METHODS OF EVALUATING WATER REQUIREMENTS

OF TREES PLANTED IN PAVED AREAS

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To my beloved wife and mother

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ABSTRACT

The particular need for reliable and accurate information on the water requirements of street trees in paved areas in Singapore is discussed and the results of literature survey for reported results of investigations of the water requirements of street trees is reported.

There is a paucity of such results, and methods for field studies of the water consumption of street trees are reviewed. The methods examined include those based on meteorological data, on measurements of soil water status and on measurements of water flux of trees.

It is concluded that measurements of soil water status would be the most appropriate in providing data for use as a basis for accurate design or criteria for road drainage works which aid the irrigation of street trees.

It is proposed that volumetric lysimeters be used in areas where space is not limiting to estimate the water requirements of small to medium sized trees. The neutron scattering meter will be used to monitor soil water content depletion and tensiometers to indicate water potential gradients at a range of existing tree plantings to provide information on the actual water requirements of existing trees.

CHAPTER 1

INTRODUCTION

1.1 STREET TREES IN SINGAPORE

The planting and care of street trees in Singapore is carried out by numerous local authorities. The Parks and Recreation Department has the major responsibility of planting in public areas.The plantings are carried out in many urban situations, for example median strips, roadsides and boulevards. The planting program is both extensive and intensive and the nurture of the planted trees is requiring increased effort, more advanced knowledge and much expertise.

The planting program has the strong support of the Government but on occasions concerns have been expressed for the health of the trees and directions given to ensure that adequate water is supplied to enhance the trees and thus their benefits; namely, improved aesthetics of paved areas in streets and boulevards. As a consequence of these directions engineering works are under consideration to channel surface runoff from the paved areas to the root zone of the trees.

Such works may be expensive and well-based information on the water requirement of the trees is necessary to ensure effective and efficient design. However, reliable and accurate information with a scientific or technical base is lacking.

This study was initiated in response to this lack of information. The approach adopted was to study texts and the literature to provide a scientific understanding of the water requirements of the trees and to extract information which could form the basis of guidelines to the water requirements of street trees in paved areas in Singapore and to formulate investigations and research programs to ensure that reliable and accurate information is obtained.

Much work has been done on the water requirements of plants and the relationships between plant growth and water. The literature is voluminous but most studies were made where there was a primary concern of crop yield in relation to water supply. Agricultural and horticultural plants have received particular attention but also forest trees.

The literature on the water requirements of urban trees in paved areas was found to be scant indeed. This was surprising for town landscape designers and municipal arborists have shown much concern about the water requirements of urban trees and scenes of dead or dying trees in planting sites with sealed pavements right up to the tree bases have long worried administrators and the tree lovers. For example, the editorial in Australian Parks (Anon, 1968) called for more information and discussion on the effect of sealing around the base of trees on water availability and there is some diversity in the practice of providing openings in sealed pavements adjacent to trees.

In many cities it is common practice to plant street trees in a green verge or if the tree has to be planted in a paved area an unsealed opening is provided around the base of the tree. A literature search has not found a definitive study of the need for these openings nor the performance of the openings. Brarmann (1966) cited various sizes of opening, 1m x 2m; 1.5m x 1.5m; and 1m x 2.5m, in cities in the United States of America. He suggested that 1.2m x 1.2m was desirable but for practical reasons accepted a dimension of 1m x 1.2m for New York City. Bernatzky (1978) recommended that at least $20m^2$ be left open around the tree trunk to meet the water requirement of the tree.

In Singapore, the unsealed area around a tree has been progressively enlarged from $4m^2$ to $16m^2$. However because the unsealed area seems so small compared to the entire root zone of a tree it is doubted whether the incoming precipitation (throughfall and stemflow) is sufficient to support the tree and engineering measures are taken to bring in more water to the root zone of the trees.

Under present engineering practices underground pipes are installed for irrigation (and aeration), roads are cambered so that more surface water is collected for drainage to the trees and sumps are constructed adjacent to trees. The justification for these measures is the belief that it is better to do something to save a tree than to let it die by doing nothing.

Lack of water may not of course be the only factor contributing to the death of trees in paved areas. Pollution, lack of aeration, restriction to root growth by compacted soil and change in the soil level during construction could be more detrimental than lack of water (Tattar, 1978; Bernatzky, 1978; Yingling et al.,1979).

Thus, like many other problems, not enough is known about the water requirements of urban trees in Singapore and to answer the questions that are raised by the need for design criteria and for better understanding and management of the trees it is necessary to study their water requirements.

1.2 OBJECTIVES OF THE STUDY

In the daily maintenance of urban trees watering is a routine task in the dry season of many cities, particularly for young trees.

Watering can be done by an automatic sprinkler system or with a water tanker. For efficiency it is necessary to know for example how much irrigation water should be applied. While reliance may be placed on the visual inspection of trees or soil based on working experience, more reliable and scientific methods are desirable.

The water applied to a tree planted in the ground is taken up by the tree, held in the soil or lost to the root zone by redistribution. The amount of water applied therefore does not equal the amount required by the tree for survival and growth. It is desirable to know accurately the amount of water a tree needs to maintain its growth processes. This knowledge would be particularly useful for planning purposes when irrigation of the planting site may be by means of engineering works.

The questions when and how much irrigation water should be applied to existing trees; how much water various species of trees need; and the change in these requirements are of paramount importance in relation to the water requirements of urban trees in paved areas. These questions were the basis of the formulation of the objectives of this study.

This study had the following objectives:

(1) To review the methods and instruments that are commonly used for estimating or evaluating water losses from a plant community or single trees.

(2) To understand the principles and theories on which these methods are based.

(3) To examine the application of these methods and instruments in regard to their limitations and the most appropriate conditions.

(4) To select methods and instruments suitable for use for determining the water requirements of single trees planted in paved-up areas in an urban city.

1.3 TERMINOLOGY

1.3.1 Street trees and urban trees.

Many terms have been used in the literature to refer to trees planted in the urban setting. Shade tree (Tattar, 1978), ornamental tree (Creech, 1976), street tree (Sekiguchi et al.,1973), urban tree (Himelick, 1976), metropolitan tree (Smith and Dochinder,1976), municipal tree (Collins,1976) and amenity tree (Dudley,1976) have all been used.

Not all trees in urban areas are planted in a restricted growing area. Trees are also planted in school fields, playgrounds, parks, open spaces, ovals and green belts in the city where there is adequate growing space and the surrounding ground surface is not sealed. They are not the subject of this study.

Trees planted next to streets, highways, pedestrian walkways; or in the plaza, shopping malls, car parks, boulevard and the central divider of carriageways, have one thing in common; their root systems are often under layers of pavement made of impervious or semi-impervious materials like tarmac, brick, tile and concrete. These trees can be said to be street orientated and in this study, trees that are planted in paved-up areas are termed street trees. It is the water requirement of these street trees that is examined in this study.

When a general reference is to be made about trees planted in the urban setting, the term urban trees will be used.

1.3.2 Evapotranspiration and transpiration.

Evaporation is the transfer of water from the liquid to the vapour state (Linsley and Franzini,1964) and it can take place from a free-water surface, from a plant canopy and from the soil. Evaporation of water intercepted by the plant canopy will have some relevance to this study and will be termed interception loss (White, 1979).

The process by which plants remove water from the soil and release it to the atmosphere as vapour is called transpiration. For a fully vegetated soil surface, transpiration is thought to be the principal mechanism responsible for the depletion of soil water (Hillel,1972). However, when the soil surface is partially bare and partially covered by plant canopy, it is difficult to separate the soil water depletion into evaporation from the soil and transpiration from the vegetation. The term evapotranspiration is used to denote the process by which soil water is depleted as a result of either jointly or separately evaporation from the soil and transpiration by partial plant canopy cover (Hanks and Ashcroft, 1980).

Both the terms evapotranspiration and transpiration will be used in this study.

1.4 SCOPE OF STUDY

A study of the water requirements of plants involves the soil, the plant and the atmosphere which are linked closely in a dynamic system called the 'soil-plant-atmosphere continuum (SPAC)' (van

Haveren and Brown,1972).To a very large extent the atmosphere controls the rate of evapotranspiration but the tree appears to occupy a central position as it acts as a channel through which water is transmitted from the soil to the atmosphere. However, the water is held in the soil.

The rate and ease at which this soil water is made available to the plants will influence an irrigation program and in Chapter 2 fundamental aspects of soil water are examined. These aspects include the definition and calculation of the soil water potential and soil water content which quantify respectively the energy holding the water in the soil and the amount of water held in the soil. The age-old concept of field capacity and permanent wilting percentage are briefly discussed as they define the amount of soil water which is available for plant use.

The methods and instruments for measuring soil water, both its content and its potential, are discussed in Chapter 3 but only those that are used in field measurements are mentioned. The merits and limitations of each of the methods are also examined.

Chapter 4 reviews the methods commonly used in determining water loss by trees. As stated earlier, water use by trees depends on interacting factors among the soil, plant and the atmosphere. The chapter is therefore arranged to discuss the methods according to soil data, climatic data and the plant itself. Here again emphasis is on field evaluation and laboratory technique is excluded. The principles and the basic assumptions on which these methods are based are examined critically to see if they are suitable for use in an urban environment.

In Chapter 5, methods and instruments thought to be suitable for estimating the water requirement of street trees are listed. The criteria for choosing any of the methods are outlined. It should be emphasized that the underlying consideration is to select methods that could be used for carrying out field observation in Sinagpore.

Finally, Chapter 6 summarizes the main points discussed and the recommendations made on the selection of methods and instruments for fulfilment of the objectives of this study.

CHAPTER 2

SOIL WATER

2.1 INTRODUCTION

Soil is the medium in which plants grow and obtain water and nutrient. It is a very complex matrix, comprising a skeleton of solid particles that vary from organic peat to gravel which encloses voids which may be filled with gas and liquid. All three components can affect plant growth. The physical properties of the soil, namely, the soil texture, soil structure and soil porosity influence root growth which will in turn affect plant growth and development. They are however not the subject of this study. This chapter discusses the soil water, in particular the terms and concepts used to describe the amount of water and the energy with which it is held in the soil.

2.2 SOIL WATER POTENTIAL

The term water potential is used to define and quantify the different kinds of forces acting on the water in a soil-plant-continuum. It has been expressed in various units which are listed in Appendix 2.1. In this study, bars will be used as the unit of measurement.

Water potential measures the differences between the free energy of water at a point in the system under study and that of pure water at the same temperature (Slatyer,1960). The water potential of pure free water is taken as zero bar.

Total water potential (ψ_T) of soil water can be seen as the algebric sum of matric (ψ_m), osmotic (ψ_π), gravity (ψ_g), pressure (ψ_p) and overburden (ψ_Ω) potentials.

$$\psi_T = \psi_m + \psi_\pi + \psi_g + \psi_p + \psi_\Omega \quad \text{------------------------Eq.2-1}$$

Matric potential (ψ_m) is related to the adsorption forces of the soil matrix. It is associated with both the attraction of soil particles for water and the attraction of water molecules for each other. It includes the unbalanced forces across air-water interfaces which give rise to surface tension. In a saturated soil, ψ_m is taken as zero where there is no air-water interface. As the soil dries, the matric potential decreases. The matric potential for four soil water conditions is given in Table 2.1.

Table 2.1 Values of matric potential at four soil conditions.

Soil condition	Matric potential (Bars)
Saturation (Approximate)	-9.8×10^{-4} $\simeq 0$
Field capacity (Approximate)	-9.8×10^{-2}
Wilting point (For many plants)	-15
Air dry (Relative humidity = 0.85)	-216

Source : Hanks and Ashcroft, 1980. p.24.

Osmotic potential (ψ_π) is created across the semipermeable membrane of root cells by soluble salts in the soil water. While not important in determining liquid water flow in the soil on a macro scale, it does affect the uptake of water by roots. For example, even in a very moist soil (ψ_m = -0.5bar) salts in the soil water can exert an osmotic potential which will cause tree roots to experience low total water potentials. Osmotic potential is hence important in heavily fertilized soils and in arid regions where salt accumulates (Kramer,1969). Urban trees are seldom heavily fertilized and Singapore is not in arid regions and therefore for the purpose of this study, this term could be neglected.

Gravity potential (ψ_g) arises because of gravitional forces acting on objects on the earth's surface. The ψ_g of soil water at any point is determined by the elevation of the point in relation to some arbitrary fixed reference point. Depending on whether the reference point is at or below the point of interest the ψ_g is either taken as zero or positive. Hence, the ψ_g is determined by the relative elevation and not by chemical or pressure condition of soil water. For the study of plant-water relation, because the root zone is not very deep, the ψ_g corresponds to only about 0.1bar and can be neglected (Baver et al.,1972).

Pressure potential (ψ_p) is due to the weight of water at a point under consideration in relation to a reference point. Under field conditions it applies mostly to saturated soils (Hanks and Ashcroft,1980). It is considered positive if the soil water is at a hydrostatic pressure greater than atmosphere; conversely, it is negative. That is, it is positive when water is under a free-water surface, negative when the water has risen in a capillary tube above the free water; and zero while the water is at the free water surface. As this study deals with situations where irrigation is required ahd therefore the soils are not saturated, this term can also be neglected.

Overburden potential (ψ_{Ω}) exists when the wetted soil swells and its weight becomes involved as a force acting upon water at a point in question. In most cases, it is included as an implicit part of a pressure potential or matric potential (Baver et al.,1972) and its omission is not serious unless one is dealing with swelling soils.

In the study of soil-water-plant relationships, matric and osmotic potentials have the greatest relevance in contributing to the soil-water potential (ψ_s) (Baver et al.,1972), and ψ_s is taken as the sum of the matric and osmotic potentials. That is,

$$\psi_s = \psi_m + \psi_\pi \quad \text{------------------------------------} \quad \text{Eq.2-2}$$

The water potential of soil water in an unsaturated soil is negative. Larger negative values of water potential indicate that the soil water is less available to the plant root, i.e., the roots must spend more energy in overcoming the forces holding the water in the soil to extract a given amount of soil water.

Differences in water potential between two points give rise to water flow within the soil. For example water will flow from a point of a higher water potential (say -5bars) to another point at a lower water potential (say -15bars). A most important point in relation to availability of soil water to trees is that it is the energy gradient, and not the physical proximity or the water content gradient, that determines the availability of water to the plant.

2.3 SOIL WATER CONTENT

Soil can be considered as a large reservoir in which water is stored for long periods of time and is available for plant use.

The amount of soil water retained in the soil depends on the physical properties of the soil. A lightly-textured coarse sandy loam retains less water than a fine-textured silty clay loam. However, it is the water potential that determines the availability of soil water to tree roots. Therefore, as illustrated in Figure 2.1, at a specific water potential (ψ_1), although a clayey soil may contain more water ($\theta_c > \theta_s$), the water (θ_c) is held just as tightly as in the sand. At the same water content (θ_c) the water is held more tightly in the clay than in the sand ($\psi_1 < \psi_2$).

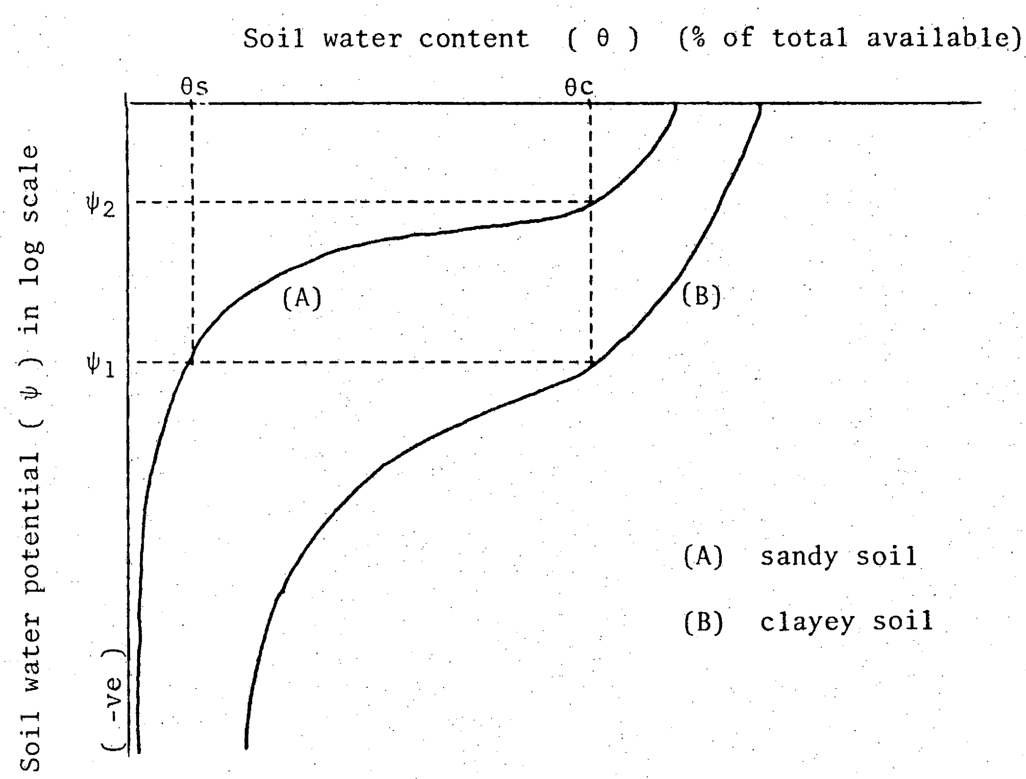


Figure 2.1 Soil water characteristic curve for sandy soil and clayey soil.

Source : After Hillel, 1972. p. 64.

It can be seen from Figure 2.1 and Table 2.1 that for a particular soil, the water potential increases as the soil becomes wetter. Table 2.2 shows the matric potential of a sandy loam and silt loam at selected water contents. At a particular water content the water is held more tightly in silt loam, that is by a higher negative potential, than is the sandy loam.

Table 2.2 Matric potential of two soils at several water contents.

Volume water content, θ_v	Matric potential, ψ_m (Bars)	
	Sandy loam	Silt loam
0.05	-7.0	-
0.06	-3.4	-
0.10	-0.5	-
0.16	-0.2	-
0.20	-0.1	-4.0
0.26	-0.06	-0.8
0.30	-0.04	-0.3
0.40	0	-0.04
0.46	-	0

Source : Hanks,1965.,quoted in Hanks and Ashcroft,1980. p.43.

Soil water content (θ) is the amount of water in a unit volume or mass of soil which has been expressed in terms of either wet or oven-dry soil. Soil water content is normally expressed in two ways.

(1) On a volume basis, θ_v (volume of water per unit volume of moist soil).

(2) On a dry mass basis, θ_m (mass of water per unit mass of dry soil).

The calculation of soil water content is described in Appendix 2.2.

