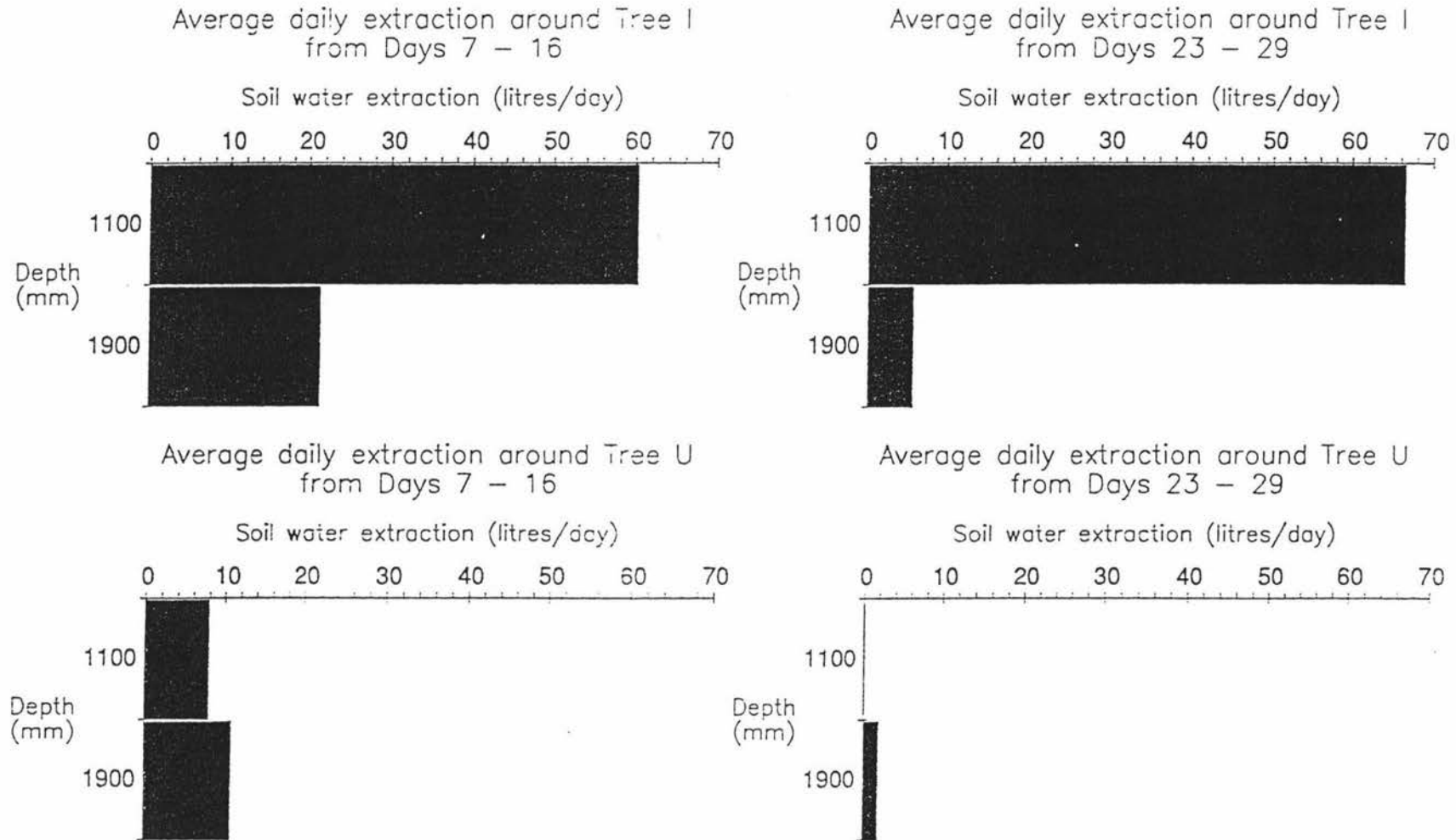


Figure 6.1. Soil water extraction from 0 - 1100 mm and 1100 - 1900 mm depth around Trees I and U during the first and second period of extractions.

Plant water stress can be indicated by a high stomatal resistance and a low leaf water potential. The stomatal resistance measured by a porometer showed significant differences between Trees I and U only on Days 14, 16 and 25. It seems that the stomatal resistance values are not a very sensitive way to monitor plant water stress in apple trees. On the other hand, the leaf water potential measured by a pressure chamber indicated the greater plant water stress of Tree U compared to Tree I more sensitively. Based on the values of leaf water potential, Tree U had been under stress from Day 11 (see Figure 5.11.). The effect of stress on fruit growth could also be seen from the fruit volume measurements. Tree U had slower fruit growth than Tree I during the last 9 days of the study period.

6.5. GENERAL DISCUSSION

There is a close relationship between water in the soil, the plant and the atmosphere. The rate of evaporation is a function of soil, plant and atmospheric conditions.

Figure 6.2. shows the water use estimated by the Priestley and Taylor method and measured using the heat pulse technique. The values of Priestley and Taylor regional evaporation, assuming 100 percent canopy cover, are much higher than the water use measured by the heat pulse technique. As mentioned above the projected canopy area during the 1987/1988 experiment was 55 percent. When a projected fractional canopy area of 0.55 was multiplied by the Priestley and Taylor regional evaporation, the water use value calculated was lower than the water use value measured by the heat pulse technique (Figure 6.2.). A likely reason for this discrepancy is that the canopy area during the summer 1988/1989 experiment was somewhat larger than during the summer 1987/1988 experiment. A greater canopy area would be expected as the 1988/89 experiment was conducted over a month later in the growing season than the 1987 experiment.

