# Studying water in the soil-plant-atmosphere continuum: a bibliographic guide to techniques

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# PREFACE

The study of the transfer of energy and water in the soil-plant-atmosphere continuum (SPAC) has applications in the fields of agriculture, ecophysiology, hydrology and micrometeorology. These are technically demanding areas of research in which the selection of appropriate techniques and their proper application is frequently crucial to the successful solution of the problem at hand. Furthermore, it is a multidisciplinary study in which soil physicists need to know something about plants, plant physiologists something about soil, and both need an understanding of micrometeorology. This guide is intended to direct researchers in the field of soil-plant-atmosphere water relations to some of the relevant literature.

Recently, several textbooks and reviews have been published on this subject. For the fundamental concepts in micrometeorology the reader is directed to Monteith (1975), Jones (1983) and Rosenberg et al (1983) with discussions of the appropriate instruments and their use found in Szeicz (1975), Fritschen and Gay (1979), Unwin (1980) and Sheehy (1985). A less complex presentation of micrometeorological aspects is to be found in Oke (1978). Standard texts in soil physics are Hillel (1980), Hillel (1982) and Hanks and Ashcroft (1980), and an introduction to soil physical modelling in the soil-plant-atmosphere context is given by Campbell (1985). Methods of measuring various physical parameters associated with soil water status and movement are extensively dealt with in Klute (1986a). A recent synthesis of topics related to plant water relations is to be found in The Encyclopaedia of Plant Physiology (New Series) volumes 12A and 12B (Physiological Ecology parts I and II), with some of the instruments used being reviewed in Marshall and Woodward (1985) and by Kirkham (1985). Slavik (1974), although somewhat outdated, remains a standard reference on the methods of studying plant water relations. The interaction between plants and the microclimate is also discussed by Campbell (1977), Gates (1980), Grace (1977) who concentrates on wind and the plant, Jones (1983) and Nobel (1983).

## ABSTRACT

The parameters used to describe the flow of water, and energy to a lesser extent, through the soil-plant-atmosphere continuum are reviewed and the techniques used for estimating their values contrasted. The measurements which are necessary to satisfy various research objectives are discussed. The appropriate methods of measurement are suggested for given circumstances and the key references for each method presented.

## SAMEVATTING

Die parameters wat gebruik word om die vloei van water, en tot 'n mindere mate energie, deur die grond-plant-atmosfeer kontinuum te beskryf word geevalueer en die tegnieke wat gebruik word vir die skatting van hulle waarde word vergelyk. Die afmetings wat nodig is om die verskillende navorsingsmikpunte te bevredig word bespreek. Die geskikte metodes van afmeeting vir gegewe omstandighede en die sleutelverwysings vir elke metode word voorgestel.

## ACKNOWLEDGEMENTS

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The contents of this document represent a collaborative effort by a large number of people. Those who made written contributions are acknowledged as chapter authors. Participants in the workshop who contributed in discussions and presentations are thanked for their involvement. A full list of contributors can be found at the back of the document.

This document was typed and corrected by Marié Breitenbach of the FRD, who also made the arrangements for the workshop on which it was based. Without her efficiency neither would have seen the light of day.

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# ENERGY AND WATER IN THE SOIL-PLANT-ATMOSPHERE CONTINUUM: AN INTRODUCTION

**R J Scholes and M J Savage**

## WATER BALANCE AND THE HYDROLOGICAL CYCLE - R J Scholes

The basic elements of the terrestrial hydrological cycle at a field scale are illustrated (Figure 1). The remainder of this publication deals with methods of estimating the magnitude of either the flows (arrows) or reservoirs (boxes) shown.

The water balance for a site can be written as:

$$W = P - R - ET - D$$

where W is the change in the water content of the rooting zone,

P is the net precipitation
= gross precipitation - interception (I),

R is the net runoff
= runoff - runon,

ET is the total evaporation
= transpiration (T) + evaporation from the soil surface ($E_s$),

D is deep drainage out of the bottom of the rooting zone.

By convention, the units of all of the terms of the water balance equation are equivalent depths of water (mm) rather than volumes of water. This is because the water balance is for an area (whose boundaries are often unspecified); a volume divided by an area gives a depth. Also very conveniently, 1 kg $m^{-2}$ is approximately equivalent to a 1 mm depth of water.

## CONCEPTS, TERMINOLOGY AND UNITS USED IN THE SPAC - M J Savage

It follows from the laws of thermodynamics that a complete knowledge of the water status at a point in a system must include a knowledge of both the quantity of water present (water content) and its 'intensity' (ie energetic state) or water potential. If the relationship between these two different elements of the water status is known, then only one need be measured. Quantity-intensity relationships are not unique to water relations; a titration curve (the relationship between the quantity of acid and its intensity pH) is one of many such relationships. The ideal measure of water status (Kramer 1987) should be thermodynamically sound, applicable to both soil and plant material, unique in its effect on different plant species, correlated with plant water stress, simple to