In the study of plant-water relationships, it is most useful to express water content in terms of the volume of soil because the soil occupied by a tree root system is normally measured by volume, rather than by weight. The total amount of water in the soil or the amount added, can then be conveniently expressed as cm or cm per m of soil depth. This is also a common way of stating rainfall and irrigation requirements.

2.4 FIELD CAPACITY AND PERMANENT WILTING PERCENTAGE

When water is applied to a soil surface, either by irrigation or due to natural precipitation, it either ponds on the surface prior to runoff, or it infiltrates into the soil profile. In the early stages of infiltration into an unsaturated soil the matric potential rather than gravity potential predominates in determining the potential gradients governing the water flow. When rain or irrigation ceases, the surface infiltration process ceases if there is no ponding but downward water movement within the soil continues as soil water redistributes within the profile. This redistribution process determines the amount of water retained at various depths in the soil profile.

Figure 2.2 illustrates the infiltration process from an irrigation furrow into an initially dry soil. At the commencement of infiltration the matric potential causes infiltration to be nearly uniform in all directions. Subsequent to the time period represented by infiltration into zone t_1 the matric potential becomes less dominent and infiltration into the zone represented by t_2 is markedly influenced by both matric and gravitional potentials. Infiltration into the zone represented by t_3 is markedly under the

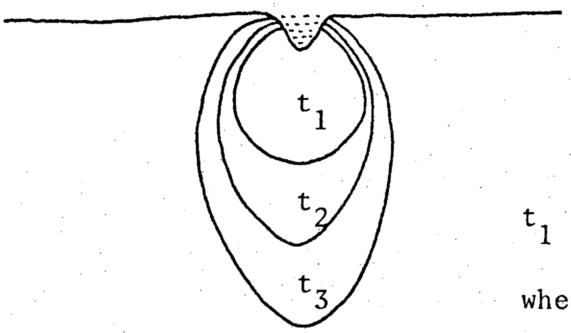


Figure 2.2 Infiltration from an irrigation furrow into an initially dry soil.

Source : After Hillel,1972. p.138.

influence of gravitional potential . The wetting and drainage of soils is described in more detail in Appendix 2.3.

After wetting of a soil profile by the infiltration of rainfall or irrigation some water may drain through the soil and the soil water may also be reduced by evaporation and transpiration. Two levels of soil water content during the processes are of particular importance in relation to plant water requirements.

Field capacity (FC)

Field capacity is defined as the water content of a freely drained soil one to three days after the soil has been thoroughly wetted by rain or irrigation at which time the drainage of water has become very slow and the water content has become relatively stable. Thus at field capacity water is held in the soil in opposition to gravity potential .

Most soils do not drain to a fixed water content and then maintain it indefinitely and so field capacity is not a true equilibrium state and its value is related to the conditions under which it is measured, as well as to the characteristics of the soil.

The water content at field capacity in relation to an idealized soil and to two soils is illustrated in Appendix 2.4. Peters (1973) stated that in many soils the forces at which water is held at field capacity are closely correlated to a soil water potential of -0.3 to -0.5 bars.

Permanent wilting percentage (PWP)

Permanent wilting percentage is defined as the water content of a soil at which plants remain permanently wilted and water extraction by plants has ceased. It is assumed to vary with soil type but independent of the plant. Slatyer (1957) strongly criticized this idea and stated that it should be a variable dependent also on the plant. However, in 1967, Slatyer found that most plants wilt in the range of -10 to -20 bars. Hence, for practical purposes, PWP is regarded as the water content at a water potential of -15 bars (Peters, 1973).

Although both field capacity and permanent wilting percentage are not true constants they are useful parameters for the assessment of soil moisture in relation to plant growth. Hanks and Ashcroft (1980) suggested that -0.3 bar and -15 bars can be accepted as good approximations for field capacity and permanent wilting percentage respectively for most soils, plants and weather conditions.

The field capacity and permanent wilting percentage are illustrated in Figure 2.3 in relation to the soil water content and the matric potential of two soils, for both the wetting and drying cycles. Unlike the silty clay loam, the sandy loam does not have a hysteresis loop. Marked changes in water potential occur with small changes in water content at about the permanent wilting percentage while there are only small changes in the water potential with marked changes in water content at about the field capacity.

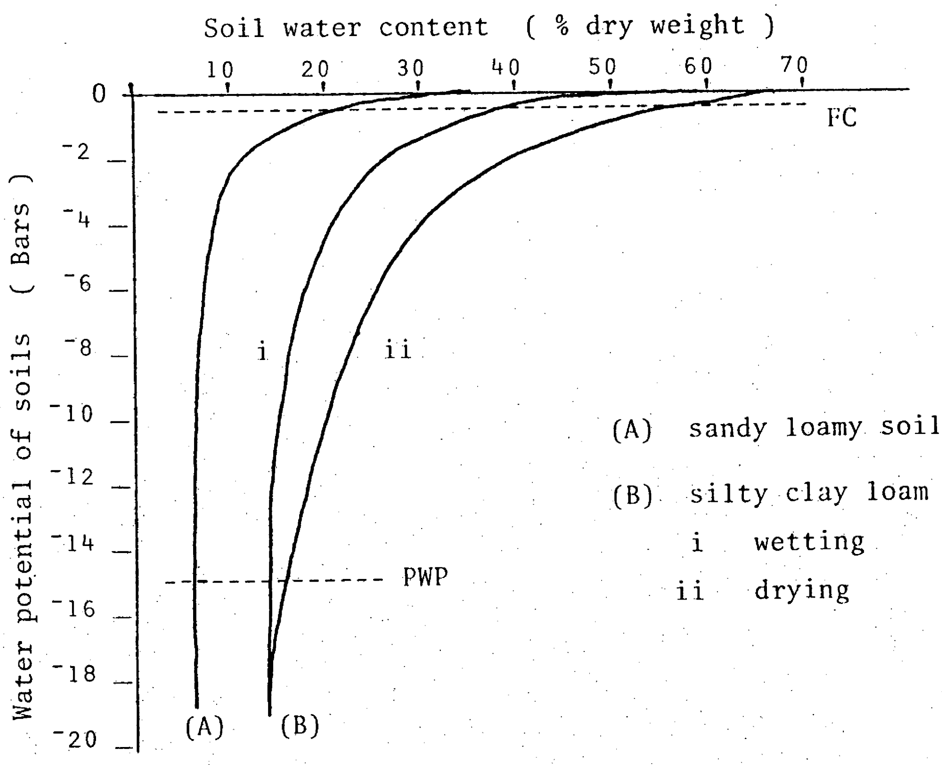


Figure 2.3 Matric potentials of a sandy loam and a clay loam soil plotted over water content.

Source : After Kramer,1969. p.61.

For most soils, about 25 to 75% of the water content is held at a soil water potential of between 0 to -0.8 bar (Richards and Marsh,1961). Hence, as illustrated in Figure 2.4, a reduction of matric potential from 0 to -0.8 bar removes about 25% of water from a clay soil and about 75% water from a loamy sand. The significance of this in relation to meeting the water requirements of trees will be discussed in Chapter 5.

2.5 AVAILABLE WATER CONTENT (AWC).

The field capacity and the permanent wilting percentage are used widely to represent the upper and lower limits of water in a soil that would be available for plants. The amount of water retained in a soil between the two limits therefore indicates the amount of

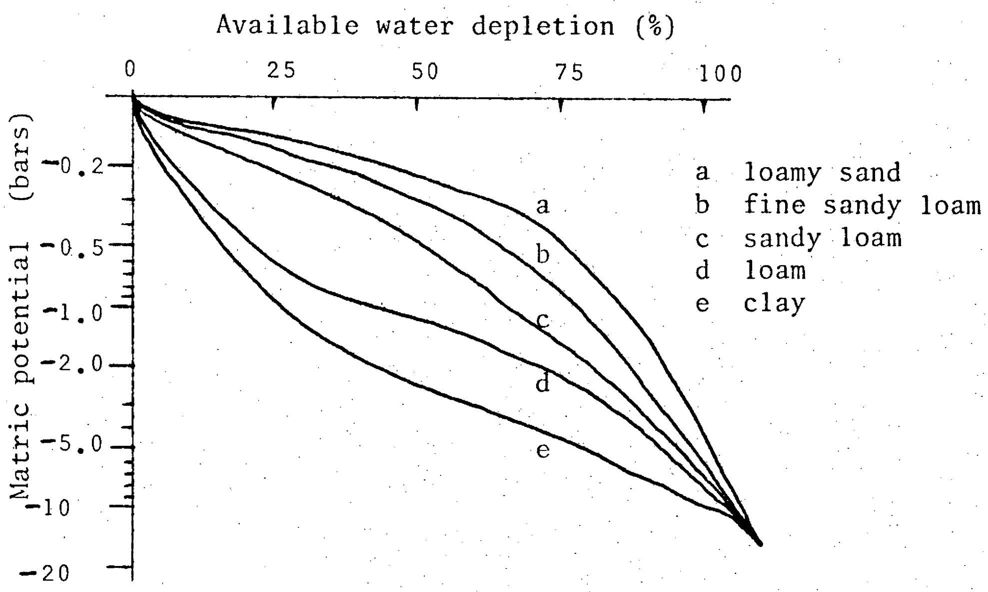


Figure 2.4 Water retention curves for several soils plotted in terms of percentage available water removed.

Source : After Richards and Marsh,1961.

soil water available for plant growth and is termed the Available water content. It must be emphasized however that FC, PWP and AWC are not fixed constants for there is a wide range in the water content retained in the soil within each of the major classes of soil type. Table 2.3 gives the typical water values for the various soil types.

Table 2.3 Available water content of different-textured soils.

Soil types	FC	PWP	AWC
	(water content in mm for a 10-cm soil)		
Sand	13	3	10
Loamy sand	22	4	18
Sandy loam	27	5	22
Clayey loam	34	14	20

Source : After Seemann, 1979c. p.294.

There has been much argument as to whether the water held between the FC and the PWP is equally available for plant growth. There are three schools of thought.

(1) That soil water is equally available throughout, from FC to PWP.

(2) That availability of soil water decreases with decreasing soil wetness.

(3) That there is a critical point between FC and PWP that divides the available range of soil wetness into readily available and decreasingly available ranges.

The controversy arises because experiments from which these conclusions were based were carried out under different conditions and, more importantly, each experiment used different criteria as indicators of the plant response to soil water. Plant responses in transpiration rate, photosynthesis, vegetative growth, flowering, fruiting, seed and fiber production may be different at different states of soil water (Hillel,1972).

Evapotranspiration is the major factor influencing changes in water content from the field capacity to the permanent wilting percentage and change in evapotranspiration rate in relation to water availability is therefore an important relationship. In this context it should be noted that :

a. Soil water content per se is not a good criterion for availability. Different soils vary widely in their available water in the range between FC and PWP (see Table 2.3). In general, finer textured soils have a wider range between FC and PWP than coarse-textured soils.

b. The rooting pattern of plants affects the volume from which plants can extract water from the soil. Hence, in any particular soil, increased rooting depth in the profile as a whole can compensate for a narrow range of available water in one or more horizons (Kramer,1969).

c. A distinction should be made between survival and good growth of the tree. In urban tree silviculture, timber yield or fruit production is not usually an aim and it may be tolerable for matured urban trees to experience some water stress before the wilting point is reached. However, in establishing newly planted saplings or semi-matured trees, it is essential that the young plants are provided with adequate water. The irrigation program should therefore aim at maintaining an optimal soil water status. In actual practice, irrigation is deemed necessary when available water content is depleted by about 50 to 80% (Richards and Marsh,1961; Seemann,1979c).

d. Micrometeorological conditions also influence the rate of evapotranspiration and in many situations exercise the greatest influence.

When interpreted properly, the available water content is an important field characteristic of soil and is a useful parameter for the assessment of soils particularly in relation to irrigation practice.

2.6 SUMMARY

The following soil water parameters have been identified and discussed.

(1) Soil water potential.

(2) Soil water content.

(3) Field capacity.

(4) Permanent wilting percentage.

(5) Available water content.

Field capacity, permanent wilting percentage and hence available water content have been related to soil water potential and soil water content. The measurement of these two parameters is thus of fundamental importance. Methods and instrumentation for measurement will be discussed in Chapter 3.

CHAPTER 3

METHODS AND INSTRUMENTATION FOR SOIL WATER MEASUREMENT

3.1 INTRODUCTION

The fundamental importance of appropriate measurements of soil water parameters has been discussed in Chapter 2.

Under field conditions, soil water parameters vary with space and time in a given soil type and measurement procedures must take this variability into account.

In this study which is directed toward determining the water requirements of urban trees to enable the development of appropriate watering procedures, the measurement of soil water parameters under field conditions is of first importance. The following descriptions have this in mind rather than being concern with measurements under laboratory conditions. Furthermore the descriptions concentrate on the principles and merits of the commonly used methods of measurement which could be applicable in paved areas.

Methods for measurement of soil water can be categorized as measuring soil water content or soil water potential. In the measurement of soil water content, the methods can be either direct or indirect. Direct methods are those in which water is removed from a sample and the amount removed measured. Indirect methods are those in which some properties affected by soil water content are measured and the measurements related back to water content by calibration procedures.

For measurement of water potential, instruments are available for measuring pressure potential (piezometers), matric potential (tensiometer for field measurement, pressure chamber for laboratory measurement), and total water potential (thermocouple psychrometer). Since only matric potential is of relevance in this study and field method rather than laboratory technique is sought, tensiometer will be discussed.

3.2 MEASUREMENT OF SOIL WATER CONTENT

3.2.1 Direct measurements

In direct methods, soil water is removed from a soil sample either by evaporation, leaching or chemical reaction and the amount of water removed measured or inferred. The normal procedure involves collecting a soil sample with a soil auger (for gravimetric determination) or with a core-sampler (for volumetric determination). Detailed procedures for gravimetric and volumetric determination have been given by Gardner (1973).

3.2.1.1 Gravimetric determination

Oven-drying is a common procedure for the removal of the water. The soil sample is dried at 105°C to constant weight and the difference in weights of the sample before and after oven-drying enables calculation of the water content. The problems with direct measurement by this gravimetric method include :

(1) Soil sampling.

Direct sampling necessarily disturbs the site. This could be impractical in a paved-up area as the paving materials would have to be repeatedly excavated and relaid.

(2) Definition of dryness of the soil.

The definition of the dry state of a soil is subjective.

Traditionally a temperature range between 100°C and 110°C is accepted for drying soil with 105°C most frequently used. However, there is no unique temperature at which absorbed water is released from different soil minerals. At too high a temperature, loss in weight may be due to loss of water, oxidation or decomposition of organic matter (Gardner,1973).

(3) Accuracy.

There are many factors in direct measurement method that affect the accuracy of the results.

For example,because of the great variability in soil water distribution in the field, considerable replication of sampling is necessary to give valid estimates of the soil water content and some weighing error is unavoidable during the measurements of the wet weight, dry weight and the weight of the container.

However, in most field studies it is the reproducibility and not absolute accuracy that is most important. Baver et al. (1972) concluded that with reasonable care in controlling drying-oven conditions, weighing and handling of the soil samples, water content values reproducible to within ±0.5% can be achieved.

3.2.1.2 Volumetric determination

In the volumetric determination of soil water content, the volume from which the sample was taken must be known. This can be done by using a sampling device like the core-sampler. Alternatively, the bulk density of the soil (mass of soil per unit volume) is determined and the volumetric water content is obtained by the formula

$$\theta_v = \rho_b \cdot \theta_m \qquad \text{(see Appendix 2.2, Eq.2-4)}$$

where θ_v is the volume water content,

ρ_b is the bulk density of the soil and

θ_m is the mass water content.

Because both the bulk density and the dry mass water content require the dry mass of the soil, the accuracy of the inferred volumetric water content therefore depends on the accuracy of the weighing processes which give the dry mass figure.

3.2.1.3 Usefulness of direct methods

The usefulness of direct methods is twofold.

(1) They can be used to determine the water content of a soil at field capacity and permanent wilting percentage and hence the available water content can be calculated. This can provide a measure of the reserves of soil water, in itself a useful parameter in the planning of the frequency of application of irrigation water.

(2) The water content obtained for a particular site can be used as a basis for calibration when soil water potential measurements are taken.

3.2.2 Indirect measurements

Because of the necessity for extensive extractive sampling, and the destructive and time and labour consuming nature of direct methods, a number of indirect methods have been developed which permit making frequent or continuous measurements in situ at a particular site. The principle of these indirect methods is that certain physical and physical-chemical properties of soil vary with water content, although such relationships may be complicated.

The indirect methods involve measuring properties of the soil or a property of some object placed in the soil such as a porous absorber which comes to water equilibrium with the soil. The water content of a porous absorber at equilibrium depends upon the energy status of the water rather than the water content. Water content must therefore be obtained by some forms of calibration procedure.

The neutron moisture meter is widely used for monitoring water content profiles and because it seems the most appropriate equipment for monitoring water content in studies associated with the water requirements of trees in paved areas,it is discussed in some detail below.

3.2.2.1 The Neutron Moisture Meter

This meter is based on the phenomenon that fast neutrons emitted from a source are attenuated in the soil by the hydrogen content of the soil. Monitoring the flux of attenuated neutrons provides an indication of the soil water content.

Hydrogen has a greater capacity to moderate neutrons than other elements occuring in soils and it is assumed that the neutron flux around a counter varies solely with the concentration of hydrogen and hence of water (Cotecchia et al.,1968).

The source of fast neutrons and the counter for neutrons with reduced velocity are housed in a probe which is connected through an amplifer to a portable scaler, as illustrated in Figure 3.1. In use, the probe is lowered into an access tube inserted into the soil profile and counting rates may be determined at various desired depths. The count rates, adjusted for background and standardised to counts normally made in a tank of pure water, are calibrated against direct

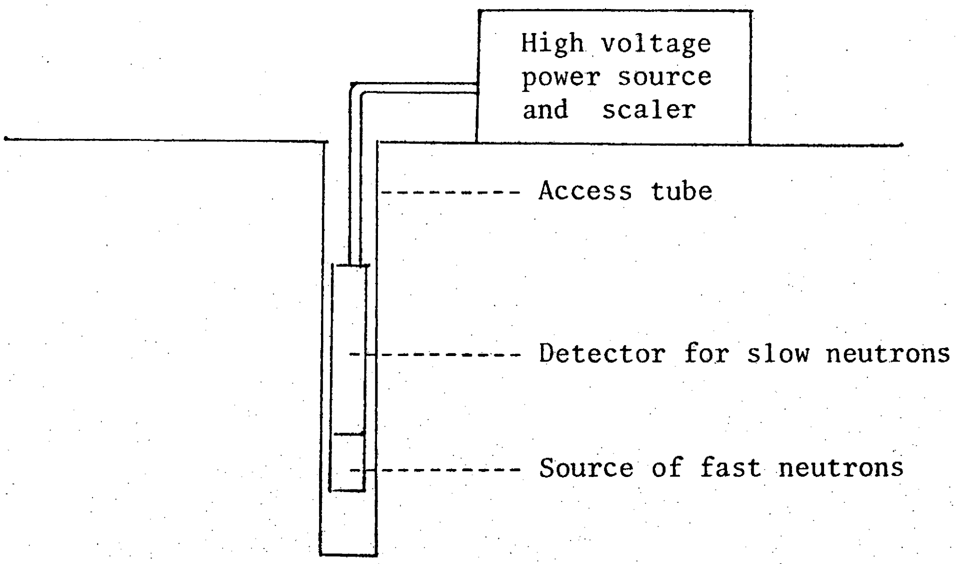


Figure 3.1 Diagram of neutron soil moisture meter.