Assuming that the Priestley and Taylor values multiplied by the fractioned canopy area give a reliable estimate of tree water use, the projected canopy area can be estimated by dividing the amount of water

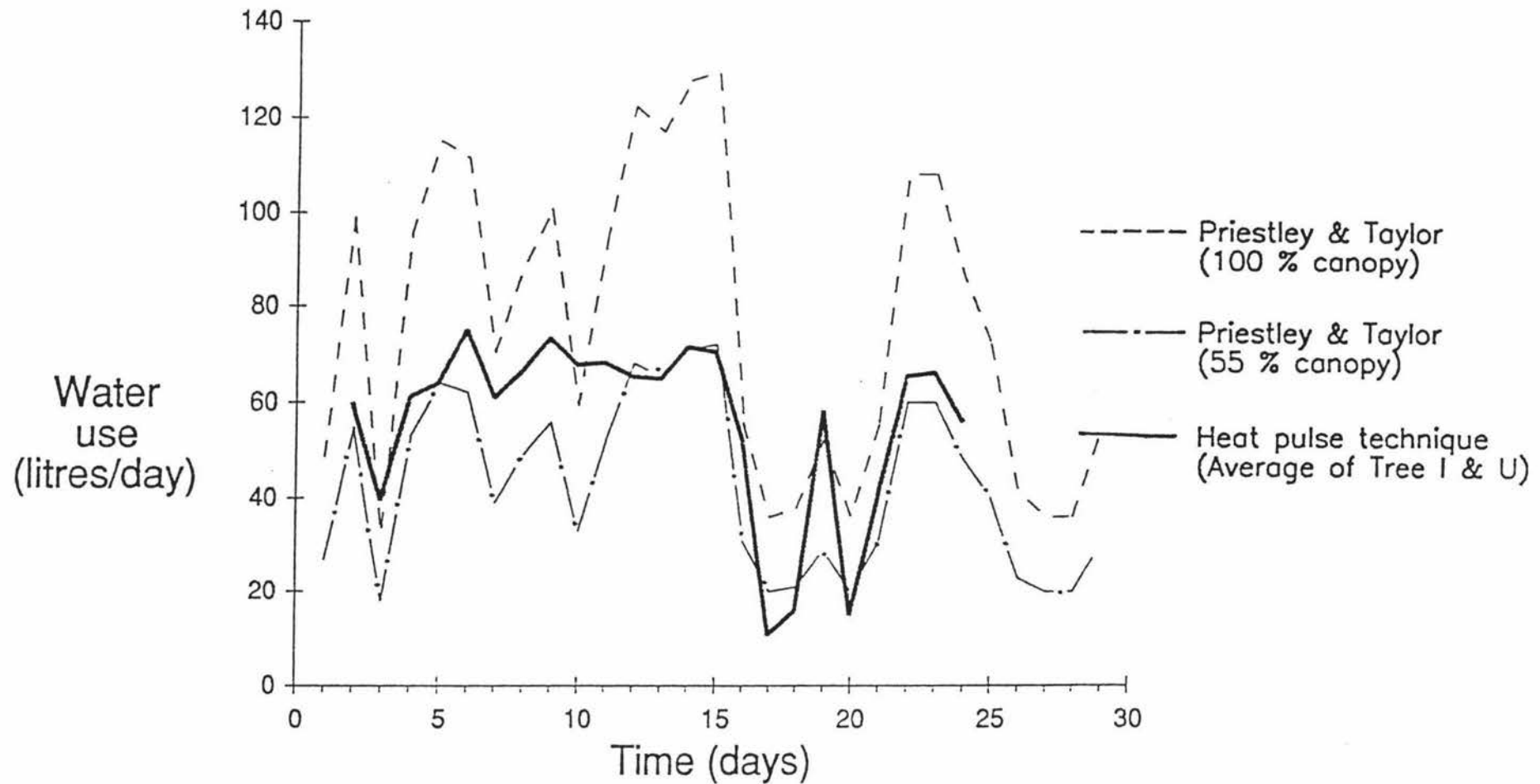


Figure 6.2. Water use per tree measured by heat pulse technique and regional evaporation of Priestley and Taylor method.

use measured using the heat pulse technique by the Priestley and Taylor estimate for 100 percent canopy cover. Average water use from Days 1 to 24 measured by the heat pulse technique and estimated from Priestley and Taylor equation assuming full cover was 55.7 and 84.3 litres per tree per day respectively. Thus, the estimated projected canopy area of the apple trees was 66 percent. Figure 6.3. shows fairly good agreement between daily heat pulse measurements and Priestley and Taylor estimates assuming 66 percent canopy cover.

Figure 6.3. also shows that the water use measured by neutron probing and time domain reflectometry around Tree I was higher than the water use measured by the heat pulse technique from Day 7 to 16. The likely reason is that the heat pulse technique only measured sap flow through the apple trunk, but the neutron probe and TDR measured the soil water change due to transpiration of the grass and evaporation from the bare soil under the irrigated apple tree as well as transpiration of the apple tree itself. On the other hand, compared to Tree I, water use measured by neutron probing and time domain reflectometry in the top of 1900 mm around Tree U was much lower during the first period of extraction. Furthermore, no soil water extraction at all was measured during the second period of extraction. This was an interesting finding, since although there was a negligible amount of soil water extraction from the top of 1900 mm of soil, Tree U was still transpiring at a rate slightly higher than Tree I. Thus, Tree U may have extracted its water from below 1900 mm through its deeper root system. As mentioned in Chapter II, the site of the experiment was adjacent to the Karamu Stream. So there was a strong possibility of the existence of a water table to maintain a supply of soil water to the bottom of the root system at some depth greater than 1900 mm. Another possibility is that the root system of Tree U extended horizontally beyond the covered area and extracted its water from there.

Cloudy days with rain occurred on Days 17, 18 and 20. The water use on those days measured by the heat pulse technique, which only detected sap flow through the trunk, was always lower than the Priestley and Taylor estimates (Figure 6.3.). This was probably because the Priestley and Taylor estimate would include the

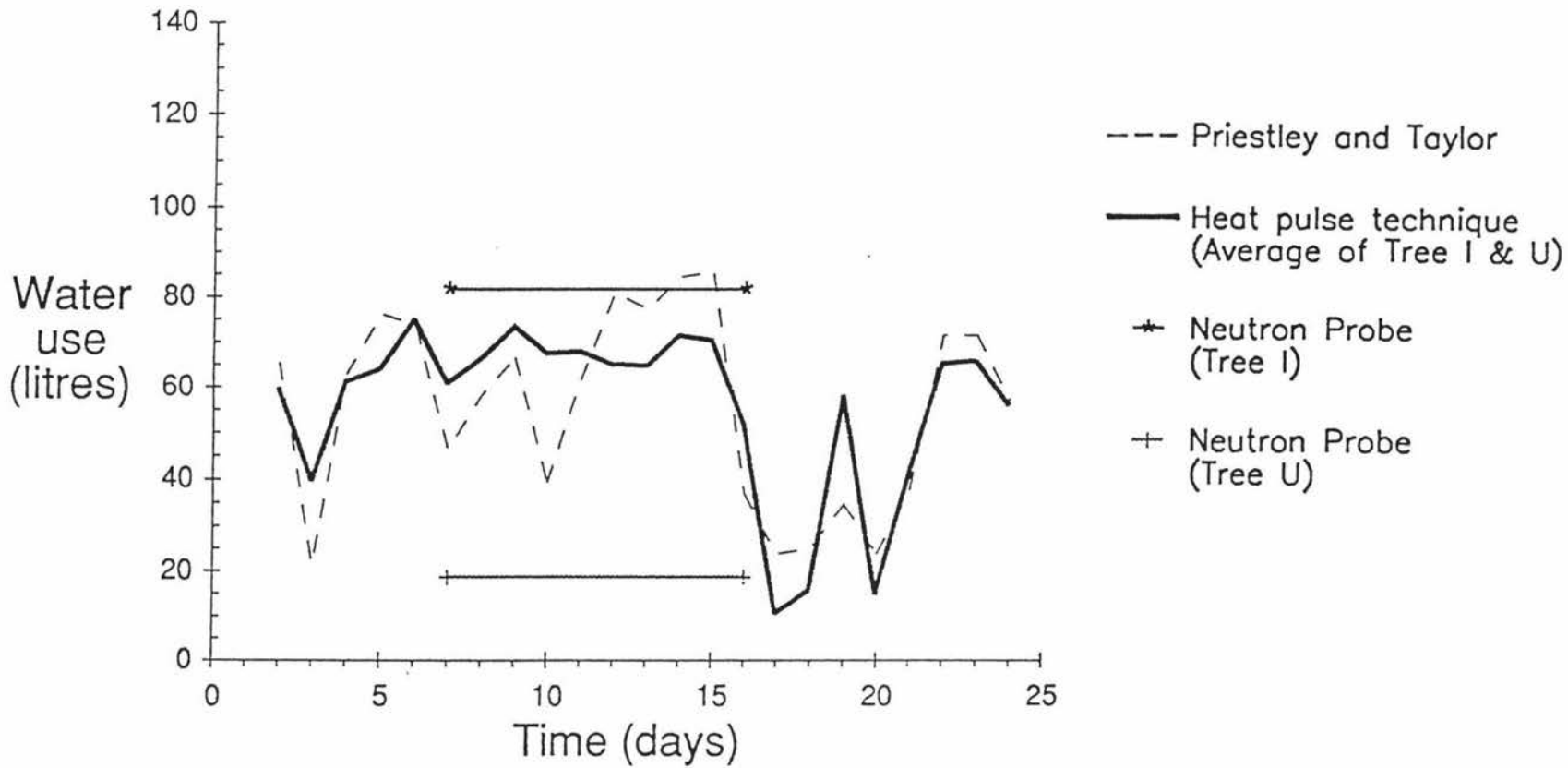


Figure 6.3. The comparison between water use per tree measured by neutron probe (assuming full root distribution), heat pulse technique and regional evaporation of Priestley and Taylor method (assuming 66 % canopy cover).

evaporation of intercepted rain from the leaves, but the heat pulse measurements would not. On those days little transpiration occurred. On the other hand, a cloudy day without rain, such as Day 3, had a higher water use measured by the heat pulse technique than estimated by the Priestley and Taylor method (Figure 6.3.). Although there was no sunshine on Day 3, the humidity was relatively low (Figure 6.5.).

Figure 6.4. shows daily apple tree water use was well correlated with the Priestley and Taylor estimate of regional evaporation during the experiment. It may be that the water use can be found by multiplying the Priestley and Taylor estimate by the typical projected canopy area. The projected canopy area of the apple trees for November was about 0.55. For mid December-January it may be about 0.66. For October it is likely less than 0.55 and for February it may be bit more than 0.66. These values will probably vary depending on variety, age, tree spacing and pruning method.

Figure 6.5. shows the relationship between rain, humidity and sunshine duration during the experiment. For example on Days 17 to 21 and Days 26 when there was little sunshine, some rain, and humidity tended to be higher. During the first period of extraction (Days 7 - 16), there was almost no rain (only 0.8 mm on Day 16), more sunshine and lower humidity than during the second period of extraction (Days 23 - 29). So it is not surprising that Tree I extracted more soil water in the first than the second period. Furthermore, average daily soil water extraction measured by neutron probing and time domain reflectometry for the first and second periods of 1988/1989 experiment was more than twice the extraction during the period from 9 November 1987 to 1 December 1987. The first likely reason for this was that the average air temperature during the first and second period of extraction of summer 1988/1989 was higher (19.0 °C) than the extraction period from 9 November 1987 to 1 December 1987 (16.6 °C). The second likely reason would be higher solar radiation values during 1988/1989 than 1987/1988 experiments. The Priestley and Taylor estimate assuming 100 percent canopy area for the 1987/1988 and 1988/1989 experiments were 51.2 and 96.5 litres per day respectively on sunny days. The Priestley and Taylor estimates depend of course on