Source : After Hanks and Ashcroft,1980. p.14.

volumetric determinations of soil water content. The calibration procedures are described in Appendix 3.1.

The instrument measures the volume water content of an approximately spherical volume of soil of radius 15 to 30 cm around the probe. The radius increases as the water content of the soil decreases (Kramer,1969). The monitoring of such a large volume of soil, thus smoothing out local variability, and the absence of a lag period while soil water equilibrates with a sensing instrument are two important advantages of the instrument. It is portable, easy to operate and can give an accuracy of approximately ± 1% volume water content (Cox and Filby,1972). The instrument does have certain limitations for universal application in the field. Some of the problems are:

(1) Chemical properties of the soil.

The presence of other hydrogen-containing compounds in the soil, such as organic matter, as well as other elements, notably chlorine, iron and boron (Kramer,1969), affect the counts. Cotecchia et al.(1968) found that the chemical composition of various soils had a marked influence on measurements, because of the diversity of the moderating, diffusing, capture properties of the various components.

(2) Physical properties of the soil.

The bulk density of the soil influences the readings (Holmes,1966). While the way in which bulk density affects the readings has been controversial (Ølgarrd and Haahr,1968), the problem is overcome by appropriate calibration procedures which take account of the bulk density of the particular soil. This will be discussed in Chapter 5.

Rocky soils present problems in that it is difficult to install the access tubes for the neutron probe particularly as hand-held equipment is not satisfactory for drilling the relatively large holes needed for easy tube placement. Koshi (1966) evaluated methods of installing the access tube, the influence of voids and rocks around tubes and the accuracy of using factory calibration curves in rocky situations. He found that voids around access tubes of less than 1 cm (3/8 in.) diameter and rocks (unless they are large) had little or no influence on slow neutron count rates. However, factory calibration curves seemed to give too high a soil water content and it was necessary to develop a calibration curve by using soil samples taken from the site.

(3) In practice, measurements taken close to the soil surface are not reliable because the neutrons scatter in a spherical zone. Koshi(1966) mentioned that the determination of water

content of the surface soil, using neutron scattering meter, has been a problem. He took gravimetric samples for surface measurement but found that the variations in the readings between the gravimetric and neutron meter methods were so great that it was not possible to develop a calibration curve. Thus for surface measurements of surface soil special techniques are needed. Hydrogenated surface shield was used to place on soil surface to increase accuracy of reading. Because they shield the neutron from scattering out of the soil profile, such surface moderators also reduce the risk of exposure of operators to radiation. Pook and Hall(1974) used polythene and cadmium as surface moderators for the measurement of water content in shallow layers of forest topsoils. They found the use of surface moderators was successful in extending the application of the normal calibration to count data obtained at 10 cm depth, but not to count data at less than 10 cm depth.

Despite these limitations, the neutron scattering meter is one of the most useful tools for field measurement of soil water content. The main advantage of the neutron scattering meter is that it is not destructive and once the access tubes are installed, repeated measurements can be conveniently taken.

3.2.2.2 The Gypsum Blocks

If porous blocks are embedded in the soil, the water content of the block will change with that of the soil and this produces changes in electrical resistance of the block. These can be calibrated against the soil water content. The electrical resistance of gypsum, fibre-glass or nylon blocks is commonly measured. Gypsum blocks are the most widely used because they are cheap and simple to operate. They are sensitive over a range of water content equivalent to about -0.5 to -15 bars of matric potential and are therefore more satisfactory in dry soils. The nylon and fibre glass blocks are more sensitive in wet soils.

Electrodes of stainless steel are imbedded in the gypsum block. To instal a block in the soil, a hole is formed vertically from the soil surface or horizontally in the side of a trench. The block is wetted thoroughly and placed in the hole which is then repacked with soil to ensure good contact to the surrounding soil. Leads are connected to a Wheatstone bridge for measuring resistance. Lamb (1967) recommended that the hole be dug at a slope of about 75^{o} from the horizontal and the blocks are arranged in a spiral to ensure undisturbed soil above each block. Also, the leads should be looped to prevent direct drainage of water down the leads to the block.

After installation, the blocks are left overnight to reach equilibrium with the soil. Resistance measurements are then taken and converted to water content from a calibration curve. The calibration curve must be determined by using soil from the site where the block is embedded, for different soils have different calibration curves. The calibration is done by taking soil samples for laboratory tests or by embedding a similar electrode in a small container of the soil and taking simultaneous readings of resistance and the weight of the container as the soil dries.

3.2.2.3 Other methods

Gamma rays are absorbed by matter and the gamma ray attenuation method has been used to detect changes in soil water content. Gardner

(1973) noted that the gamma ray method had been used successfully to follow the change in water content in the root zone of growing plants.

A newly developed instrument, the surface water-density gauge, may be useful to measure soil water contents immediately underneath pavements without drilling through the paving. In this instrument the photon source and detectors are in the same horizontal plane above the surface. A sketch of the instrument is shown in Figure 3.2. The effective depth of measurement of water content is only 13 cm (5in.) (Anon,1977). Actively absorbing tree roots grow far below this 13 cm depth and the instrument could not be used in determining the water content through the root zone. It could be useful in detecting changes in water content which might have infiltrated the surface and so give a rough indication of whether water is present in the soil under the pavement.

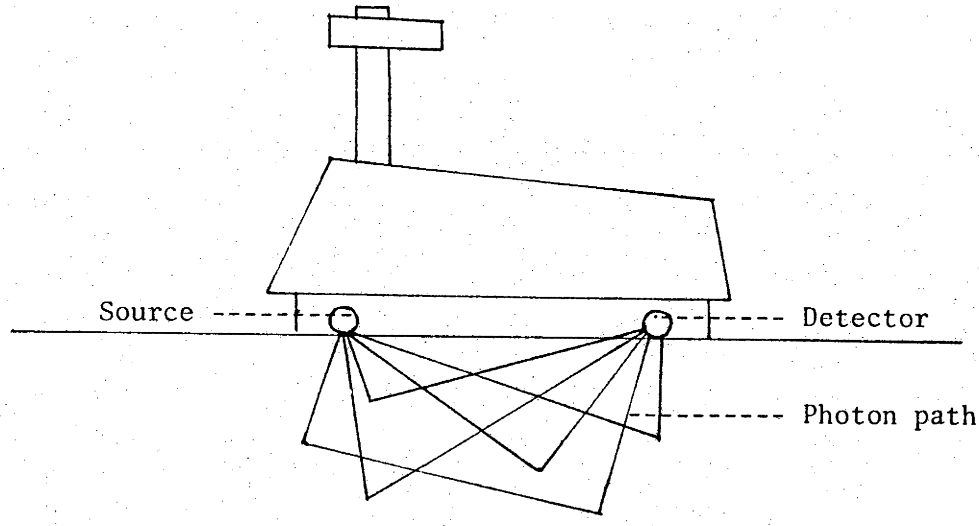


Figure 3.2 A backscatter geometry of a surface moisture-density gauge.

Source : Troxler Electronic Laboratories, Inc., 1977.

Surface moisture-density gauges 3400 series instruction manual.

There are also methods based on the use of ultrasonic waves and the dependence of soil thermal properties on water content. However these methods are not yet commonly applied for routine practical use in the field.

3.3 MEASUREMENT OF SOIL WATER POTENTIAL

Soil water studies have long been carried out in terms of water content. However, to be most useful for studies of plant and soil water, the energy status of soil water is required for it takes account of the dynamic system in which water moves and becomes available to root system. The total soil water potential is an index of the energy status and, as discussed previously, for the purpose of plant and soil water study, can be taken as the sum of matric and osmotic potentials. Instruments commonly used for field measurements to guide irrigation usually measure only the matric potential and not the total potential. This however is not of great concern if the soil is non-saline and fairly wet (Cox and Filby,1972).

The tensiometer is the most widely used instrument for the in-situ measurement of matric potential. It consists of a porous ceramic cup, connected to a manometer through a tube. All these parts are filled with water and the cup is positioned at the measurement point. Water flows through the cup wall to bring the cup water into hydraulic equilibrium with the soil water. The manometer indicates the pressure drop on the water in the porous cup which is in equilibrium with the matric potential of the water in the soil and therefore the matric potential of the soil water is determined.

The highest reading possible is theoretically equivalent to -1 bar but in practice is about -0.8 bar. However, the relatively small range 0 to -0.8 bar encompasses the greater part of the soil wetness range for plant growth (Richards,1973). Correlating soil water potential with the available water depletion, Richards and Marsh (1961) showed that the range 0 to -0.8 bar accounted for 25 to 75% of the soil water taken up by plants for most soils (see Figure 2.4 p.19).

With irrigation, the aim is to maintain a favourable soil water status for plant growth. The apparently limited range of the tensiometer is quite adequate for use in the field. It has in fact been found that it is usually at the range of ψ_m between 0 to -0.8 bar that plants should be irrigated (Hanks and Ashcroft,1980). Installing tensiometers at several depths and following the readings with time provides information for efficient irrigation. When the prescribed water potential is reached for the soil depth where the feeder root concentration is greatest, then irrigation is necessary. The rate of change of water potential with time under field conditions is influenced by climatic factors and the species and vigor of the plant involved. Irrigation timing based on tensiometer readings (in fact for many other methods as well), takes account of soil and climate as well as plant requirements.

Tensiometers read water potential directly, without the need to calibrate (Cox and Filby,1972), and could be used in paved areas. The installation under ground is similar to that required by the neutron probe and once installed repeated measurements can be taken readily.

CHAPTER 4

METHODS OF DETERMINING WATER LOSS BY TREES : A REVIEW

4.1 INTRODUCTION

The water uptake by a tree depends on the relative rates of transpiration and absorption which in turn depend on the interacting factors involving the plant, the soil and the climate. Of all the water taken up by a tree only about 5% is retained by the tree and 95% of the water is lost by transpiration (Kramer,1969).

The evaluation of water losses by trees can be approached by looking at the soil and soil water, the plant and the climate. One approach to determining water loss is to neglect the 5% water retained by the tree and to determine the depletion of the soil water content at the root zone and take into account the water loss through drainage (and possibly runoff). The second approach is to measure the climatic factors as an indication of evaporative potential and to correlate water loss with meteorological data. A third approach focuses on measuring the amount of water loss from the plant itself (Swanson and Lee, 1966).

The first two approaches essentially measure evapotranspiration losses and the third, the transpiration rate. All these three approaches may have applications in studies of water loss by trees in paved areas and they are discussed in this chapter in relation to single trees in an urban environment.

4.2 ESTIMATING EVAPOTRANSPIRATION FROM SOIL MOISTURE DATA

4.2.1 Hydrological approach -- The water balance method.

The relation between the water input and water output from a site over a period of time can be represented by the following equation :

$$P_n + I - \Delta D_e = E_t + R_o + D_r \qquad \text{--------------------- Eq.4-1}$$

in which

P_n is the precipitation input,

I is the irrigation input,

ΔD_e is the increase in soil water content in the root zone,

E_t is the evapotranspiration loss,

R_o is the net runoff, and

D_r is the drainage loss from the root zone.

Evapotranspiration (E_t) can therefore be represented by

$$E_t = P_n + I - \Delta D_e - R_o - D_r \qquad \text{--------------------- Eq.4-2}$$

This approach is used mainly for investigating evapotranspiration in hydrological catchment areas but there are difficulties in measuring accurately the various items. The main difficulty is in determining changes in groundwater storage and deep seepage (Ganopadhyaya et al.,1966). Evapotranspiration as determined from Eq.4-2 is,in these studies,a residual and therefore the accuracy with which it is estimated depends on the errors made in the measurement or estimation of all components of the equation (Talsma and Lelij,1976).

The difficulty could be even greater in applying the approach to an urban street tree situation. Firstly, the urban water balance is at present imperfectly understood (Oke, 1974). Secondly, almost all the parameters in the right hand side of Eq.4-2 cannot be monitored or calculated with sufficient precision. The problems are as follows.

(1) Measurement of precipitation.

The amount of precipitation is usually measured by raingauges which sample rainfall at a point. At the point of observation, already an error of at least 5% must be expected (Smith, 1975). On an area basis, the average rainfall is obtained by taking rainfall readings from several recording stations and extrapolating by either Thiessen network or isohyetal maps. The stations are scattered points and represent only a fraction over the entire sampled area (Linsley and Franzini, 1972), although reliable estimates of depth of rainfall over extensive rural and urban areas can be obtained with sufficient stations (see for example Figure 4.1). However, street orientation and shielding by adjacent buildings may cause large variations in rainfall between points in a city area and a rainfall reading at a point may not be a reliable estimate of the precipitation which is input to a single tree site. Furthermore, not all rainwater recorded will actually reach the ground because the city interception and storage by building materials can absorb about 50% of the precipitation if the area is 95% paved (Watkins,1963; quoted by Oke, 1974). Thus for urban trees in paved areas it may be necessary to measure rainfall on an individual tree basis if reliable rainfall inputs to the tree are required. This is not practical.

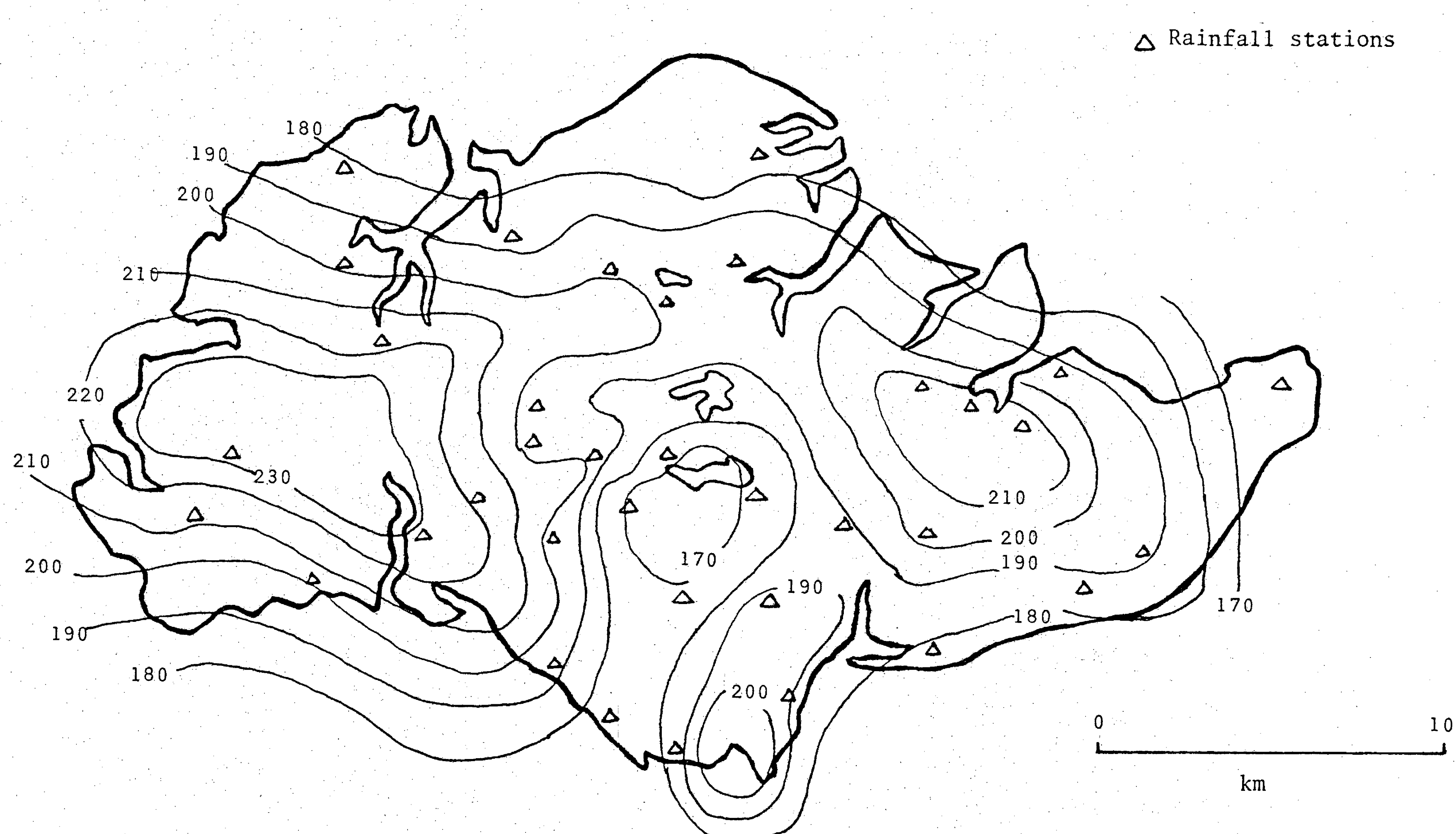


Figure 4.1 Isohets and locations of rainfall stations in Singapore island.

Source : Singapore Meteorological Service Report, 1976.

(2) Surface runoff and drainage.

The precipitation as recorded by raingauges may bear little relevance to the actual amount of rainwater entering the root zone of street trees for impervious coverings cause rapid runoff of precipitation (Landsberg,1970) whereas in irrigated agricultural fields, the grass or crop offers greater resistance to runoff (see Table 4.1). The amount of runoff in the field is generally small and may be neglected (Hillel,1972). Furthermore, for irrigated agricultural fields, the drainage term may also be assumed as negligible.

Table 4.1 Values of Retardence Coefficient (Cr) for various surfaces.

Surface	Cr
Smooth asphalt surface	0.0017
Concrete pavement	0.0120
Tar and gravel pavement	0.0170
Closely clipped sod	0.0460
Dense bluegrass turf	0.0600

Source : Linsley and Franzini, 1972. p.59.

Theoretically, if an area is entirely covered by asphalt or concrete pavement and the entire impervious area is connected to the drainage system and not onto soil, then runoff volume could equal to all the precipitation (Linsley and Franzini, 1972). However, this is not usually the case in practice. All roads, regardless of the types of pavement structure (rigid, semi-rigid, flexible pavement or paving stone surfacing), are subject to pavement deterioration (OECD, Road Research Group, 1978a). Cracks developed on the road surface can lead water to penetrate into the underlying soil profile (OECD, Road Research Group, 1978b), and will increase soil water contents below the pavement.