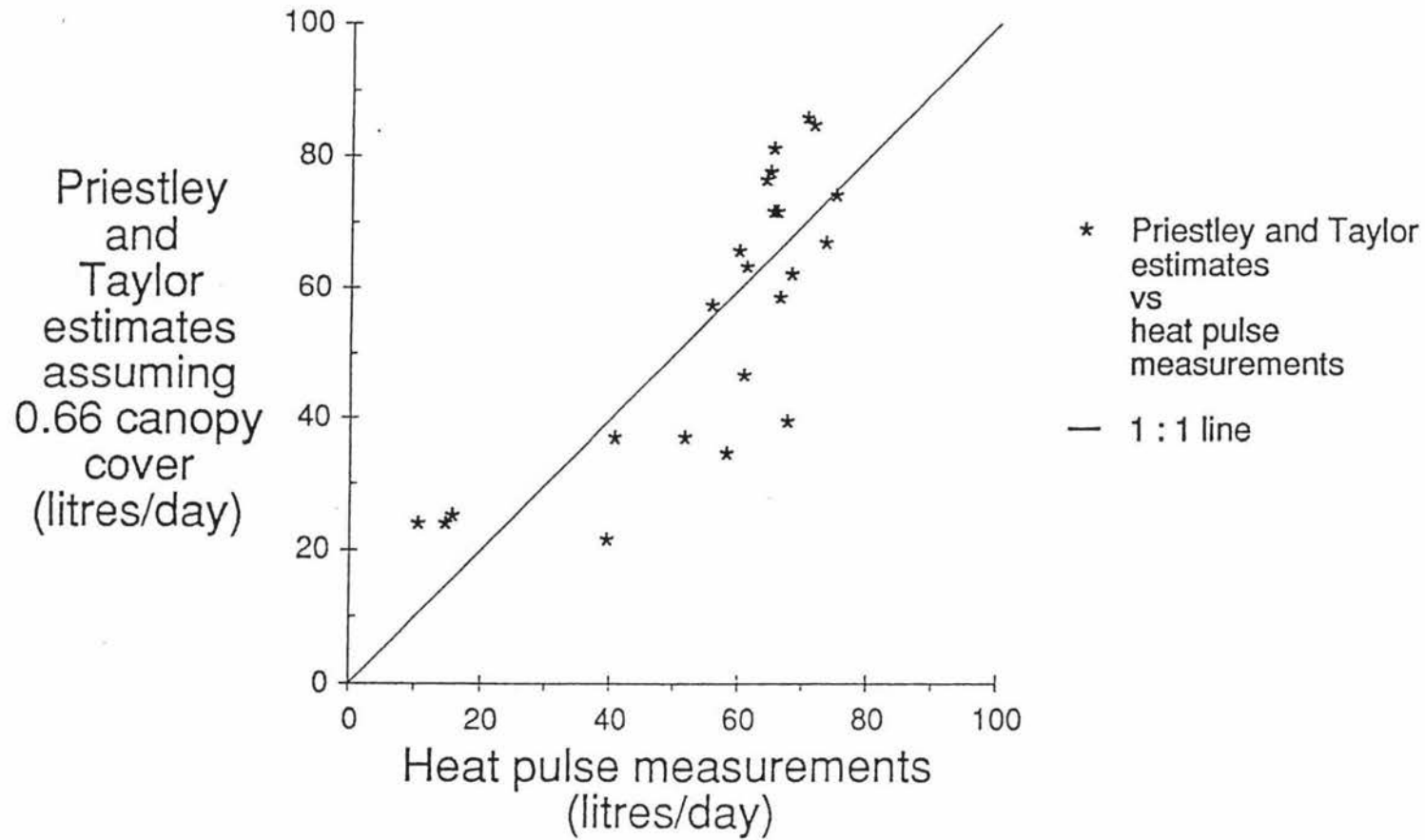


Figure 6.4. The relationship between the Priestley and Taylor estimates and the heat pulse measurements.

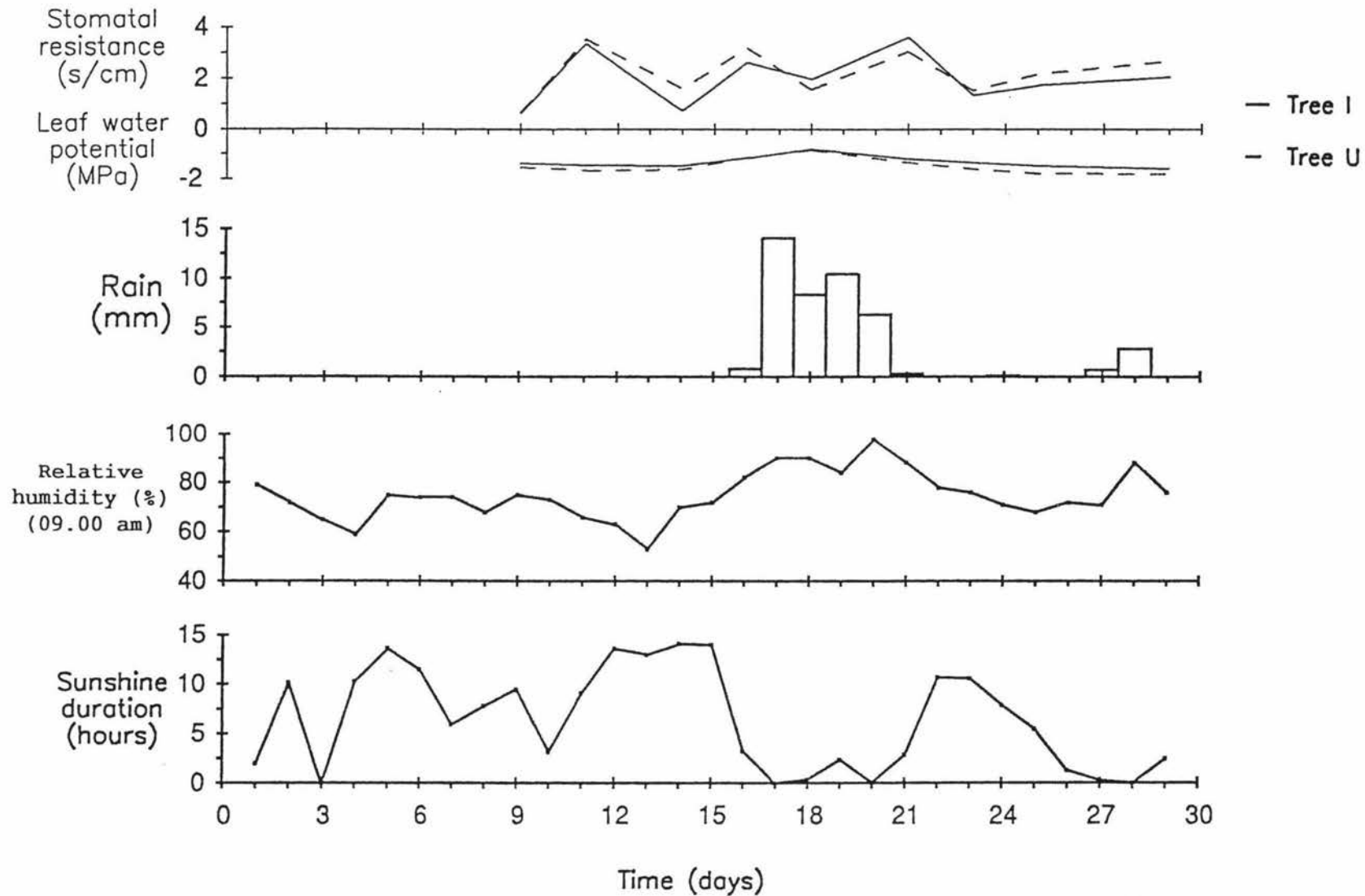


Figure 6.5. The relationship between meteorological data to the stomatal resistance and leaf water potential.

air temperature and solar radiation. Another likely reason could be a greater canopy area during the 1988/1989 experiment compared with the 1987/1988 experiment.

Figure 6.5. also shows the relationship between stomatal resistance and leaf water potential. Higher stomatal resistance was usually coupled with lower leaf water potential, except on Days 18 to 21 when stomata did not function normally due to rain and low sunshine. Stomatal resistance was not a good indicator of water stress in the trees, and the values had a large standard deviation. On the other hand, the values of leaf water potential measured were more consistent with a smaller standard deviation, and a significant difference between Trees U and I during most of the experiment. An exception was on Day 16, 17 and 18 when the value of leaf water potential was almost the same for the two trees, and was higher than other days, probably because of the environmental conditions, with high humidity and rain. So the leaf water pressure potential values provided a better and more sensitive indication that Tree U was under stress than did the porometer data.

Although the unirrigated apple tree (Tree U) had slightly higher water use than the irrigated apple tree (Tree I) showing no effect of water stress on transpiration, Tree U may have extracted soil water from greater depths than Tree I. It apparently got most of its water from below 1900 mm depth or beyond the covered area. In either case, Tree U would have had a smaller active rooting volume than Tree I during the latter part of the study. This apparently caused the lower plant water potential and reduced apple growth rate. There may also have been interactions between soil water uptake and nutrient availability that affected Tree U.

6.6. CONCLUSIONS

From the research on the pattern of water use by two apple trees, one irrigated and the other unirrigated, in Hawke's Bay from Day 1 (13 December 1988) to Day 29 (10 January 1989) the following conclusions can be drawn :

1. For the irrigated apple tree (Tree I) two periods of soil water extraction can be considered, one from Day 7 to Day 16 and the other from Day 23 to Day 29. The first period was preceded by water input only from irrigation, but the second period was preceded by inputs from irrigation and rainfall.
2. The average daily water use from 0 - 1900 mm depth measured by neutron probing and time domain reflectometry for Tree I was 81.7 ± 19.4 and 72.6 ± 29.8 litres/day, and of Tree U was 18.7 ± 4.1 and -4.0 ± 5.9 litres/day, during the first and second periods of extraction respectively.
3. Average daily water use as sap flow, measured by the heat pulse technique from Day 1 to Day 24 of Tree I and Tree U was 62.9 ± 5.6 and 68.9 ± 6.8 litres/day respectively.
4. Daily water use of the apple trees during the December - January period of 1988/1989 (which is in the middle of summer season) was more than twice that during November 1987 (which is still spring season).
5. The plant root system 'prefers' to extract soil water from the near the surface when there is a small soil water deficit relative to "field capacity", but the plant root system will extract deeper soil water when the soil water deficit becomes greater in the topsoil.

6. Leaf water pressure potential measured by the pressure chamber was a more sensitive indicator of water stress of the apple trees than was stomatal resistance measurement. The leaf water pressure potential data indicate that Tree U was under stress from Day 11.
7. Water stress had a detrimental effect on apple fruit growth on Tree U after about one month without irrigation or rainfall on the site near the Karamu Stream. However a water table at depth may have provided a larger reservoir of soil water than would be available on other soils. Alternatively water extraction from outside the covered area may have occurred.
8. Priestley and Taylor evaporation estimates were reasonably well correlated with daily heat pulse water use.
9. Leaf water potential and apple fruit growth rate were more sensitive indicators of water stress than was tree water use, which was not affected by the applied stress.

6.7. THE POSSIBLE PRACTICAL IMPLICATIONS OF THE STUDY

In this section some possible practical implications based on the results of experiments are suggested. This section may be useful to farmers in Hawke's Bay, especially around the Karamu Stream, helping them to manage their irrigation systems during summer. This section discusses the typical water use, the possible existence of a water table to supply available soil water, the size of the soil water reservoir, the typical water input and the desirable application rate of irrigation.

6.7.1. THE TYPICAL WATER USE

Before farmers apply irrigation, they need to know the typical water use in their orchards. The reason is that the typical water use can be used to estimate the optimal water input from irrigation to avoid either over-irrigation or under-irrigation.

The data obtained during the summer of 1987/1988 probably can be used to represent the typical November water use, since the experiments were carried out from 9 November 1987 to 1 December 1987. While data for the summer of 1988/1989, obtained from 13 December 1988 to 10 January 1989, probably represent the typical mid December-January water use. The typical November water use measured by neutron probing and time domain reflectometry was only 35 litres/day (2 mm/day over 18 m²), which is less than half of the typical mid December-January, values of about 77 litres/day (4.3 mm/day over 18 m²). This is due to not only the different projected canopy area, but also the differences in both air temperature and solar radiation, which are reflected in the Priestley and Taylor evaporation estimates. As shown in Figure 2.3., the typical water use in October is less than in November, while the typical water use in February is also less than in January. Thus, the typical water use is highest in December and January. Figure 2.3. also shows that the value of monthly Penman evaporation is greater than the average monthly rainfall from about the middle of September to the end of March. Apparently, orchards in Hawke's Bay may need irrigation from about mid October until March in an average year.