Thus it can be seen that in terms of urban trees there are at least 3 terms in Eq.4-2 which cannot be measured or estimated with certainty, viz rainfall, runoff and drainage loss. Consequently, this water balance approach is mostly applied in large areas, relative to that occupied by urban tree planting, of more or less heterogeneous vegetation over long periods of time.

4.2.2 Lysimeter method.

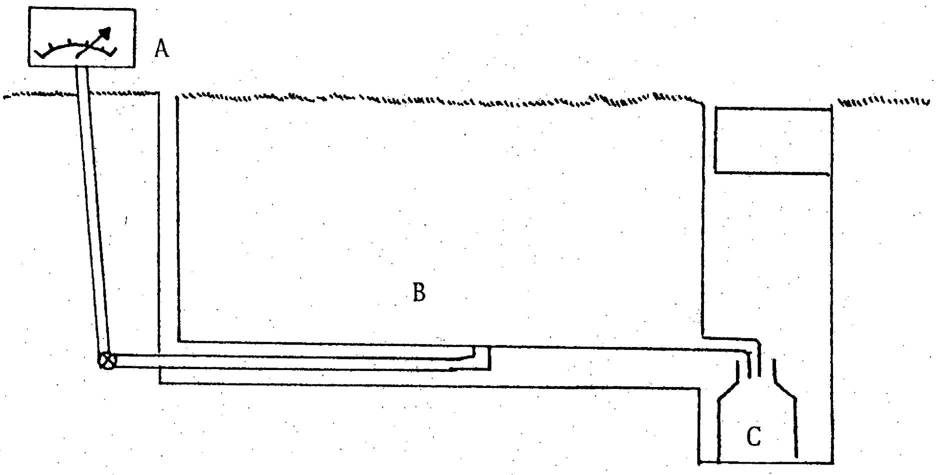
In Eq.4-2, if runoff (R_o) and drainage (D_r) can be either eliminated or measured, then the difference between inputs (P_n + I) and changes in storage (ΔD_e) would give the evapotranspiration, that is ,

$$E_t = P_n + I - \Delta D_e \quad \text{--------------------------------Eq.4-3}$$

Furthermore, for periods between irrigation or rainfall, (i.e. when P_n and I are zero),

$$E_t = -\Delta D_e \quad \text{--Eq.4-4}$$

This change of soil water storage can be measured in situ by the use of either gravimetric or volumetric lysimeters. In the gravimetric lysimeter, changes in the water content are reflected by the change in the weight of the lysimeter. An efficient weighing lysimeter (Figure 4.2) should be equipped with a drainage system and a device to take into consideration the temperature sensitivity of the weighing system.



A. Scale showing change in weight
B. Lysimeter tank
C. Collection of drainage

Figure 4.2 A schematic representation of a weighing lysimeter.

Source : After White, 1979. p.77.

In the volumetric lysimeter, the moisture in the soil is brought up to field capacity at the beginning and end of a measuring period. The water use, that is evapotranspiration, can be estimated by adding the amount of water added to the rainfall and subtracting the drainage or percolating water which must be collected at the bottom of the lysimeter and measured.

In lysimeter tanks, percolation can be collected and measured, and there is no seepage as the soil profile is not continuous. Thus changes in water content of the soil, as indicated by the change in weight of the lysimeter can give a continuous measurement of evapotranspiration (neglecting the comparatively minute weight changes due to respiration and photosynthesis). For satisfactory results, it is necessary that the lysimeter is

(a) constructed in-situ by confining an undisturbed monolith, that is, it is not merely re-filled with soil;

(b) large enough to not restrict root growth too severely;

(c) maintained so that the condition for growth is the same as in field conditions.

This requires, inter alia, that the surface of the soil in the lysimeter is at the same level as that of the surrounding surface. The diameter of the lysimeter should exceed 1m, the depth should be at least 2m for deep-rooted perennial trees; and it should be surrounded by a considerable area of the same geometry (Robins, 1973). It should be noted that these conditions could rarely be met in a normal street tree-planting site. In Singapore, for example, the planting verge rarely exceeds 2m width. There may however be special situations where lysimeters could be useful for field investigations, for example as in the case of a young sapling planted in a car parking lot.

4.2.3 Soil moisture depletion methods.

Measuring changes in the soil water content within the root zone is another approach to measuring water loss. The various methods and instruments already described in Chapter 3 can be applied in such an approach.

A pre-requisite of this method is that the soil should be fairly uniform and the ground water sufficiently deep not to influence soil-water fluctuations within the root zone (Veihmeyer,1968). Depletion of the soil water, as calculated from water content changes between two sampling times, is taken as the loss due to evapotranspiration. A water-consumption curve can be obtained by plotting the water losses against time. As repeated soil water content measurements are to be made over a period of time, measuring devices like tensiometers and gypsum blocks are best suited for they do not disturb the site once they are properly installed.

The changes in the water content are usually small relative to the total water content and large errors can occur in the measurement of differences in total water content. This is a disadvantage of the method.

In situations where groundwater interference is expected or water movement in the root zone cannot be controlled or accounted for, then the depletion of soil water may not be due to evapotranspiration although such an assumption has sometimes been made (Kijne,1974). Under such circumstances, tensiometers (and other similar devices) can, instead of measuring evapotranspiration, be used to provide an indication of the depletion of available water in the root zone as has been mentioned in Chapter 3.

4.3 ESTIMATING EVAPOTRANSPIRATION FROM METEOROLOGICAL DATA

4.3.1 Aerodynamic-Profile method.

This method is also known as the Turbulent vapour-transfer method(Robins, 1973), the Turbulent vapour-transport method (Rijtema, 1965) and the Vapour flow method (Kramer,1969).

The rate at which water vapour passes upward from an evaporating surface is measured by taking into consideration the vapour pressure and wind velocity at two heights. Because the evaporation of water needs latent heat, it is related to the transport of sensible heat which is in turn affected by the turbulent air movement in the atmospheric boundary layer.

The equation for the mean vertical transfer of sensible heat can be written as (Hanks and Ashcroft, 1980) :

$$H = -\rho_a C_p K_H \frac{\delta T}{\delta Z}$$

$$= -\rho_a C_p K_H \frac{T_2 - T_1}{Z_2 - Z_1} \qquad \text{-------------------Eq. 4-5}$$

in which

H is the sensible heat flux (cal.cm.$^{-2}$ sec^{-1})

ρ_a is the air density (g.cm^{-3}) (= 1.2 x 10^{-3} at 20^{o}C, 1013mb.)

C_p is the specific heat of dry air at constant pressure (= 0.242 cal.g^{-1}.^{o}C^{-1})

K_H is the eddy-transfer factor (cm^2.sec^{-1})

T_2 and T_1 are the temperatures (^{o}C) at two heights,

Z_2 and Z_1 are the two heights (cm).

Similarly, the basic equation for the transfer of water vapour is (Hanks and Ashcroft, 1980) :

$$E = -\frac{\rho_a \varepsilon}{P_a} K_v \frac{\delta e}{\delta Z}$$

$$= -\frac{\rho_a \varepsilon}{P_a} K_v \frac{e_2 - e_1}{Z_2 - Z_1} \qquad \text{-----------------------Eq. 4-6}$$

where

E is the flux density of water vapour (g.cm^{-2}.sec^{-1})

ε is the ratio of molecular weight of water to that of air (= 0.622)

e_2 and e_1 are the vapour pressure of the air at two heights (mb or bar)

P_a is the atmospheric pressure (mb or bar)

K_v is the eddy transfer coefficient for water vapour ($cm^2.sec^{-1}$)

the remaining notations are the same as for Eq. 4-5.

The difficulty in using Eq. 4-6 is in evaluating K_v because it necessitates the measurement of wind speed. In some cases, K_v can be approximated by (Hanks and Ashcroft, 1980) :

$$K_v = \kappa^2 \frac{(\mu_2 - \mu_1)(Z_2 - Z_1)}{\ell n\,(Z_2/Z_1)^2} \quad \text{----------------Eq. 4-7}$$

where

κ^2 is the von Karman constant ($\simeq 0.4$)

μ_2 and μ_1 are the average wind speed ($cm.sec^{-1}$) at heights Z_2 and Z_1 (cm) respectively.

The measurement of the wind speed is in itself a difficult task because wind speed changes with time, height, site and exposure (Smith, 1975) and the measured wind speed may not be that experienced by the plant. While cup-counter anemometers are commonly used for measuring wind speed they are not satisfactory at a street tree planting site because the anemometer measures the horizontal component of the wind but does not record the vertical air turbulent movement due to the heated tarmac paved surface. This deficiency of the anemometer may seriously underestimate the vector wind velocity (Miller,1980).

The method depends on the reliability and sensitivity of the instruments and requires strict adherence to boundary conditions. It is not suitable for routine field application other than very specialized measurements (Winter, 1974; Robins,1973 and Veihmeyer,1968).

4.3.2 Energy balance method.

This method is based on the assumption that net radiant energy at the land surface is used for evaporation, transpiration, heating the air and the soil, and for photosynthesis. The total energy can be partitioned and expressed as

$$R_n = LE_t + H + G + M \quad \text{------------------------Eq. 4-8}$$

in which

R_n is the net radiation and is the overall difference between the total incoming and total outgoing radiation (including both short-and long-wave radiation),

LE_t is the rate of energy used in evapotranspiration ($cal.cm^{-2}.day^{-1}$) ($L = 590\ cal.g^{-1}$ at 25^oC)

H is the sensible heat, that is the energy flux used in heating the air,

G is the heat stored in the soil

M is the other miscellaneous energy such as used in photosynthesis, respiration and heat stored in the plant-air layer.

For general use in an 'ideal' condition, i.e., a short, dense, uniformly vegetated surface, equation 4-8 has been simplified by adopting the following assumptions.

(1) That the heat stored in the vegetation is small (Tanner, 1963) and energy consumed in photosynthesis is generally only about 5% of the daily net radiation (Lemon,1965). These components of Eq.4-8 may thus be smaller than the experimental error in measuring the other major components (Kijne,1974) and generally ignored. However, I feel that this assumption is disputable and there is a need for critical review of its application to an urban environment because :

(a) if R_n happens to be low, as in an overcast sky, and the plant is carrying large amounts of leaves, M may account for up to 10% of R_n (Kijne, 1974);

(b) in urban areas, building and pavement materials notably alter the evaporation term of the heat balance (Landsberg,1970);

(c) trees, as compared to grass, would intercept more radiation due to denser foliage (Bernatzky,1978).

(2) The term G, the amount of heat stored in the soil, is thought to account for only a small component of the overall energy balance (Hillel,1972). Tanner (1963) suggests that depending on the canopy cover and the season, the soil storage term may account for between 5 to 15% of net radiation but rarely exceeds 10 to 15%, in ideal condition. In a forest situation, only 5% of the solar radiation reaches the forest floor (Bernatzky,1978).

In paved areas, rainwater is quickly drained off from the street and only a small amount of heat is lost through surface water evaporation (Landsberg,1970). The radiant energy reaching the ground is increased and caused elevated soil temperature (Howe,1979; Carter,1967; Bernatzky,1978).

Hence, in an urban soil,the item G should not be ignored. Even under 'ideal' conditions, with vegetation cover and when soil moisture is not limiting, this soil storage term, while thought to consitute only a small fraction of net radiation, is not neglected.

Thus, neglecting only the term M, Eq.4-8 has been re-arranged to

$$R_n - G = LE_t + H \quad \text{------------------------------Eq. 4-9}$$

Net radiation can be measured directly by net radiometers which measure both the incoming and outgoing radiation (Seemann,1979a). The measurement of heat flux in the soil poses some difficulties (Seemann, 1979b). Tanner (1963) outlined three methods by which soil heat flux can be measured,

(a) the temperature gradient method,

(b) the flux plate method,

(c) the calorimeter method.

Thus to solve for equation 4-9, a second relation between LE_t and H is needed. This can be obtained by combining Eqs. 4-5 and 4-6

$$\frac{H}{E_t} = \frac{C_p \, P_a \, K_H \, (T_2 - T_1)}{\varepsilon \, K_v \, (e_2 - e_1)} \quad \text{---------------------Eq.4-10}$$

Hence,

$$\frac{H}{LE_t} = \frac{C_p \, P_a \, K_H \, (T_2 - T_1)}{L \, \varepsilon \, K_v \, (e_2 - e_1)} \quad \text{----------------------Eq.4-11}$$

where

$$\frac{C_p P_a}{L \varepsilon} = \gamma \qquad \text{--------------------------------Eq. 4-12}$$

is the psychrometer constant

$= 0.66$ mb. $^{o}C^{-1}$

Bowen (1926,quoted by Kijne,1974), assumed that K_H equals to K_v and defined a Bowen ratio (β) as

$$\beta = \frac{H}{LE_t} = \gamma \frac{T_2 - T_1}{e_2 - e_1} \qquad \text{-----------------Eq. 4-13}$$

Re-arranging Eq.4-9 and substituting the Bowen ratio,Eq.4-14, which is used for estimating evapotranspiration in energy balance methods, is obtained.

$$LE_t = \frac{R_n - G}{1 + \beta} \qquad \text{-----------------------Eq. 4-14}$$

Instruments are needed to measure net radiation (R_n), soil heat flux (G) and corresponding temperature and vapour pressure at two heights (T_2, T_1, e_2 and e_1) for β.

The formula works best when water is not limiting, that is, when the temperature difference is small and the vapour pressure difference is large and therefore, β is small.

In humid regions, evapotranspiration loss can be approximated by

$$LE_t = R_n - G \qquad \text{--------------------------------Eq. 4-15}$$

because β is $\pm$ 0.1 and hence it can be assumed that about 70 to 80% of the net radiation energy is used for evapotranspiration. In dry conditions, such an approximation cannot be used because β could be as large as 10 and Eq.4-15 would give an over-estimated value of LE_t.

4.3.3 Combined method - The Penman's equation.

Penman (1948, quoted in Penman,1963) combined aerodynamic and energy balance methods to estimate evapotranspiration from commonly collected meteorological data. However, because use is made of the Dalton equation which describes evaporation from a saturated surface, Penman's method estimates the potential evaporation from a free water surface, and a reduction factor is used to obtain the potential evapotranspiration. Thus, the application of the Penman method requires calculating the potential evaporation from a free water surface and the reduction factor.

4.3.3.1 Calculation of potential evaporation from the free water surface.

Penman's equation for calculating the potential evaporation from a free water surface is given by :

$$E_o = \frac{\frac{\Delta R_n}{L} + \gamma E_a}{\Delta + \gamma} \qquad \text{-------------------------Eq. 4-16}$$

where

E_o is the potential evaporation (mm.day^{-1})

Δ is the slope of the temperature-vapour pressure curve at the observed temperature (T_a) at a height of 2m, assuming a saturated vapour pressure at the surface,

R_n is the net radiation $(mm.day^{-1})$,

L and γ are the latent heat of vaporization and psychrometer constant respectively,

E_a is a drying power of the air $(mm.day^{-1})$ which depends on air speed and vapour pressure and is given by the equation (Kijne,1974)

$$E_a = 0.35\ (0.50 + 0.54\mu_2)\ (\varepsilon_a - e_a)$$

where

μ_2 is the wind movement at 2m height $(m.sec^{-1})$

ε_a is the saturated vapour pressure of the air at temperature T_a (mm.Hg)

e_a is the observed vapour pressure of the air (mm.Hg).

In this equation, the numerical values are obtained in the following ways.

R_n is measured with a recording net radiometer,

μ_2 is measured with a cup anemometer and

all other variables can be read from tables.

It should be noted that in the above equations, wind speed (μ_2) is measured at a height of 2m above the ground. Wind speed (μ_Z) measured at other height (Z) can be adjusted to the required height by the following relationship (Gangopadhyaya et al.,1966) :

$$\frac{\mu_2}{\mu_Z} = \left(\frac{2m}{Z}\right)^n$$

in which

Z is the height of the anemometer above ground (m)

n is a constant.

4.3.3.2 Calculation of reduction factors.

Crop Coefficient

To estimate the potential evapotranspiration (E_{tp}) for a green crop fully and uniformly covering the soil and with unlimited supply of water, a reduction factor, called the Crop Coefficient (f) is introduced.

$$E_{tp} = f \cdot E_o \qquad \text{--------------------------------Eq. 4-17}$$

The crop coefficient has been investigated by many workers. Penman (1956, quoted by Rijtema, 1965) concluded that f is mainly determined by the daylength. Rijtema(1965) concluded that f is mainly determined by the difference in reflection of the two surfaces of the plant leaves. Hanks and Ashcroft (1980) listed 3 factors which will influence the numerical value of f : (1) the plant, (2) the time of the year and (3) the location.

Penman (1963) gave the value of 0.7 for grass at equatorial region whilst for the same region, the f value for a perennial plant is 1 (Hanks and Ashcroft,1980).

Soil Coefficient

Actual evapotranspiration (E_{ta}) by plants in the field is generally appreciably lower than the potential evapotranspiration (E_{tp}) (Hillel,1972) because of limitations in water supply.

The E_{ta} can be calculated from E_{tp} by again introducing a soil coefficient (K_s) :

$$E_{ta} = K_s \cdot E_{tp} \qquad \text{--------------------------------Eq.4-18}$$

When water is not limiting,

$$E_{ta} = E_{tp},$$

that is,

$$K_s = \frac{E_{ta}}{E_{tp}} = 1$$

As water availability is decreased, the value of K_s is also reduced. The differences in opinion as to whether soil water is equally available to tree roots at various soil water content between field capacity and permanent wilting percentage was discussed in Chapter 2 and different relationships between K_s and water content (θ_v) have been suggested (see Figure 4.3).

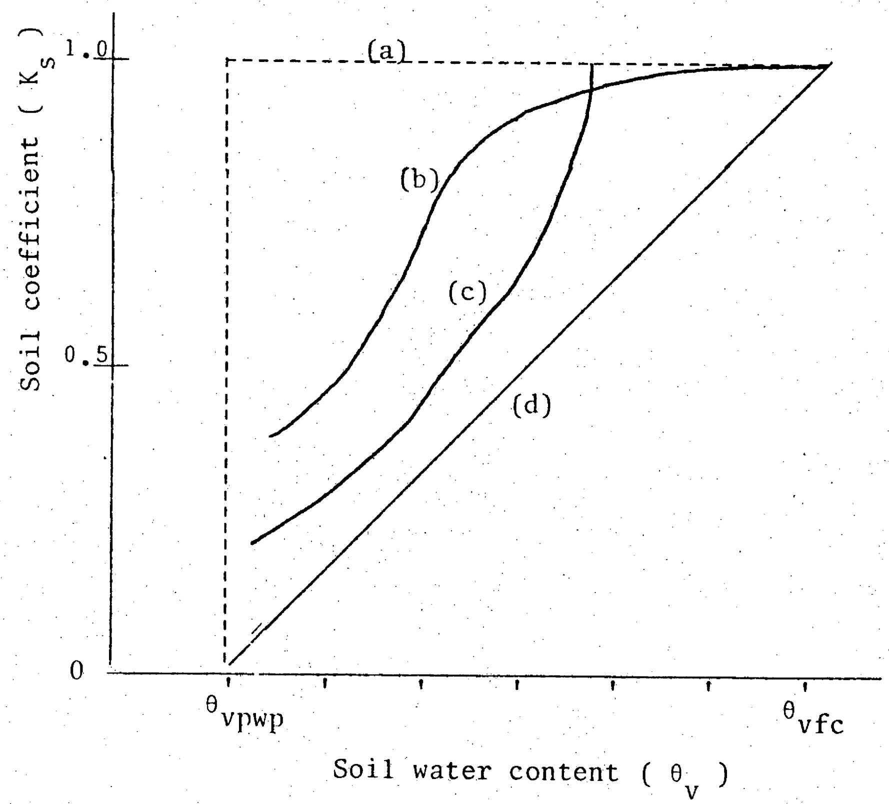


Figure 4.3 Relationship between soil water content (θ_v) and soil coefficient (K_s).