6.7.2. THE POSSIBLE SOIL WATER SUPPLY FROM THE WATER TABLE

During the experiment soil water extraction measured by neutron probing and time domain reflectometry from 0 to 1900 mm depth around Tree U was much less than around Tree I (see Figure 6.1.). But, the heat pulse technique found that Tree U extracted slightly more soil water than Tree I (see Figure 5.4.). As the site of the experiment was near the Karamu stream, a possible reason for this discrepancy was

that the water table supplied capillary soil water to the root zone below 1900 mm. Also the roots of Tree U possibly explored beyond the projected rainout shelter area, and extracted water from there. If these additional water sources had not been available, Tree U may have suffered earlier and more serious stress due to having no water input for almost a month. When there is a soil water source from a water table close to the root zone, the normal definition of available water holding capacity will be in error (Scotter, 1989).

6.7.3. THE SOIL WATER RESERVOIR

The volume of water which may be extracted by the apple root system from a soil profile initially at "field capacity", without any stress being felt by the apple tree, can be defined as the readily available soil water holding capacity for the tree. The volume of the soil water reservoir depends on the soil volume explored by roots, which may depend on the age of the tree, and the soil physical properties. The area of horizontal root distribution is not always the same as the projected canopy area. Snow (1987) found that the root distribution area of 5 year old Kiwifruit which had a planting distance 5 x 5 m was smaller than its projected canopy area. But this study found that 18 year old apple trees, with 5 x 3.6 m planting distance, had a larger root distribution area than the projected canopy area.

Based on Figure 2.2., the typical volume of soil explored by roots can be estimated. The root density can approximately be classified into 3 classes (see Figure 2.2(a)), as

- Class A : 0 - 400 mm depth : high root density,
- Class B : 400 - 1000 mm depth : moderate root density,
- Class C : 1000 - 1600 mm depth : low root density.

The typical horizontal root spread is half of the planting distance, so the roots are distributed fairly uniformly everywhere between apple trees (see Figure 2.2(b)). The root distribution may differ for younger apple trees, such as those less than 10 years.

To estimate the typical available water in the soil reservoir, the volume of soil explored is multiplied by the volumetric soil water content difference between the "field capacity" and "stress point" conditions. As the roots were distributed uniformly between trees in the horizontal direction, the available water can be expressed as an equivalent depth stored in a rooting zone with a certain effective depth. As a result, the readily available soil water (RASW) storage capacity in the soil water reservoir can be defined as

$$\text{RASW} = \int_0^Z (\theta_{\text{FC}} - \theta_{\text{SP}}) dz$$

where θ_{FC} = soil water content at "field capacity" (m^3/m^3),
 θ_{SP} = soil water content at "stress point" (m^3/m^3),
 Z = effective depth of root zone.

Rahardjo (1988) found that the "field capacity" condition occurred approximately on the 8th day after excess wetting (see Figure 3.7. in Rahardjo, 1988). So the typical soil water content can be estimated by using the soil water content profile for Tree U on 17 November 1987 (average soil water content between 16 and 18 November 1987) as shown in Figure 6.6. While the "stress point", which shows the soil water content in the root zone when plants begin to experience water stress, is often approximated by the soil water content at about - 100 kPa soil water pressure potential. Rahardjo (1988, page 9) found the average volumetric soil water contents of Sites A and B at - 100 kPa were 0.105, 0.042 and 0.062 for 100, 400 and 700 mm depth respectively and these values are shown in Figure 6.6. In Figure 6.6., the "stress point" is also shown as the soil water content profile when Tree U began to have a smaller apple growth rate than Tree I, which occurred on Day 21. Finally, the typical readily available soil water storage capacity in the soil water reservoir can be estimated as 36 mm or 648 litres from 0 - 400 mm depth, as about 89 mm or 1602 litres from 0 - 1000 mm depth, and as about 170 mm or 3060 litres from 0 - 1900 mm.

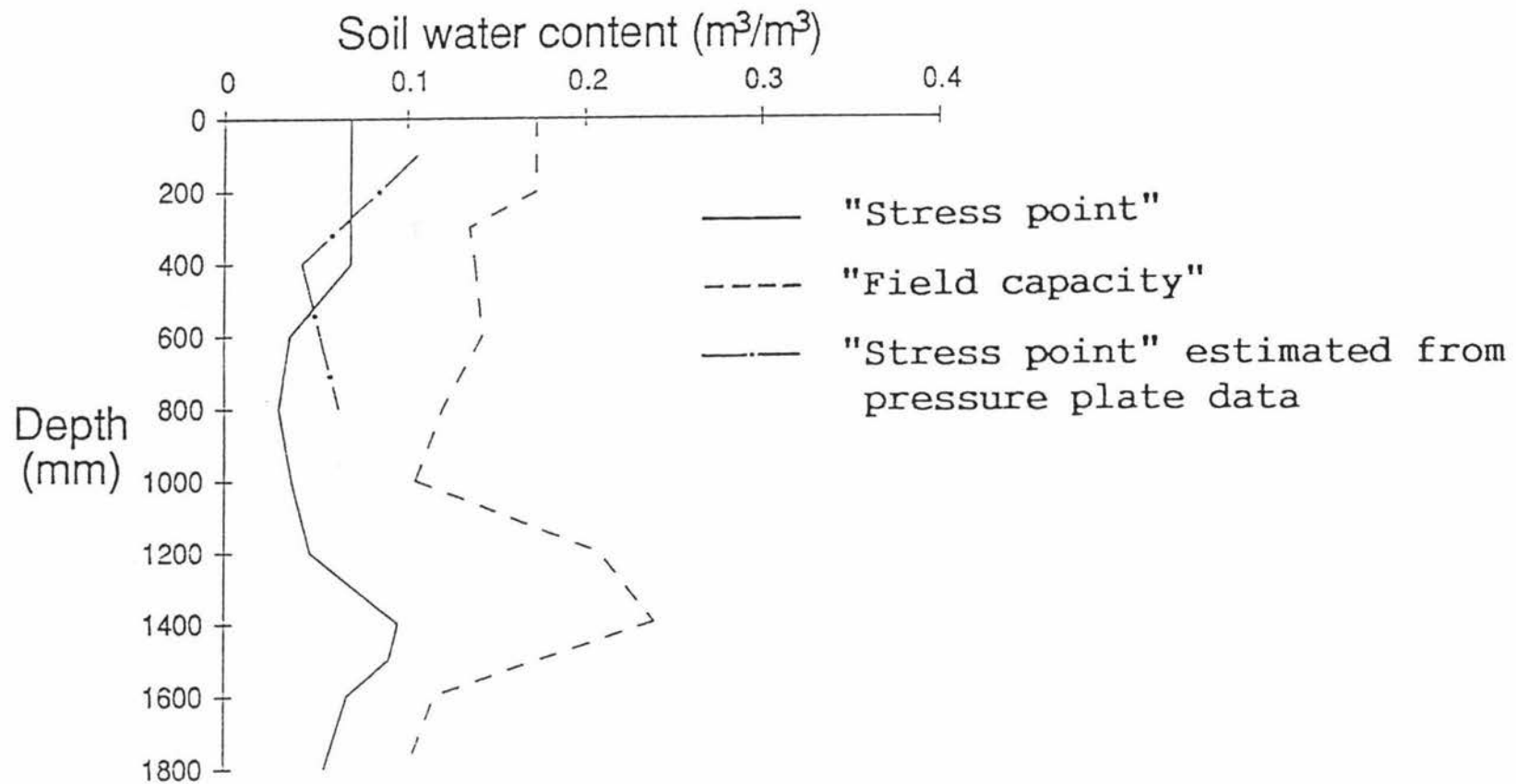


Figure 6.6. The average "field capacity" and "stress point".

6.7.4. THE TYPICAL WATER INPUT FROM IRRIGATION

Once we know the typical readily available soil water in the soil water reservoir and the typical water use for a certain period, the typical water input from irrigation needed to maintain soil water near "field capacity" can be estimated. A soil water balance table can be a good way to estimate the typical water input needed on an orchard. When a soil is at "field capacity", there is maximum readily available soil water in the reservoir. The difference between the actual storage and "field capacity" storage is called the soil water deficit. The value of the soil water deficit indicates the water input needed from irrigation. Water inputs due to irrigation and rainfall need to make up the deficit to "field capacity" (zero deficit). Inputs bringing the soil above "field capacity" will cause drainage. To achieve efficiency in irrigation, growers must manage the frequency of irrigation application by considering the amount of irrigation required, the capacity of the irrigation system and the most suitable application rate for irrigation.

Once the soil is at "field capacity", the readily available soil water is about 170 mm. Providing the typical water use is about 4.3 mm/day and water in the whole root zone is equally "available", the apple trees in the orchard can extract soil water from 0 - 1900 mm depth for 39 days without stress. Based on data in Figure 6.1., the root system normally prefers to extract soil water from the topsoil rather than from the subsoil. Thus, growers should perhaps keep the soil water deficit below about 36 mm. The readily-available soil water reservoir at "field capacity" divided by the typical water use will provide an estimate of the soil water extraction period from "field capacity" to "stress point". This means that assuming a daily water use of 4.3 mm, growers need to irrigate by bringing the soil back to "field capacity" at least every 8 to 20 days during rain-free periods in the summer. So if for some reason, such as a broken pump, the growers cannot irrigate, they have a time tolerance of from 8 - 20 days in which to get it fixed before serious crop damage occurs. However, the growers also have to consider water inputs from rainfall. So, bringing soil water to about 15 mm below "field capacity" may be

better than bringing soil water to "field capacity" exactly, because unpredictable water inputs from rainfall can cause drainage. Weather forecasts and experience will help growers to manage the irrigation of the orchard.

6.7.5. THE DESIRABLE APPLICATION RATE OF IRRIGATION

The application rate (m/s or mm/hour) multiplied by the application period (hours) of the irrigation system is equal to the irrigation application (mm or m).

If the application rate exceeds the saturated hydraulic conductivity, water inputs may create ponding problems. Thus the maximum application rate has to be defined by considering the soil hydraulic conductivity value at the site.

Soil water pressure potential and soil water content affect hydraulic conductivity (Buckingham, 1907). Zero soil water pressure potential always provides the highest hydraulic conductivity. When soil becomes drier, the hydraulic conductivity will be smaller. Clothier *et al.*, (1989) found the relationship between hydraulic conductivity and soil water pressure potential of Twyford sandy loam shown in Figure 6.7. Based on these relationships, the application rate should be less than 1×10^{-5} m/s. Thus an application rate more than 1×10^{-5} m/s (36 mm/hour) may induce ponding problems at the site. While an application rate less than 5×10^{-6} m/s (18 mm/hour) is probably suitable.