Source : From Tanner, 1967; quoted by Hanks and Ashcroft, 1980.

Denmead and Shaw (1962) showed that all the relationships shown in Figure 4.3 can occur and stated that,

(1) if evaporative power of the atmosphere is high, then water availability may decrease as soil water content drops. This is the condition of the linear relation as shown in curve (d),

(2) if the evaporative power of the atmosphere is low, then relation (a) may apply, i.e.,water is equally available to the plant between FC (θ_{vfc}) and PWP (θ_{vpwp}),

(3) under field condition, with large rooting depths, relations (b) and (c) may apply.

Rijtema(1965) presented a theoretical evaluation of K_s and showed that it is determined by parameters like temperature, wind speed, light intensity and roughness of the leaves of the plant.

Advected heat may cause serious errors in the value of evapotranspiration as calculated by the Penman's method. In fact, Penman's method is not intended for use in situations where there is advection (Kramer,1969) and a further empirical reduction factor, determined locally, would be needed for use of this equation in an urban area. For example, Pruitt(1960) used a reduction factor of 0.97 to the calculated E_{ta} for central Washington.

4.3.4 Empirical methods

4.3.4.1 Thornthwaite method.

Thornthwaite (1948, quoted by Lee,1980), based on records of mean air temperature and length of day (which are strongly correlated with incident radiation), derived a formula for estimating potential evapotranspiration for a large catchment area. The empirical expression for a monthly potential evapotranspiration (E_{tp}), with a day length of 12 hours, is (Gangopadhyaya et al., 1966) :

$$E_{tp} = 16 L_a \left(\frac{10 T}{I} \right)^a \qquad \text{--------------Eq.4-19}$$

where E_{tp} is the monthly potential evapotranspiration (mm),

L_a is an adjustment for the number of hours of daylight and days in the month and is related to latitude,

T is the mean monthly air temperature (^oC),

I is a heat index obtained by summing the 12 monthly values of heat index i given by

$$i = \left(\frac{T}{5} \right)^{1.514}$$

a is a cubic function of I, given by

$$a = 6.75 \times 10^{-7} I^3 - 7.71 \times 10^{-5} I^2 + 1.79 \times 10^{-2} I + 0.49$$

The method has limited general application. In the first place, it gives only unadjusted rates of potential evapotranspiration as crop and soil coefficients are not incorporated. More importantly, because it is based on empirical data, the equation could not validly be used for areas having a different climate from that in which the formula was developed (Thornthwaite, 1954., quoted by Penman, 1963).

4.3.4.2 Other empirical methods.

There are other empirical methods, notably the Blaney and Criddle method and the Turc method. All empirical methods make use of climatic data (see Table 4.2) and are applicable to a large catchment area and a large irrigated field grown with agricultural crops.

TABLE 4.2 Meteorological Data Required for Various Methods of Calculating Potential Evapotranspiration

Methods	T	n	μ	e	p
Penman	x	x	x	x	-
Turc	x	x	-	-	x
Blaney-Criddle	x	-	-	-	-
Thornthwaite	x	-	-	-	-

T is temperature, n is hour of sunshine, μ is wind speed, e is vapour pressure, p is precipitation.

Source : Kijne, 1974

While these formulae may be useful for hydrological studies and for agricultural irrigation programs and may attain a degree of accuracy in their area of origin, they have to be used with care in different climates, especially when the conditions and assumptions under which the formulae were postulated do not apply. For example, Rose (1969) reported that the theory of Penman is not applicable when evapotranspiration is limited by water transport in the soil and Kijne (1974) concluded that the formulae by Blaney-Criddle and by Thornthwaite are not suitable for monsoon-type climate.

4.3.4.3 Review of Empirical methods.

This literature study has in mind the formulation and development of proposals for the study of the water requirements of street trees in paved up areas in Singapore. Singapore has two monsoon seasons totalling 10 months (Singapore Meteorological Service Report, 1976). The literature advises care in extrapolating the empirical formulae to areas with meteorological conditions outside those for which the formulae were developed. The literature search has not indicated formulae developed for areas with a climate such as Singapore nor for urban paved streets. It is concluded that the empirical methods for estimating the evapotranspiration are not appropriate for use in the context of this study.

4.4 ESTIMATING TRANSPIRATION RATE

The water balance method and the various methods utilizing meteorological data as described in previous sections are more suitable for estimating water losses from a plant community. A direct approach of estimating water loss in trees due to transpiration is the measurement of either the water movement in the tree or the amount of water vapour given out by the tree canopy.

Four methods are discussed below for the direct measurement of water use by a single tree, the situation most relevant to this study. These methods focus on the direct evaluation of water movement from and through the trees themselves (Swanson and Lee, 1966):

(1) The use of lysimeters for measuring evapotranspiration loss has already been mentioned. For estimating transpiration loss, the lysimeter must be covered to prevent evaporation,

(2) the quick-weighing method,

(3) the water vapour loss method, and

(4) the sap flow method.

4.4.1 The quick-weighing method (cut-shoot method)

In this method, the transpiration rate is determined by measurement of weight loss from cut plant shoot or detached leaves.

This method implies that the weight loss is due to loss of water from transpiration alone and that water used in photosynthesis is negligible.

The detached shoot or leaf is weighed immediately after being separated from the tree and reweighed on a special balance after a few minutes. The obvious critisism of this method is that the detached part may have a different physiological response to the immediate environment than the entire tree. Moreover, placing the detached part of the plant in the balance exposes it to an environment entirely different to the normal microclimate of the entire tree in the field (Kramer,1969). Another issue is the correct selection of the branch or the leaf for cutting. Different parts of a tree canopy receive different radiation intensities and will have different transpiration rates. For example, leaves at the shady side of a tree have been found to evaporate 25% less water than those on the sunny side (Bernatzky, 1978), and different parts of the tree have also been found to be transpiring at different rates (Kramer and Kozlowski,1979).

The most problemetic step with this method is,thus,with the extrapolation from the detached plant portion to the entire tree.

4.4.2 Water vapour loss method

The principle of this method is to enclose a portion of the entire tree within a transparent, impermeable housing. The transpiration rate is calculated from the rate of flow of the incoming and outgoing air and the difference in their moisture content. A transparent plastic tent is commonly used to enclose the small tree. The tent is then inflated by an airstream. Instruments for measuring changes in water content of the air include wet and dry-bulb thermometers,wet and dry thermocouples, corona hygrometer, microwave hygrometer, electrical resistance hygrometer, infrared gas analyzers and psychrometers (Kramer,1969). However, quantitative measurement of water vapour in the air is difficult (Tanner,1963) and to date, no ideal or universal instruments have yet been developed for this purpose (Forrester,1979).

There are several signigicant criticisms of the procedures.

The conditions inside the plastic tent would be different from those of the ambient environment. The plastic material transmits more radiation of shorter wavelengths and the mean air movement in the empty tent is less than 0.05 $m.sec^{-1}$ (one-tenth mile per hour) (Swanson and Lee,1966). This poses a number of problems. Some instruments, like the psychrometer, need an air movement speed of at least $5m.sec^{-1}$ for constant readings (Hoffman,1979). Slower ventilation speed will influence the vapour pressure and diffusion resistance which affect transpiration (Thurtell,1979).

The ground cover may influence the readings and the method may give evapotranspiration rate instead of the transpiration rate of a single tree. To overcome this problem, a separate, identical tent could be erected immediately next to the one enclosing the tree. This second tent would measure the evapotranspiration rate of the ground cover vegetation and the difference between the two tents gives the transpiration rate of the single tree (Swanson and Lee,1966). Alternatively, the lower edge of the tent could be gathered in closely around the tree base to eliminate measuring the evapotranspiration of the whole plot (Decker and Skau,1964).

4.4.3 Sap flow method

Measurement of the velocity of the sap flow in tree trunks has been used to estimate the transpiration rate of big trees in the field. Methods for detecting and measuring the sap flow include dye injection, radioactive tracers, heat transport (heat pulse method) and the latest technique depends on the principle of magnetohydrodynamics (Meidner and Sheriff, 1976).

Of all these methods, the heat pulse method is non-destructive, causes little harm to the tree and seems to be most satisfactory (Kramer and Kozlowski, 1979). In this method, heat is applied to the tree trunk by inserting a small electric heating unit under the bark. A thermocouple is placed above the heating unit to measure the time required for the heated sap to reach the thermocouple. This is taken as the rate of sap flow. Another temperature sensor is placed below the heating unit so that the factors of heat convection and conduction are taken into consideration.

Ladefoged (1960) found that the time taken for the heat to travel from the heating unit to the heat sensor is dependent on the velocity of the transpiration rate. The time interval increases as the transpiration slows down. To relate the sap velocity to the water absorption rate, Ladefoged (1960) cut the tree and stood it in a bucket of water. He then made simultaneous measurements of the sap velocity and the decrease of water in the bucket. He established a good correlation between the sap velocity and the water consumption of the tree during the experimental period. However, such a method is destructive as the tree has to be cut.

Decker and Skau (1964) made simultaneous measurements of sap velocity by heat pulse method and transpiration rate, by tent method, and found that the sap velocity was closely correlated to the actual transpiration rate for intact trees.

It thus appears that to give a quantitative measure of transpiration loss, sap flow method has to be used in conjunction with some other methods. By itself, the sap flow method can be a reliable indicator of the direction of rapid changes in transpiration rate and at best, as an indicator of the relative magnitude of gradual changes in the transpiration rate (Decker and Skau,1964). The limitation of the tent method as a measure of transpiration loss has already been discussed. A non-destructive method will have to be found which can translate the linear velocity measurements into volumetric flows. This requires relating the velocity values to the flow pattern in a tree stem. Herein lies the problem with this method. The water-conducting system of a tree is very complex and it is not easy to measure the sap velocity,in a way that is representative of the total fluid flow,for the proportion of the total cross section of the tree trunk involved in water conduction. Hence, short of cutting down the tree, linear velocity measurement may not enable reliable extrapolation to volumetric flows for the whole tree.

CHAPTER 5

PROCEDURES FOR DETERMINING THE WATER REQUIREMENTS OF TREES IN PAVED AREAS

5.1 INTRODUCTION

The particular problems leading to the initiation of this study were discussed in Chapter 1 and the aims of the study stated.

In Chapters 2, 3 and 4 procedures for measuring soil water, evapotranspiration and transpiration were described.

The selection of appropriate procedures for determining the water requirements of trees in paved areas in Singapore is discussed in this chapter.

5.2 SELECTION OF METHODS

5.2.1 The context of selection.

The purposes of evaluating water requirements are, in the context of this study, twofold.

(1) In the case of existing trees to know when it is necessary for irrigation water to be applied and how much should be added for efficient application of the water.

(2) In relation to planning for the water requirements of proposed street tree plantings, to provide information for the consideration of engineering design of drainage works associated with road construction which would ensure adequate water for the trees.

Knowledge about soil water depletion at the root zone is important for determining when and how much water is needed for tree growth. However, care must be exercised in interpreting soil water depletion at the root zone as it is erroneous to assume that a soil water depletion at the root zone must mean internal water stress of the tree. Nevertheless, it should be noted that as long as the soil water content is 'high', a tree can compensate for excessive water loss during the day by a low rate of transpiration at night, eliminating any internal water stress that may have developed (Kramer and Kozlowski, 1960). On the other hand, if the soil water content is low, leaves may not regain turgidity at night and this leads to permanent wilting (Slatyer, 1967).

Measurements of both soil water content and soil water potential have been used as parameters to indicate soil water depletion and hence the need to irrigate (Sachs et al., 1975; Richards and Marsh, 1961).

It was noted in Chapter 2 that the water available for use by a plant is that between field capacity and permanent wilting percentage. This amount is related to the soil properties. Seemann (1979c) indicates that for any particular soil, the optimal water supply for agricultural plant growth is attained if the available water content at the root zone is between 50 and 80%.

Aesthetics is a most important aspect of landscape plantings while biological production is usually not. Thus the irrigation requirements for such plantings could be quite different to those for agricultural crops (Sachs et al., 1975) but the literature review associated with this study suggests that they have not been closely or widely investigated. Nevertheless, the concept of defining a range of available water content as a criterion for the irrigation of street trees seems a useful approach in practice but this requires investigations at specific planting sites if soundly based watering requirements are to be defined.

It is important to note that a high soil water content may be more damaging than a low water content for high water content may reduce the aeration in the soil. This in turn may have a severely detrimental effect on root growth (Grable and Siemer,1968) and water absorption (Letey et al.,1961). Thus it is important that, any specification of the range in the available water content in the soil, be within that considered as optimal for plant growth.

Sachs et al.(1975) used gravimetric soil water content as an indication of soil water status in experiments for determining the minimum irrigation requirements for landscape plants. Gardner and Lambert (1973) reported that soil water content measurements have often been used to obtain an estimate of evapotranspiration, provided that the water flux across the bottom of the root zone can be neglected.

Apart from soil water content, soil water potential has also been used to provide an indication of the depletion of available water in the root zone of plants. Sekiguchi et al.(1973) used tensiometers to study the soil water depletion at the root zone of street trees under pavements. This work is discussed later. Soil water potential has become an important criterion for irrigation and many irrigation programs now involve adding water to soil when the soil water potential reaches a predetermined value considered appropriate to a particular plant (Gardner,1964).

The above mentioned methods of in situ soil water measurements, that is of soil water content and soil water potential, do not measure how much water is used by the tree in the transpiration process unless the water flux across the bottom of the root zone can be eliminated or also measured. This could require the installation of a lysimeter for it is very difficult to measure the water flux across the bottom of the root zone. Hillel (1973) commented that for many soils, tensiometer measurements indicated that there are appreciable potential gradients below the root zone and water can contribute to the root zone by either downward percolation or upward seepage from the groundwater. Under such conditions, it is not possible to determine transpiration loss from a mere measurement of the soil water content.

Alternatively, methods such as those described in section 4.3 could be used to give an indication of water flux through the tree itself rather than that through the soil. However, as discussed below, site constraints severely limit the applicability of most of these methods.

5.2.1.1 Space at street tree planting sites.

Tree planting strips along most streets are often no more than 2-m wide verges with kerb foundations and underground utility lines on either side of the green verge. The installation of lysimeters would not be practicable in such locations, not only because it involves breaking up the tarmac or concrete pavement, but also because of limitation of space. Tensiometers, gypsum blocks and neutron probe tube housings could be installed at these sites for their installation would not require extensive disturbance of the pavement and extensive working space, but vandalism may present problems. However, if the trees at the site are large matured specimens having a large root ball or a wide and wild root spread then even these methods may become impracticable.

On the other hand, it could be possible to instal lysimeters in, for example, car parks and pedestrian malls where space would not usually be as limiting as along streets. In Singapore a car-parking space measures 2.5m x 5m and this area could be converted into an in-situ lysimeter. Constant vehicular movement may make weighing lysimeters impracticable or inaccurate and volumetric lysimeters as described by Gangopadhyahy et al. (1966), may be used instead.

Ventilated tents or chambers have been applied to the measurement of transpiration of both large and small trees. There seems no practical reasons why they should not be applied to some street tree situations, but crown spread may limit their application to some trees, for the scaffolding necessary to support the plastic sheath must encompass the periphery of the crown and this may cause unacceptable obstruction to the public.

5.2.1.2 Costs.

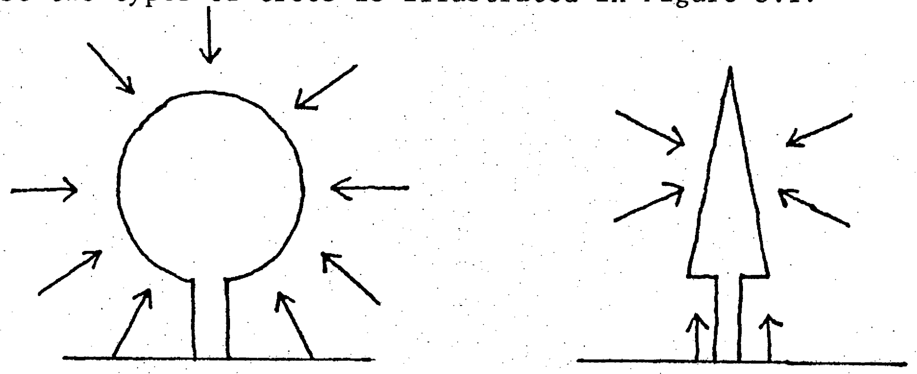
The selection of instruments and procedures to investigate water requirements of street trees in Singapore must be undertaken in relation to the funds that may be available. These will be quite limiting and it is accepted, given the need for replication of measurements in terms of species, age of trees and planting sites, the instruments selected must be flexible in application, and are appropriate to both large and small trees at a range of site conditions.

Lysimeters and ventilated tents are not flexible although ventilated tents are the more flexible in a relative sense. Although for young trees lysimeters could be constructed fairly cheaply, the information would be of limited value given the range in age of trees for which water requirements must be determined.

5.2.1.3 Meteorology.

The various methodsfor estimating evapotranspiration based on meteorological information were described in Chapter 4 and some reasons why they may not be appropriate were indicated. Apart from those reasons, the geometric shape of the isolated single street tree must also be taken into consideration.

In the case of a rounded or oval shaped tree the tree canopy receives not only the direct radiation from the sun and the diffused radiation from the sky, but also the radiation emitted by the surrounding environment and especially by the soil. Hence, both the top and the underside of the tree canopy receive radiation. However, for a fastigiate tree the contribution of radiation from the soil is negligible in comparison to the other components (Primault, 1979), and therefore, under the same climatic condition, it receives less radiation than the rounded tree. The difference between the energy received by these two types of trees is illustrated in Figure 5.1.



(A) (B)

(A) A spherical shape tree receiving radiation from both the atmosphere and the ground.