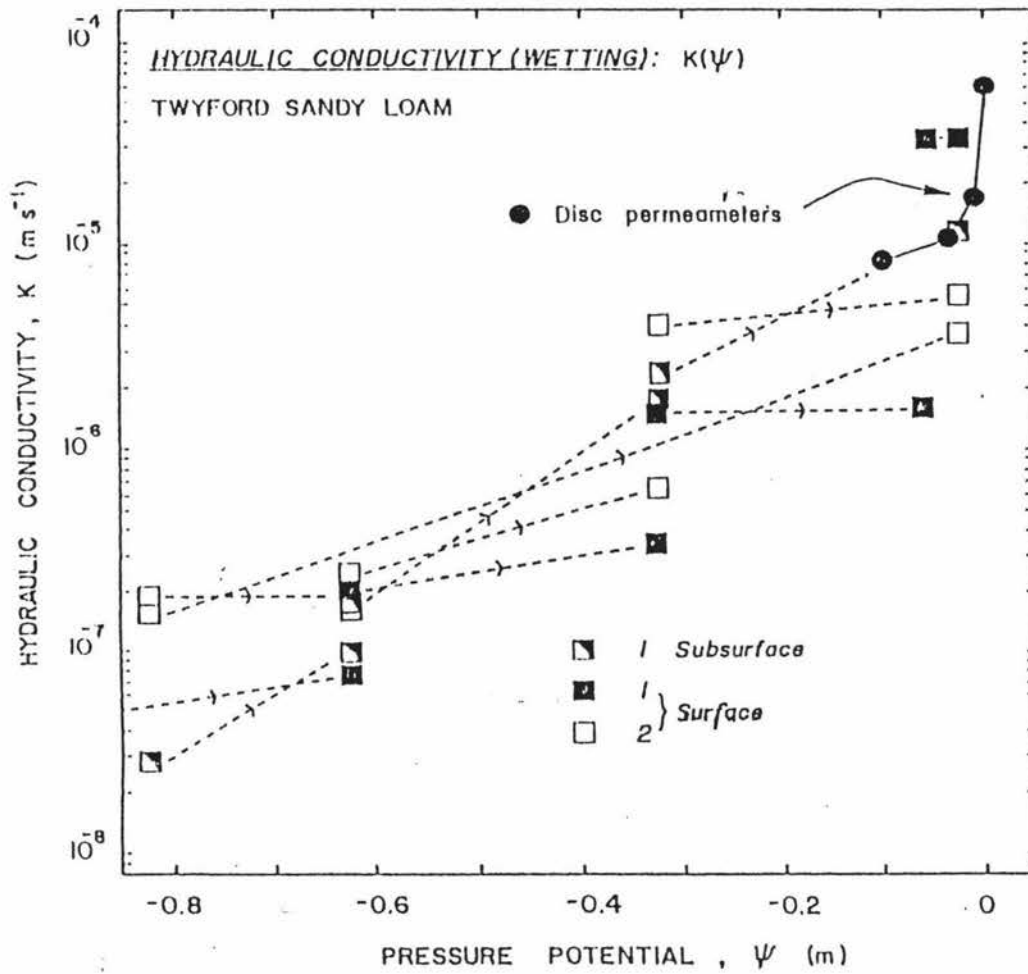


Figure 6.7. The wetting hydraulic conductivity, $K(\psi)$, of Twyford sand loam from three cores, with disc and ring measurements for varying ψ_0 (after Clothier *et al.*, 1989).

6.8. SUGGESTIONS FOR FUTURE WORK

Although the rainout shelter had been used in 1987/1988 and 1988/1989 experiments, improvements in the design of the covers of the rainout shelter used on Tree U are still needed. Leakage is still an annoying problem. Although, the zip had been changed, leaking occurred again in the 1988/1989 experiments. A better method to overcome leaking through the zip has to be considered. Furthermore, to avoid the possibility of soil water extraction around Tree U from beyond the projected cover, the rainout cover needs to be enlarged.

After the experiments during the summers of 1987/1988 and 1988/1989, a number of things remain unknown. Possible future work would be to measure soil water content (by neutron probing) and hydraulic conductivity down to water table depth. It would be interesting to find out where Tree U was getting its water from.

It would also be useful to know how much evaporation occurs from the grass and herbicide bare soil strip under the trees, and how much rain is intercepted. Further comparison of the measured water use and that predicted by the Priestley and Taylor method or some other method is warranted. Measuring the projected canopy area and water uptake of apple trees during the whole fruiting during summer would be useful. It would be allow better estimates of apple tree water use.

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APPENDIX A

A SCHEME TO CALCULATE DAILY PRIESTLEY AND TAYLOR EVAPORATION E_r
 (Scotter, personal communication)

Inputs needed

Latitude (S, degrees)

Date

Maximum air temperature (T_{\max} , °C)Minimum air temperature (T_{\min} , °C)EitherIncoming solar radiation (R_s , J/m^2)Or

Sunshine hours (n, h)

Note :

(a). All angles are in decimal degrees.

(b). S is negative in the Southern Hemisphere.

Scheme

Step 1 : Find Julian day (M) from date (i.e. day of year from 1 to 365 or 366).

Step 2 : Find angle of declination (D) (range -23.5° to $+23.5^\circ$)

$$D = 23.5 \sin [(M - 79) 360/365]$$

(Rosenberg, 1974, p. 14)

$$\text{so } D = 23.5 \sin [0.986 (M - 79)]$$

Step 3 : Find half-day length in degrees (H)

(Note $H = 90^\circ$ at the equinox)

$$H = \cos^{-1}(-\tan S \tan D) \quad (\text{Sellers, 1965, p. 15}).$$

Step 4 : Find maximum number of hours measurable with a Sunshine Hour Recorder (equals actual maximum less ½ hour) (N)

$$N = (2) (24) H/360 - 0.5$$

$$\text{so } N = H/7.5 - 0.5$$

Step 5 : Find extra-terrestrial solar normal to earth's surface (R_0 , J/m^2).

$$R_0 = (1.4 \times 10^3/\pi) (60 \times 60 \times 24) [(2\pi H/360) \sin S \sin D + \cos S \cos D \sin H] (d/d)^2$$

(Sellers, 1965, p. 16)

$$\text{so } R_0 = 3.85 \times 10^7 [(\pi H/180) \sin S \sin D + \cos S \cos D \sin H] (d/d)^2$$

$$\text{where } (d/d)^2 = 1 + 0.0334 \sin [0.986(M - 274)]$$

and d and d are the instantaneous and mean distances of the earth from the sun respectively (Robinson, 1966, p. 30)

Step 6 : Find solar radiation at surface (R_s , J/m^2)

$$R_s = R_0 (a + b n/N)$$

where for New Zealand $a = 0.25$ and $b = 0.54$ (de Lisle, 1966), so $R_s = R_0 (0.25 + 0.54 n/N)$

Step 7 : Find net radiation (R_n , J/m^2)

$$R_n = 0.62 R_s - 1.47 \times 10^6 \quad (\text{Scotter et al, 1979}).$$

Step 8 : Find average air temperature (T_{av} , °C)

$$T_{av} = (T_{max} + T_{min})/2$$

Step 9 : Find $s/(s + \gamma)$ using

$$s/(s + \gamma) = 0.403 + 0.0165 T_{av} - 0.00012 T_{av}^2$$

Step 10 : Find Priestley and Taylor estimate of regional evaporation for that day (E_r , m/day) (Priestley and Taylor, 1972)

$$E_r = 1.26 s/(s + \gamma) R_n / (2.45 \times 10^9)$$

Step 11 : Multiply by 1000 to get E_r in mm/day.