(B) A conical or fastigiate shape tree receives radiation mainly from the atmosphere and less from the ground.

Figure 5.1 The effect of the geometry of isolated trees on radiation reception.

Source : Primault, 1979.

The influence of temperature, air humidity, wind and precipitation on isolated trees in relation to their geometric shape is also discussed by Primault (1979). It is not only the geometric shape itself that plays an important part but the size of trees of similar geometric shape will also, of course, influence the transpiration rate.

It would be very tempting to assume that evapotranspiration from moist land, irrespective of its cover, is equal to the evaporation rate which is determined by prevailing weather. Schulz (1976), for example, suggested that 'it is only logical that there should be good correlation between transpiration and pan evaporation,' and therefore climatic factors, and that the empirical formulae presented in the literature could be used to predict evapotranspiration.

However, merely taking meteorological data from the recording stations and applying them to the various empirical formulae presented in Chapter 4 would give the same transpiration rate for both a huge tree and a small sapling because the meteorological data would be the same for both trees and it is clear that the actual transpiration would be dependent on the size.

The major misconceptions in the use of these formulae have been given by Lee (1980). The unquestioned use of them in areas and conditions in violation of even the superficial restrictions originally imposed on them cannot be regarded as appropriate and therefore, their application to the problem of estimating the water requirements of isolated trees in urban areas seems unacceptable.

Fitzerald and Rickard (1959) state that if these methods have to be used, they must be counter-checked with measurements of soil water deficit by the gravimetric technique to see if they are applicable to the local conditions. Thus, given the need for checking and that total water irrigation must allow for drainage of water from the site, percolation to the root zone from other water sources and the possibility that the tree roots will have access to groundwater, it is considered that other procedures must be adopted at least initially.

However, it is noted that in the longer term it may be possible for direct measurements of soil water depletion at street tree planting sites to be correlated with appropriate climatic data that is relatively easy to record, and the above discussion does not suggest in any way that meteorological information would not be useful in the study of water requirements and that it need not be collected or consulted. The discussion dimply highlights that there is no reliable method of estimating evapotranspiration rates based solely on simple weather data and the problem is to find the empirical relation between them.

In Singapore the daily weather is fairly constant and there is not a great variation annually. The mean monthly temperature does not vary by more than 1.1°C from the annual value of 26.6°C and the average diurnal variation of temperature is 6.7°C (Singapore Meteorological Service Report, 1976). Hopefully, the transpiration rates of single trees can be correlated with some simple weather data and, taking into account biological factors such as the size of the canopy and the shape of the tree crown and predictions of water available from the ground water or percolation, the irrigation water requirements may be predicted with some degree of accuracy. Such information and guidelines will only emerge after many years of field observation, data collection and analysis.

5.2.2 Some General Conclusions

In relation to the defined purposes of this study, the limited availability of space for instrumentation at street tree sites, the costs, and the possibility of predicting irrigation water requirements for street trees solely from meteorological data, it is concluded that measurement of soil water depletion, and to a limited extent, the use of lysimeters are the most appropriate methods for further considerations. Measurement of soil water depletion is discussed in the following section in relation to :

(a) the selection of methods for irrigating existing trees,

(b) planning for the water requirements of proposed street tree plantings.

5.2.3 Selection of methods for determining the water requirements for irrigating existing trees.

5.2.3.1 Measurement of soil water depletion.

(A) By measuring soil water potential.

Among the many instruments discussed in Chapter 3, tensiometers have been used very successfully for monitoring soil water depletion in root zones of fruit trees in orchards (Richards and Marsh, 1961) and street trees under pavements (Sekiguchi et al., 1973). The latter work is, of course, of particular interest in this study.

Richards and Marsh (1961) reported on some irrigation programs for fruit trees based on tensiometer readings. They monitored the change in the measured soil water potential at the root zone over time and applied irrigation water when the soil water potential reached -0.5 bars (they used soil suction and the information is quoted as 50cb). According to the moisture retention curves given by them (see Figure 2.4), this corresponds to a 30 to 70% available water depletion for most soils except clay. They stated that it is often considered desirable for irrigation when 50 to 75% of the available water is depleted.

If 50% available water depletion was chosen as the value at which to irrigate, then according to the moisture retention curves shown in Figure 2.4, the water potential for the soils (except clay) would range from approximately -0.3 to -0.8 bars. In this procedure, irrigation would continue until the soil water potential increases to a predetermined value.

For deep rooted street trees a tensiometer for measuring water potential should probably be installed where there is the maximum root proliferation in the soil profile but of course,in practice,this would have to be determined as a matter of experience and judgement. More accurate indications of soil water depletion could be obtained by installing tensiometers at two depths, the upper and lower root zone. Tensiometer readings obtained by Sekiguchi et al., (1973) are shown in Figure 5.2. If tensiometers were installed at various depths down the soil profile of the root zone than it would be possible to follow the pattern of the depletion of the soil water for the entire root zone over a period of time.

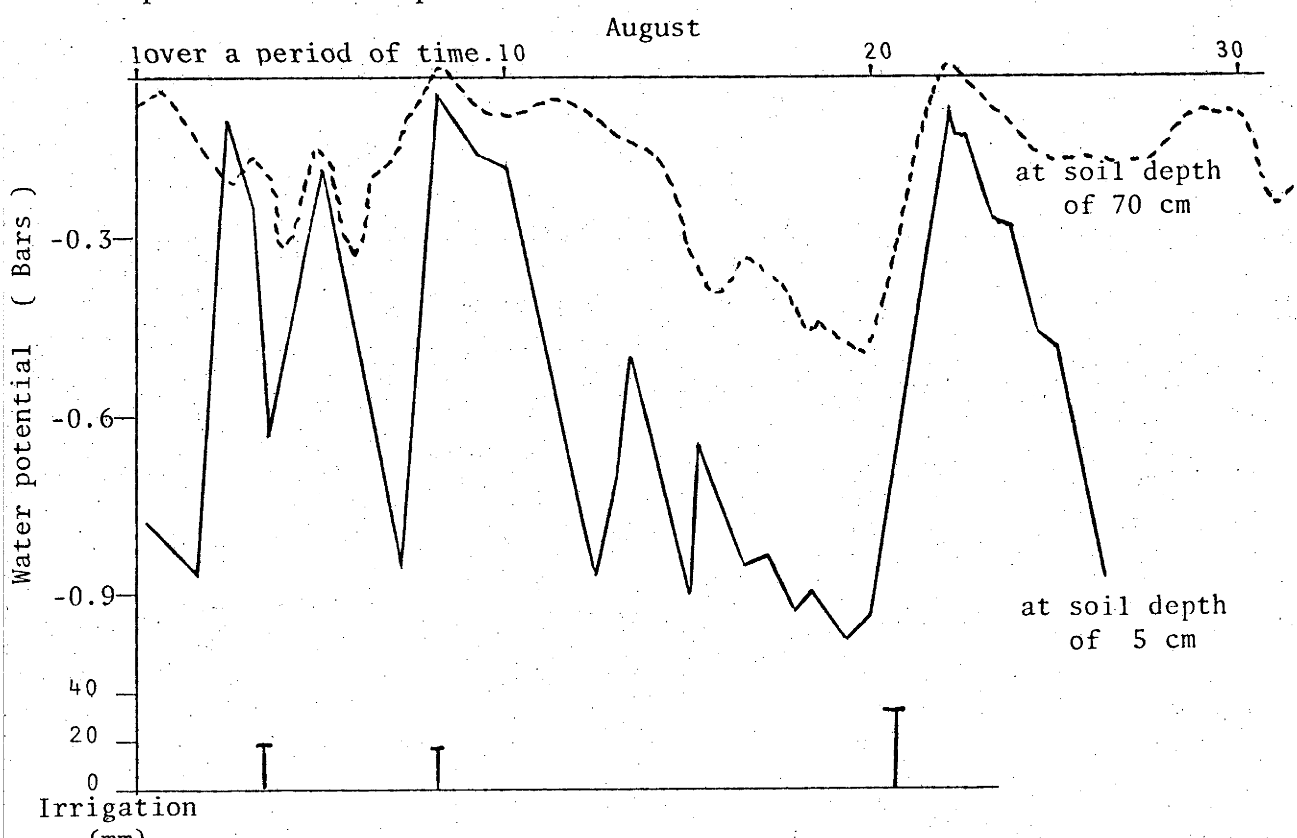


Figure 5.2 Tensiometer readings at 2 depths of soil profile under asphalt pavement.

Source : From Sekiguchi et al., 1973.

Efficient irrigation programs can be planned around two tensiometer readings. For example, with two tensiometers, a light and short duration irrigation could be applied when the top tensiometer drops below a predetermined water potential. When both top and bottom tensiometers show low water potential readings then a thorough irrigation aimed at bringing the entire soil profile back to the originally desired water potential could be carried out. Figure 5.3 shows, for example, an irrigation program for an avocado orchard based on tensiometer readings at two depths and shows that thorough watering of the entire 60cm deep soil profile was only carried out at each third irrigation. Figures in parentheses show the duration of irrigation in hours.

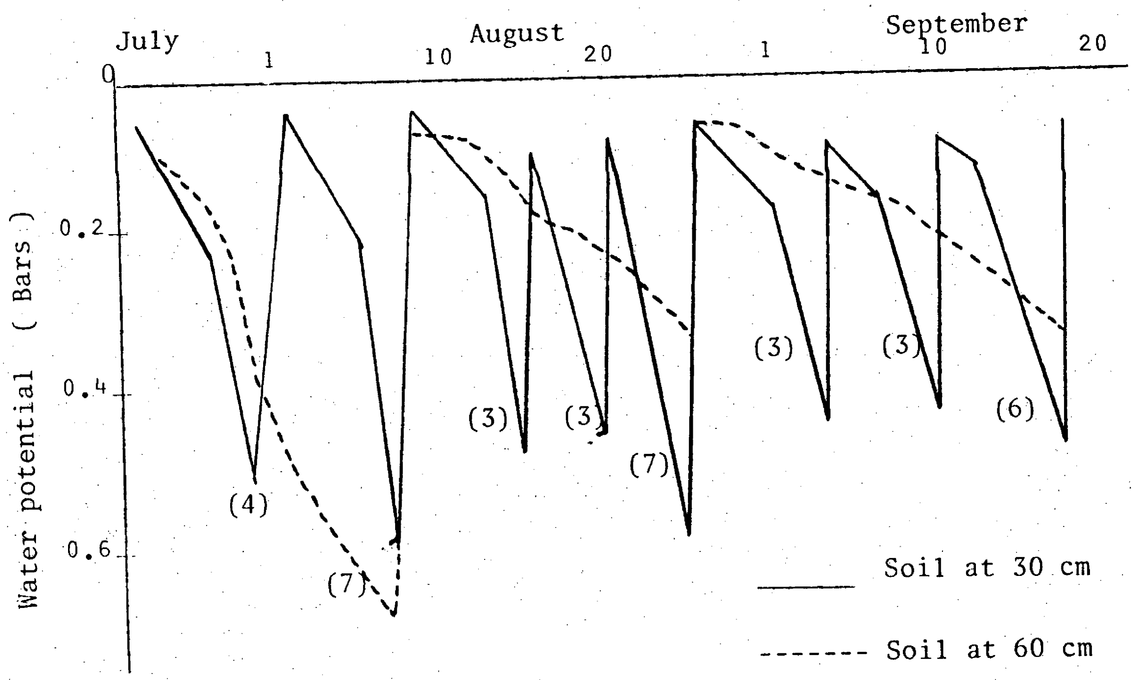


Figure 5.3 Irrigation program for an avocado orchard based on tensiometer readings at 2 soil depths. Thorough wetting of the entire 60cm deep soil profile is only carried out at each third irrigation.

Source : From Richards and Marsh, 1961.

There are no practical problems associated with the use of tensiometers that would preclude their use in urban areas and ,as indicated, Sekiguchi et al. (1973) have already used them in paved areas. To instal a tensiometer,a hole is made in the soil to the desired depth using a soil tube, an auger or solid iron pin if the soil is hard. It is important that the ceramic cup of the tensiometer be in contact with the soil and oversized holes must therefore be avoided.

Urban soils may be compacted and may contain many large stones and other hard objects (Hamilton,1979), and the installation of tensiometers would then be more difficult. In such cases, the hole is excavated with a trenching spade to the desired depth, the cup is placed in firm contact with a side of the hole without stones or hard objects and the initial backfill for covering the tube is made with excavated material from which the stones have been removed.

Tensiometers are subject to errors from temperature changes Reeve, 1973) and urban areas may be subject to higher temperature fluctuations (Bernatzky, 1978) (see Figure 5.4). There are tensiometers made of plastics,which are poor conductors of heat relative to metal, and they should therefore be considered for use in urban areas.

(B) <u>By measuring soil water content.</u>

Soil water depletions at the root zone could also be monitored by measuring soil water content changes with a neutron scattering meter. The use of the meter for measuring water content is described in Chapter 3.

Application of the meter to determining irrigation requirements is contingent on relating the measured water content to criteria such as field capacity and permanent wilting percentage. From these,the available water content is calculated and used as a criterion in determining irrigation requirements.

Bulk density of the soil must be determined because it is used for

a) converting the gravimetric water content to volumetric water content by the expression

$\theta_v = \theta_m \cdot \rho_b$ (see Appendix 3.2, Eq. 2-4)

where

θ_v is the volume water content,

θ_m is the mass water content and

ρ_b is the bulk density of the soil.

b) correlating (as discussed below) the reading of the neutron probe with gravimetric water content.

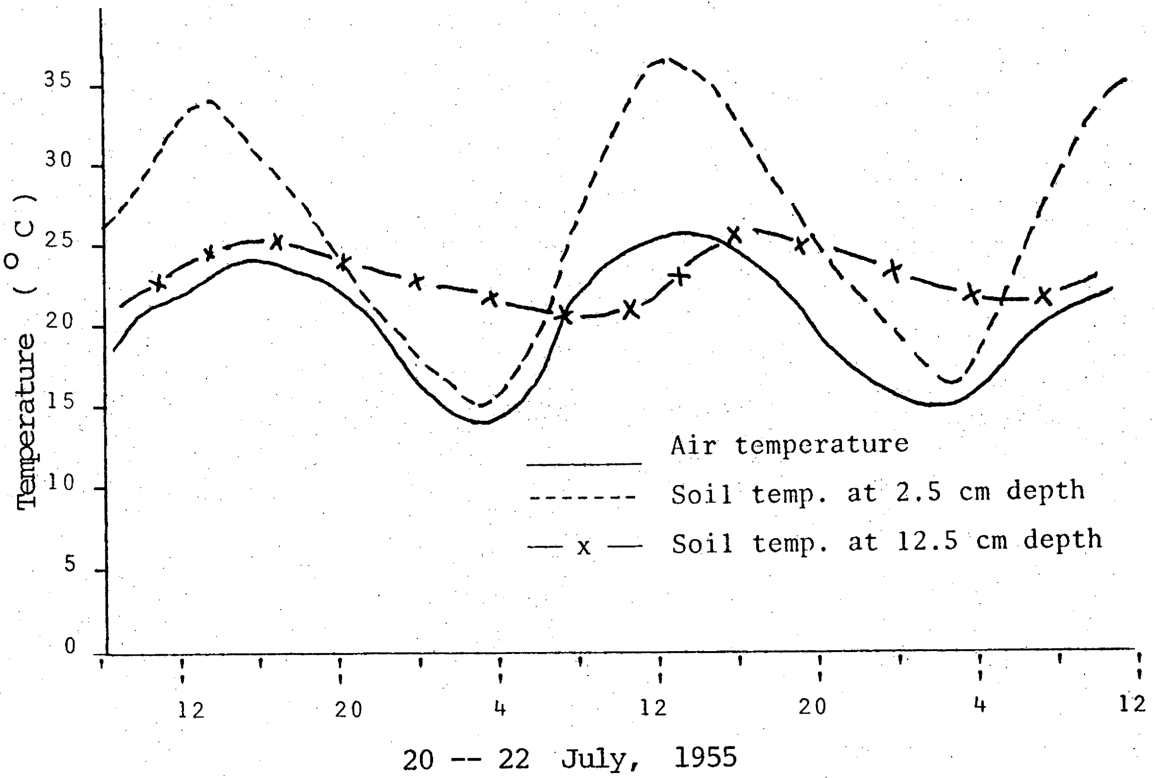


Figure 5.4 Daily course of air and soil temperature at different depths of urban street soils.

Source : Bonnermann and Rohrig,1971.,qouted by Bernatzky,1978.

It has already been mentioned in Chapter 3 that the soil water content as read from a neutron meter is affected by soil density. This is illustrated in Figure 5.5.

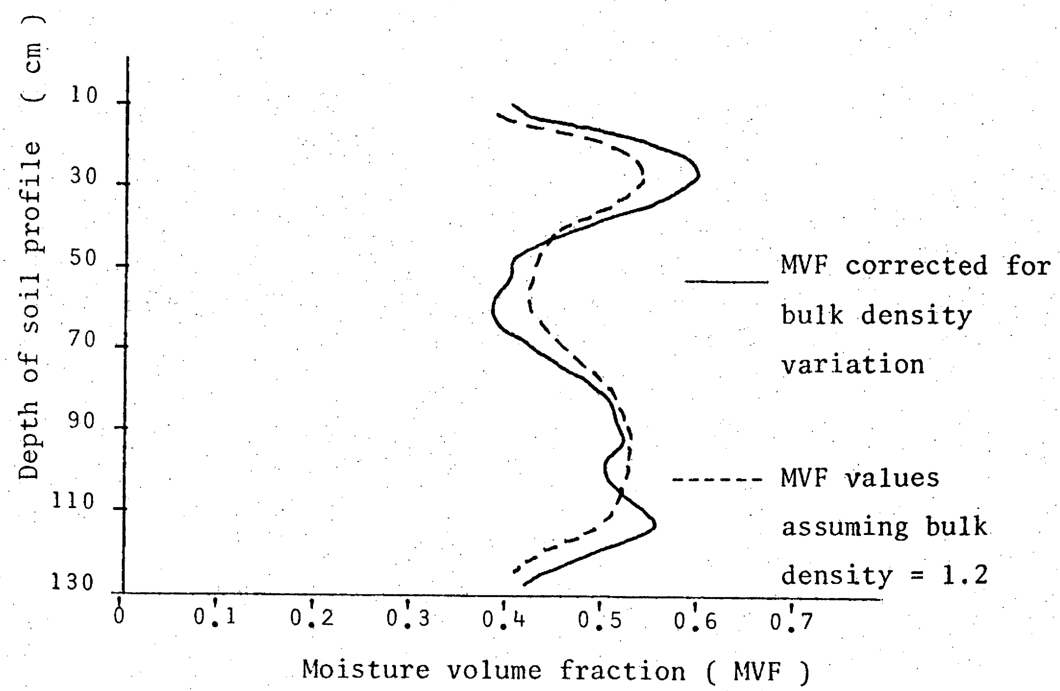


Figure 5.5 Soil water content of a soil profile as indicated by neutron meter reading with and without correction for bulk density.

Source : After Bell and McCulloch, 1969

By determining the bulk density corresponding to the standard count rate of the neutron scattering meter, the count rate can be converted to water content by relating the readings to the various bulk density curves as illustrated, for example, in Figure 5.6.

The field capacity of soil at the site can be determined by using the standard gravimetric method described by Peters (1973). It involves selecting a field site of approximately 2.5m x 2.5m of the soil to be measured, placing a raised border around it and wetting the soil of the entire sampling area to the depth of the root zone.

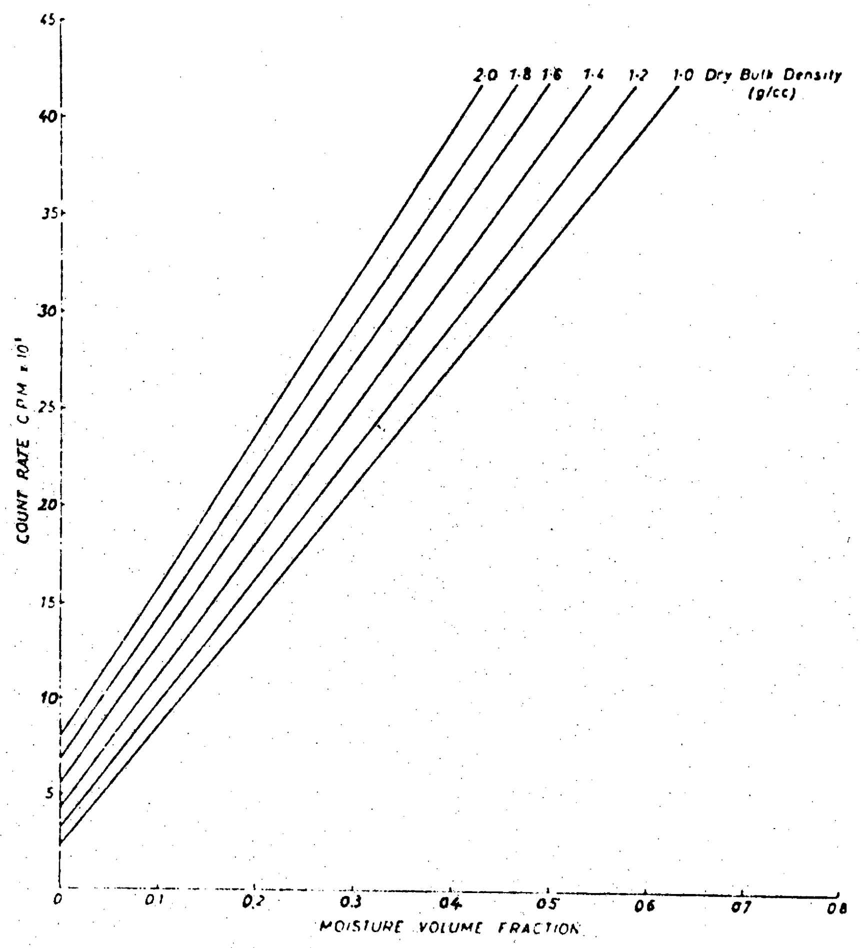


Figure 5.6 Family of calibration curves for correlating soil water content with neutron meter readings for soils of differing bulk density.

Source : From Bell and McCulloch, 1969.

The surface is than covered with plastic sheets to prevent evaporation. After two days,the plastic sheet is removed and the water content is taken by either gravimetric technique or neutron scattering meters. The water percentage at the time of sampling is taken as the field capacity. While the method is primarily intended for shallow rooting irrigation crops,it would be applicable at street tree planting sites provided that ponding is long enough for the water to penetrate into the root zone.

Determining the permanent wilting percentage for street trees presents some problems. Symptoms of water stress in trees vary with species and not all tree leaves will wilt when under water stress, for example, palm fronds and some eucalyptus. Even if leaves do wilt, the wilting may be due to a transient inability of the water supply system in the tree to meet the transpiration losses, rather than to soil water stress.

Although the leaves of some trees may change color under water stress, for example, shiny leaves becoming dull, bright leaves turning gray-green, and there may be heavy leaf fall and even death of young leaves. This kind of visual symtom diagnosis is just like the hand-feel test commonly used for checking soil water and gives only a very crude indication of when to irrigate.

As explained in Chapter 3, irrigation program should aim at maintaining an optimum soil water status and not to wait until the soil water has depleted to permanent wilting percentage. A more practical approach, as a starting point to further studies of trees in paved areas, is to take the permanent wilting percentage as approximately 50% of field capacity (Sachs et al., 1975). Hence, by monitoring the water content of the soil profile at the root zone, irrigation would be deemed necessary when the soil water content falls below 50% of the field capacity value for that particular soil, as determined by the procedures after Peters (1973) (op cit above).

The assumption is, of course, that the tree is not deep rooted with access to groundwater for in such circumstances, water would be available to the tree even when water potentials in the soil profile indicate water content well below the permanent wilting percentage.

5.2.4 Selection of Methods for Proposed Street Tree Plantings

5.2.4.1 Lysimeter method.

The most promising method for estimating transpiration loss of a single street tree is the volumetric lysimeter installation. As explained previously ,this would be practical in car parking lots and plazas where enough space is available.

The soil profile in car parks would usually be compacted to attain the required strength and according to engineering specification. This type of structureless and compacted soil is not conducive to root growth. It is a common practice for tree planting holes in these situations to be backfilled with good, friable top soil. As the soil is backfilled, it can be packed more evenly to achieve a more constant bulk density profile. This is an advantage because the volumetric lysimeter has to be used in conjuction with either the neutron scattering meter or the tensiometer to monitor the root zone soil water depletion,and by setting a fixed bulk density for the soil in the lysimeter, the complication of bulk density influenceing the neutron count rate would be avoided.

Water could be applied to a lysimeter by means of a watering tanker. Water content corresponding to field capacity would then be determined by using a neutron probe two to three days after the lysimeter has been thoroughly soaked and brought up to saturation point. When the drainage collected below the lysimeter begins to decrease, it can be assumed that the soil in the lysimeter is at field capacity. The surface of the lysimeter should be covered for the determination to prevent evaporation from the soil surface. The depletion of water content, minus the amount collected from drainage, is equated to transpiration loss. Preferably, more than one neutron probe sampling should be taken.

5.2.4.2 Cut shoot,sap flow and ventilated tent methods.

It has already been explained that the above methods would not be the most suitable for determining the water requirements of trees in paved areas. The cut shoot method is more of a laboratory procedure and suitable for smaller plants. The sap flow method requires the cutting down of trees for converting the transpiration rate to the actual amount of water consumed. The tent method does not give the actual transpiration loss as the environment in the tent is different from that of the ambient environment. It can, however, be used for comparing transpiration rates of two separate plants at the same location, both kept in the tents. But this is not the aim of this study.

CHAPTER 6

SUMMARY

6.1 INTRODUCTION

This study was carried out to assist in solving a practical problem of evaluating the water requirements of trees planted in streets and other paved areas in urban cities.

Increased public awareness of the importance and benefits of tree-planting and the work of town planners and administrators has resulted in more trees being planted in urban areas. Because of the lack of planting space, many of these urban trees are planted in narrow green verges abutting pedestrian footpaths or in the median strips of carriage ways but even more trees are planted in paved areas like car parks, pedestrian malls and shopping plazas. Trees planted in paved areas have their root system growing under paving materials impervious to air and water and it is common practice to improve the growing conditions by leaving an unsealed area around the tree collar, for aeration and water penetration and to provide space for trunk growth. However, it is questioned whether the relatively small unsealed openings are large enough to take in sufficient water for the tree's growth and suggestions are made to increase the unsealed area and even to install underground pipes to channel more water from surface runoff to the root zone. There is thus a growing concern among the tree-lovers about the water requirements of street trees planted in paved areas and, in Singapore, there is an expressed need for accurate information to ensure adequate watering of the street trees.

6.2 LITERATURE REVIEW

The literature review for this study revealed little scientific research on the water requirements of trees in paved areas. There is no lack of information on water-plant relationships for agricultural crops, horticultural plants and forest trees. Many studies have also been made concerning evapotranspiration loss and its effects on the hydrology of a water catchment. On the other hand, literature on the water loss of landscaping plants, in particular urban trees, is very scanty.

6.3 THE STUDY AIMS

Given the lack of studies,specifically in relation to watering trees in urban environments,the aim of this study was to critically examine the various methods for estimating water loss by plants and to propose methods suitable for estimating the water requirements of street trees. There were two main reasons for the exercise. Firstly, accurate knowledge of the amount of water lost by a single tree would provide a sound basis for the design of the road camber, gutters and other drainage works to channel more water from surface runoff to the trees where the natural precipitation is not enough to support the tree growth and the tree does not have access to groundwater. Secondly, reliable knowledge of when the tree is under water stress and the amount of water it needs would enable watering routine to be better planned in terms of timing and the amount of irrigation water applied.

6.4 METHODS FOR ESTIMATING THE WATER REQUIREMENTS OF STREET TREES

There are two main approaches by which water loss by a plant community, known as evapotranspiration, can be estimated. One is to consider the water budget in the soil at the root zone of the tree and, from the change in water content in the soil, deduce the water consumption rate by the tree. The second is to estimate the amount of water loss by assuming that the rate at which water is lost from a plant is determined mainly by the climatic factors and therefore to base the estimation on meteorological data.

6.4.1 Methods based on soil water measurements.

There are three methods for estimating water uptake by trees from soil data.

(1) The water balance method is more of a hydrological approach and because many of the terms in the equation cannot be measured with certainty in an urban setting, it was concluded that this method would not be suitable for the purposes of this study.

(2) Lysimeters would be suitable but their use is restricted to large areas like car parks, the malls or plazas where space is not limited. By covering the soil surface and collecting the drainage water, they can give estimates of water loss through transpiration of the tree in the lysimeter. For practical reasons, the tree must be small with a small root ball, otherwise the lysimeter will restrict root growth.

(3) In situations where groundwater is deep enough not to influence soil-water fluctuations within the root zone, and where due to site constraints the installation of lysimeters is not practical, then the depletion of soil water as calculated

from water content changes measured by neutron scattering meter or tensiometer between two sampling times, can be taken as the water loss due to plant consumption.

6.4.2 Methods based on meteorological data.

Methods that make use of meteorological data for estimating water loss by plants are the aerodynamic-profile method, the energy balance method, the combined method and the empirical method. All these methods were developed for use in ideal conditions, that is, where the plant cover is complete, water is not limited, root depth is shallow, the plant is short and the area under investigation is large. All these assumptions are invalid for a single tree growing in a paved area. Moreover, the urban climate is very complex with substantial climate variations due to factors like street orientation, building shielding and heat advection. Furthermore, the geometric shape and the size of the tree will influence the amount of radiation it will receive. One cannot, therefore, just take meteorological data from recording stations and apply them to estimate water loss by individual trees in the urban cities.

Many workers have warned against the unquestioned use of these formulae to areas with different climate from which these formulae were originally developed.

6.4.3 Methods based on measurements of water flux through the tree itself.

Instead of making use of soil or meteorological data, another way of estimating water use by a street tree is to measure the water flux through the tree itself. This actually measures the transpiration loss and there are many methods by which this could be done. Methods examined in this study were those that could be used in the field, and which do not require sophisticated instruments and laboratory techniques. These are the lysimeter, the quick-weighing method, the water vapour loss method and the sap flow method.

The quick-weighing method, also known as the cut-shoot method, is good for small plants but it is not appropriate for street trees. Cutting the branch from the tree changes the physiological condition of the plants, while weighing it in a special balance exposes it to a different environment from the ambient environment which the entire tree experiences. Both these factors will influence the transpiration rate so measured. Moreover, there is the problem of selecting the right branch, as it is known that different protions of a tree transpire at different rates.

The water vapour loss methods require that the tree under investigation be placed in a transparent plastic tent. The transpiration rate is calculated from the difference in the water vapour contents of the incoming and outgoing air streams. Here again, the tree is exposed to an artificial environment. The technical problem of this method is the erection of a tent big enough to encase the street tree and the maintenance of the air stream.

The sap flow method, also known as the heat pulse method, gives good correlation between the measured sap velocity and the amount of water lost by the tree. Unfortunately, it requires that the tree be cut so that the water-uptake can be determined separately. This would not be practical in street tree investigations and non-destructive method of correlating the linear velocity rate to volumetric water consumption have yet to be developed.

6.5 REVIEW AND CONCLUSIONS

From the foregoing discussion,it is concluded that the methods most suitable for evaluating the water requirements of street trees are connected with soil water measurement. In measuring soil water content, field capacity and permanent wilting percentage are two parameters that are of importance because from them, the available water content which is useful in setting irrigation program is calculated.

It is suggested that measurements of soil water content be made by a neutron scattering meter or by gravimetric sampling. Soil water status could also be indicated from soil water potentials which can be measured by tensiometers.

Seen in the context of this study, two methods are selected for evaluating water requirements of street trees in Singapore.

The lysimeter method gives indications of water loss due to the transpiration process and would assist in specifying the amount of water needed.

The soil depletion method, by measuring either soil water content or soil water potential, can give information on whether or not the soil is depleted of water. This helps in determining the timing of irrigation.

It is expected that long term field observation, data collection and analysis will have to be carried out before any accurate figures on water requirements of street trees can be obtained. Hopefully, some empirical relationship will be established between the water use figures and the meteorological data for the local condition under investigation.

APPENDIX 2.1

UNITS IN WHICH WATER POTENTIAL HAS BEEN EXPRESSED.

A.	Energy per unit mass	Joules. Kg^{-1}
		Erg. g^{-1}
B.	Energy per unit volume	Dyne. cm^{-2}
		lb. in^{-2}
		centibar (cb)
		millibar (mb)
		Bars
		Atmosphere(atm)
C.	Energy per unit weight	cm of water
		cm of mercury

D. pF scale (equivalent height of water in cm, with logarithm)

$$pF = \log_{10} h, \text{ where h is cm water.}$$

The concersion of these units, with reference to bars, is as follow:

1 bar = 10^2 joule. kg^{-1}

10^6 erg. g^{-1}

10^6 dyne. cm^{-2}

10^2 cb

1 atm (approximate)

10^3 cm water (approximate)

Source : Hanks and Ashcroft, 1980. p.35.

APPENDIX 2.2

CALCULATION OF SOIL WATER CONTENT

Assume that in a cube of soil, with side D and area A, all the solid particles have been compressed to depth c, the soil water to depth b, and soil air to depth a. (see Figure A-1).

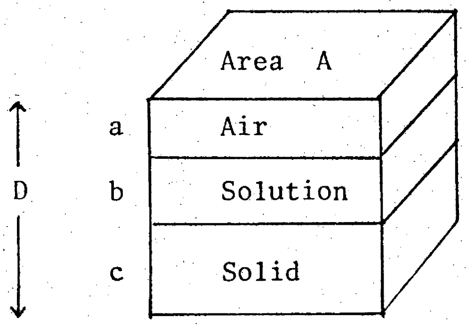


Figure A-1 Diagrammetic representation of a soil column separated into solid, liquid and gaseous phases.

Source : Hanks and Ashcroft, 1980. p.4.

Total depth	(D)	$= a + b + c$
Volume air	(V_a)	$= aA$
Volume water	(V_w)	$= bA$
Volume dry soil	(V_d)	$= cA$
Total vol. of soil	(V_t)	$= V_a + V_w + V_d = (a + b + c)A$

Let

$$\rho_w = \text{density of water} \simeq 1$$

$$\rho_p = \text{particle density} = \frac{\text{wt. of dry soil}}{\text{vol. of dry soil}}$$

$$\rho_b = \text{soil bulk density} = \frac{\text{wt. of dry soil}}{\text{total vol. soil}} = \frac{\rho_p . cA}{AD} = \frac{\rho_p . c}{D}$$

Therefore,

Volume water content (θ_v)

$$= \frac{\text{vol. of water}}{\text{total vol. of soil}}$$

$$= \frac{bA}{(a + b + c)A} = \frac{b}{D} \quad \text{-----Eq.2-1}$$

Mass water content (θ_m)

$$= \frac{\text{mass of water}}{\text{mass dry soil}}$$

$$= \frac{\rho_w \cdot bA}{\bar{\rho}_p \cdot cA} = \frac{b}{\rho_p \cdot c} \quad \text{-----Eq.2-2}$$

Volume water percentage $(\%\theta_v)$

$$= 100\% \; \theta_v \quad \text{-----Eq.2-3}$$

Mass water content (θ_m) and volume water content (θ_v) is related by the following equation.

$$\theta_m \cdot \frac{\rho_b}{\rho_w} = \frac{b}{\rho_p . c} \cdot \frac{\rho_b \, . \, c}{D \, . \, \rho_w} = \frac{b}{D} = \theta_v$$

Hence,

$$\theta_v = \frac{\rho_b}{\rho_w} \cdot \theta_m = \rho_b \cdot \theta_m \quad \text{-----Eq.2-4}$$

APPENDIX 2.3

WETTING AND DRAINAGE OF SOILS UNDER IRRIGATION.

A soil with a uniform initial water content, θ_{vi}, when irrigated, will first saturate the upper layer of the soil profile due to matric potential differences. After irrigation, water will drain from top layer until its water content reaches field capacity, θ_{vfc}. The drained water then brings the next layer of soil to its field capacity. Hence, the incoming water will wet the top layer of soil first and charge it to field capacity before it begins to add moisture to the layer underneath (Smith, 1975). Conversely, water is always first taken out of the top soil layer. The depth to which the lower soil profile will be wetted depends on the amount of water applied and the amount of water that drained from the upper layer of the soil profile (see Figure A-2).

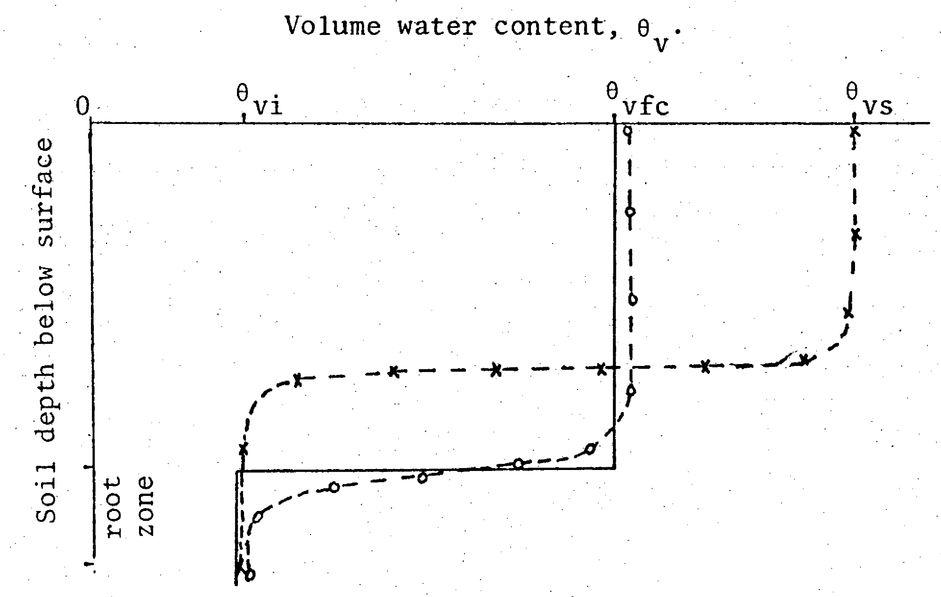


Figure A-2 Drainage of soil under field condition

Source : Hanks and Ashcroft, 1980. p.12.

———— Idealized soil 2 days after wetting.

x ----- x Actual soil immediately after wetting. Note that the upper soil layer was at saturation point but low layer was still at initial water content.

o ----- o Actual soil 2 days after wetting, i.e., at field capacity. It brings the top layer to field capacity and the lower profile at initial water content.

It can therefore be seen that frequent light irrigation will only wet the surface soil to field capacity and then water is evaporated. The soil further down the root zone may still be dry. This results in a maximum rate of water-loss with little water actually reaching the tree roots.

A thorough deep watering is thus better than two shallow ones. Kozlowski (1968) recommended thorough soaking of the soil at approximately weekly interval. Apart from obvious saving of time and labour, deep watering has less evaporation losses and encourages deeper rooting.

APPENDIX 2.4

WATER CONTENT AT FIELD CAPACITY

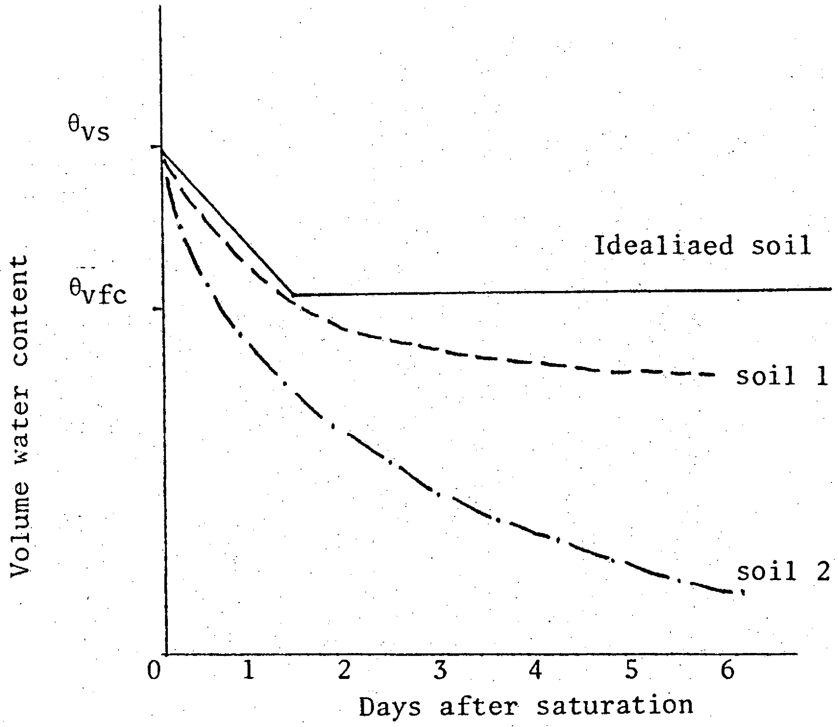


Figure A-3 Field capacity of an idealized soil and volume water content of two actual soils as a function of time following saturation.

Source : Hanks and Ashcroft, 1980. p.11.

Note that the idealized soil reached field capacity (θ_{vfc}) about 2 days after irrigation and the soil water content is held there at constant. This is the definition of field capacity under ideal condition. In actual situations, soil still drain water many days after field capacity has been reached.

Soil 1 is a more clayey soil and has a rather well-defined field capacity.

Soil 2 is a more sandy soil and is still draining after 5 days.

APPENDIX 3.1

CALIBRATION OF NEUTRON SCATTERING READINGS

A simple calibration curve for converting neutron probe reading to volume water content is provided by the manufacturer of the neutron probe. The curve should fit all soils except those with a high clay content and those that contain large amounts of chlorine, iron or boron.

To use the calibration curve, at the linear portion of the curve the volume water content (θ_v) is given by the formula:

$$\theta_v = \frac{1}{S} \left(\frac{N}{N_{std}} \right)$$

where N is the count rate in the soil,

N_{std} is the standard count rate,

S is the slope of the linear portion of the calibration curve, i.e.,

$$S = \Delta \left(\frac{N}{N_{std}} \right) / \Delta \theta_v$$

To counter check the calibration curve with gravimetric measurements,

(a) make a series of readings with neutron probe in a test hole,

(b) at a minimum of 4 positions with 15 cm of the test hole, take gravimetric samples at 8 cm intervals for both bulk density and mass water content determination,

(c) convert mass water content to volume water content by

$$\theta_v = \rho_b \cdot \theta_m$$

(d) determine the average of the 4 readings for each soil depth and plot a curve of volume water content obtained by gravimetric method against soil depth,

(e) plot the similar curve as inferred from neutron instrument readings using the calibration curve provided with the instrument and compare the curves,

(f) if a consistent difference exists between these two curves, a field calibration curve may have to be used.

In the case if the field calibration curves are roughly parallel to the manufacturer's curve then the factory calibration curve could be used for determining relative changes in the soil water content but not for calculating the absolute water content (Rawitz, 1969).

BIBLIOGRAPHY

Anon. 1968. Editorial comment. In Lothian, T.R.N. Sealing Around Trees., Austrain Parks, August, 1968. p.21.

Anon. 1977. Surface moisture-density gauges. 3400 series Instruction Manual. Troxler Electronic Laboratories, Inc. USA.

Baver, L.D., Gardner, W.H., and Gardner, W.R. 1972. Soil Physics. John Wiley & Sons, Inc. New York.

Bell, J.P., and McCulloch, J.S.G. 1969. Soil moisture estimation by the neutron method in Britain. J. Hydrol. 7 : 415-453.

Bernatzky, A. 1978. Tree ecology and preservation. Development in Agricultural and managed-forest ecology 2. Elsevier Scientific Publishing Company. Berlin.

Brarmann, E.F.Jr. 1966. Coping with the problems of plantings and maintenance of street trees in curbside excavations in business areas. Proc. 42nd. I.S.T.C. : 52-64.

Campbell, G.S. 1979. Watering-Critique. II. In T.W. Tibbitts and T.T. Kozlowski (eds.), Controlled environment guidelines for plant research. : 301-317. Academic Press. New York.

Carter, M.C. 1967. Physiology of shade trees under city conditions. Arborist's News. 32(11) : 85-90,92.

Collins, W.H. 1976. Nursery growing practices as related to selection and production of municipal trees. In F.S. Santamour,Jr., H.D. Gerhold., and S. Little (eds.), Better trees for metropolitan landscapes. : 167-177. U.S.D.A.For.Ser.General Tech.Rep. NE-22.

Cotecchia, V., Inzachi, A., Pirastru, E., and Ricchena, R. 1968. Influence of the physical and chemical properties of soil on measurement of water content using neutron probes. Water Resource Research. 4(5) : 1025-1028.

Cox, S.W.R., and Filby, D.E. 1972. Instrumentation in agriculture. Crosby Lockwood & Son. Ltd. United Kingdom.

Creech, J.L. 1976. Some approaches to collecting ornamental trees and shrubs. In F.S. Santamour,Jr., H.D. Gerhold., and S. Little (eds.), Better trees for metropolitan landscapes : 221-226. U.S.D.A. For.Ser.General Tech.Rep. NE-22.

Decker, J.P., and Skau, C.M. 1964. Simultaneous studies of transpiration rate and sap velocity in trees. Plant Physiol. 39 : 213-215.

Denmead, O.T., and Shaw, R.H. 1962. Availability of soil water to plants as affected by soil moisture content and meteorological conditions. Agron.J. 54 : 385-390.

Dudley, T.R. 1976. How to name, register, and patent selected cultivars of amenity trees. In F.S. Santamour,Jr., H.D. Gerhold., and S. Little (eds.), Better trees for metropolitan landscapes.: 235-243. U.S.D.A.For.Ser.General Tech.Rep. NE-22.

Fitzgerald, P.D., and Rickard, D.S. 1960. A comparision of Penman's and Thornthwaites's method of determining soil moisture deficits. N.Z.J.Agric.Res. 3 : 106-112.

Forrester, J.S. 1979. Humidity - Critique II. In T.W. Tibbitts and T.T. Kozlowski (eds.), Controlled environment guidelines for plant research. : 177-192. Academic Press. New York.

Gangopadhyaya, M., Harbeck, G.E., Nordenson, T.J., Omar, M.H., and Uryvaev, V.A. 1966. Measurement and estimation of evaporation and evapotranspiration. World Meteorological Organization Technical Note No.83. WMO - No.201.TP.105.

Gardner, W.H. 1973. Water content. In Methods of soil analysis. PART I. : 82-127. Black, C.A. et al. (eds.), Amer.Soc.Agron. Inc., Wisconsin. USA.

Gardner, W.R., and Lambert, J.L. 1973. Field water balance and water use efficiency. In Soil-moisture and irrigation studies. II. IAEA, Vienna.

Grable, A.R., and Siemer, E.G. 1968. Effects of bulk density, aggregate size and soil water suction on oxygen diffusion, redox potentials and elongation of corn roots. Soil Sci.Soc. Am.Proc. 32 : 180-186.

Hanks, R.J., and Ashcroft, G.L. 1980. Applied soil physics.Advanced series in agricultural sciences 8. Springer-Verlag. Berlin.

Himelick, E.D. 1976. Disease stress of urban trees. In F.S. Santamour, Gerhold, H.D., and S.Little (eds.), Better trees for metropolitan landscapes : 113-125. U.S.D.A.For.Ser.General Tech. Rep. NE-22.

Hillel, D. 1972. Soil and water. Academic Press. New York.

---------. 1973. Discussion in Field water balance and water use efficiency. by W.R. Gardner and J.L. Lambert In Soil-moisture and irrigation studies II. IAEA.Vienna.

Hoffman, G.J. 1979. Humidity. In T.W. Tibbitts and T.T. Kozlowski (eds.), Controlled environment guidelines for plant research. : 141-172. Academic Press. New York.

Holmes, J.W. 1966. Influence of bulk density of the soil on neutron moisture meter calibration. Soil Sci. 102 : 355-360.

Howe, V.K. 1979. Relation of fine root development to shade tree growth and survival. J. Arbor. 5(6) : 130-132.

Kijne, J.W. 1974. Determining evapotranspiration. In N.A. de Ridder et al.(eds.), Drainage principles and applications. Vol III. Surveys and Investigations : 53-111. International Institute for Land Reclaimation and Improvement. Wageningen.

Koshi, P.T. 1966. Soil-moisture measurement by the neutron method in rocky wildland soils. Soil Sci. Soc. Am. Proc. 30 : 282-284.

Kozlowski, T.T. 1968. Water balance in shade trees. Proc. I.S.T.C. 44 : 29-41.

Kramer, P.J. 1969. Plant and soil water relationships. McGraw-Hill Book Co. New York.

-----------., and Kozlowski, T.T. 1960. Physiology of trees. McGraw-Hill Book Co. New York.

-----------., and ---------------.1979. Physiology of woody plants. Academic Press. New York.

Ladefoged, K. 1960. A method for measuring the water consumption of larger intact trees. Physiol Plant. 13 : 648-657.

Lamb, D. 1967. Relationships between environmental factors and the composition of a mountain eucalypt forest in the Australian Capital Territory. M.Sc. Thesis. Department of Forestry. Australian National University.

Landsberg, H.E. 1970. Climates and urban planning. In Urban climates : 364-374. World Meteorological Organization Technical Note No. 108.

Lee, R. 1980. Forest Hydrology. Columbia University Press. New York.

Lemon, E. 1965. Energy and water balance of plant communities. In L.T. Evans (ed.), Environment control of plant growth. : 55-78. Academic Press. New York.

Letey, J., Lunt, O.R.,Stolzt, L.H., and Szuskiewiez, T.E. 1961. Plant growth, water use and nutritional response to rhizosphere differentials of oxygen concentration. Soil Sci.Soc.Am.Proc. 25 : 183-186.

Linsley, R.K., and Franzini, J.B. 1972. Water-resources engineering. McGraw-Hill Book Co. New York.

Meidner, H., and Sherift, D.W. 1976. Water and Plants. Blackie. London.

Miller, D.R. 1980. The two-dimensional energy budget of a forest edge with field measurements at a forest-parking lot interface. Agr. Meteorology 22 : 53-78.

OECD Road Research Group. 1978a Maintenance techniques for road surfacings : assessment, choice of treatment, planning, implementation. OECD. Paris.

------------------------. 1978b. Catalogue of road surface deficiencies. OECD. Paris.

Oke, T.R. 1974. Review of urban climatology, 1968-1973. World Meteorological Organization. Geneva.

Ølgaard, P.L., and Haahr, V. 1968. On the sensitivity of subsurface neutron moisture gauges to variations in bulk density. Soil Sci. 105(1) : 62-64.

Penman, H.L. 1963. Vegetation and hydrology. Commonwealth Agricultural Bureaux. Technical Communication No.53.

Peters, D.B. 1973. Water availability. In C.A. Black et al. (eds.), Methods of soil analysis. Part I. : 279-285. Amer.Soc.Agron. Inc., Wisconsin. USA.

Pook, E.W., and Hall, T. 1974. Application of surface moderators to measurement of water content in field topsoils with a neutron moisture depth gauge. Fld.Stn.Rec.Div.Pl.Ind.CSIRO (AUST.) 13 : 31-42.

Primault, B. 1979. The climate of trees, orchards and forests. In J. Seemann, Chirkov, Y.I., Lomas, J., and Primault, B. (eds.), Agro-meteorology : 152-162.

Rawitz, E. 1969. Installation and field calibration of neutron-scatter equipment for hydrologic research in heterogeneous and stony soils. Water resources research 5(2) : 519-523.

Reeve, R.C. 1973. Hydraulic head. In C.A. Black et al.(eds.), Methods of soil analysis. Part I : 180-196. Amer.Soc.Agron.Inc., Wisconsin. USA.

Richards, S.J. 1973. Soil suction measurement with tensiometers. In C.A. Black et al.(eds.), Methods of soil analysis.Part I : 153-163. Amer.Soc.Agron.Inc.,Wisconsin. USA.

--------------., and Marsh, A.W. 1961. Irrigation based on soil suction measurements. Soil Sci.Soc.Am.Proc. 25 : 65-69.

Rijtema, P.E. 1965. An analysis of actual evapotranspiration. Agricultural research report No.659. Centre for agricultural Publication & Documentation. Wageningen.

Robins, J.S. 1973. Evapotranspiration. In C.A. Black et al.(eds.), Methods of soil analysis Part I. : 286-298. Amer.Soc.Agron.INc., Wisconsin. USA.

Rose, C.W. 1969. Evaporation from bare soil under high radiation conditions. International Congress of Soil Sciences, 9th.Adelaide, Australia. Transaction, Vol.I : 57-66.

Sachs. R.M., Kretchun, T., and Mock, T. 1975. Minimum irrigation requirements for landscape plants. J.Amer.Soc.Hort.Sci. 100(5) : 499-502.

Schulz, E.F. 1976. Problems in applied hydrology. Water resources publications. USA.

Seemann, J. 1979a. Radiation measurement technology. In J. Seemann, Y.I.Chirkov, J.Lomas, and B.Primault (eds.), Agro-meteorology : 26-31. Springer-Verlag. Berlin.

----------- 1979b. Measuring technology. In J.Seemann, Y.I.Chirkov, J.Lomas, and B.Primault (eds.), Agro-meteorology : 40-45. Springer-Verlag. Berlin.

----------- 1979c. Water requirements of plants. In J.Seemann, Y.I. Chirkov, J.Lomas, and B Primault (eds.), Agro-meteorology : 294-297. Springer-Verlag. Berlin.

Sekiguchi, A., Minami,M., and Takenaka, H. 1973. Studies on mechanisms of soil moisture depletion at root zone of street trees. Fac. Hort. Chiba Univ.Tech.Bull.212 : 103-109. (Japanese)

Singapore Meteorological Service. 1976. Summary of meteorological observation, 1976.

Slatyer, R.O. 1957. The significance of the permanent wilting percentage in studies of plant and soil relations. Bot. Rev. 23 : 585-636.

------------- 1960. absorption of water by plants. Bot. Rev. 26 : 331-392.

------------- 1967. Plant-water relationships. Academic press. London.

Smith, L.P. 1975. Methods in agricultural meteorology--Development in atmospheric science. 3. Elsevier Scientific Publishing Co. Amsterdam.

Smith, W.H., and Dochinger, L.S. 1976. Capability of metropolitan trees to reduce atmospheric contaminants. In F.S.Santamour,Jr., H.D. Gerhold., and S.Little (eds.), Better trees for metropolitan landscapes : 49-59. U.S.D.A. For. Ser. General Tech. Rep. NE-22.

Swanson, R.H., and Lee, R. 1966. Measurement of water movement from and through shrubs and trees. J. For. 64(3) : 187-190.

Talsma, T., and Lelji, A.V.D. 1976. Water balance estimates of evaporation from ponded rice fields in a semi-arid region. Agr. Water Management. 1 : 89-97.

Tattar, T.A. 1978. Diseases of shade trees. Academic Press. New York.

Thurtell, G.W. 1979. Humidity : Critique I. In T.W. Tibbitts., and T.T. Kozlowski (eds.), Controlled environment guidelines for plant research : 173-175. Academic Press. New York.

van Haveren, B.P., and Brown, R.W. 1972. The properties and behavior of water in the soil-water-atmosphere continuum. In R.W. Brown., and B.P. van Haveren (eds.), Psychrometry in water relations research : 1-27. Utah Agr. Expt. Station. Utah State University.

Veihmeyer, F.J. 1968. Evapotranspiration. In T.V. Chow (Chief ed.), Handbook of applied hydrology. Section 11. McGraw-Hill. New York.

White, R.E. 1979. Introduction to the principles and practice of soil science. Blackwell Scientific Publications. Oxford.

Winter,E.J. 1974. Water, soil and the plant. The MacMillan Press Ltd. London.

Yingling,E.L., Keeley, C.A., Little, S., and Burtis, J.Jr. 1979. Reducing damage to shade and woodland trees from construction activities. J. Arbor. 5(5) : 97-105.