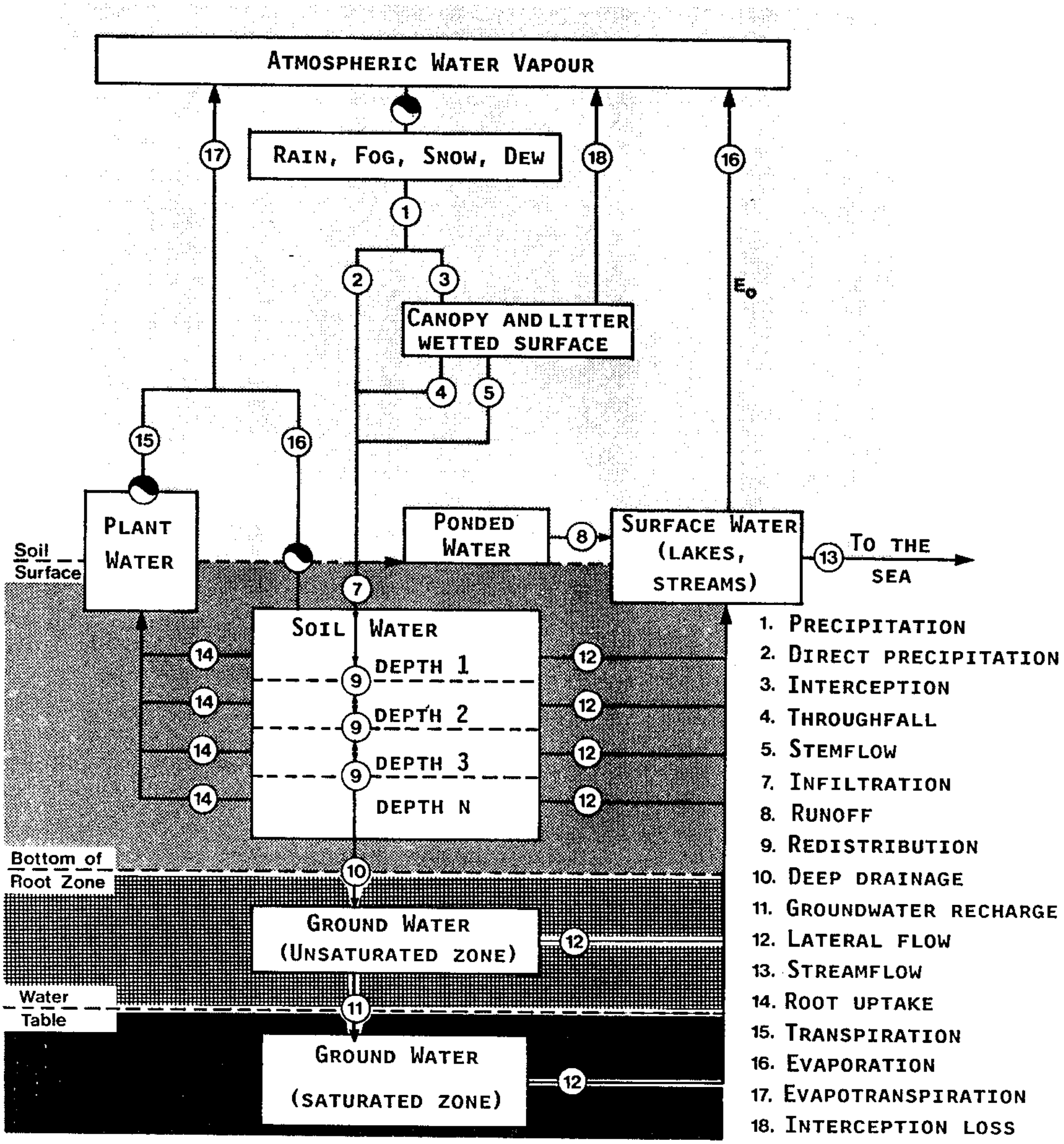

FIGURE 1. The terrestrial hydrological cycle. Boxes indicate reservoirs and arrows indicate water transport pathways. Key processes are indicated by numbered circles and phase changes by the symbol ◒.

perform, inexpensive and nondestructive. Currently, water potential is a more attractive measure than water content in many cases since it can be measured directly and nondestructively, although it is often more difficult to measure than water content.

Water content can be measured in absolute terms (with SI unit litres), but is more frequently expressed as a proportion or percentage of the total sample volume, dry mass or volume when fully saturated. These three ways of expressing water content are calculated as follows:

$$\text{volumetric water content } (\theta_v) = \frac{\text{volume of water}}{\text{total volume of sample}}$$

This is the standard way of expressing water content of the soil, since it is easily converted to depth equivalents (DE) for water balance purposes:

$DE = \theta_v \,.\, \text{depth of horizon}$.

The gravimetric water content ($\theta_m$) is calculated via:

$$\theta_m = \frac{\text{mass of water}}{\text{dry mass of sample}}$$

$$= \frac{\text{sample fresh mass} - \text{oven dry mass}}{\text{oven dry mass}}$$

Gravimetric water content is most commonly measured and then converted to one of the other forms (Hanks and Ashcroft 1980):

$\theta_v = \theta_m .$ bulk density, where

$$\text{bulk density} = \frac{\text{sample dry mass}}{\text{total volume of sample}}$$

Oven dry mass is obtained by drying the sample at between 60 °C and 105 °C until it no longer decreases in mass. The lower temperatures are used when chemical analyses are to be performed on the sample.

Relative water content (RWC) is the standard way of expressing plant water content (Slavik 1974):

$$RWC = \frac{\text{water content at the time of sampling}}{\text{water content when sample is saturated}}$$

The relative water content has values between 0 and 1. It is sometimes used in soil physics in generalized soil water equations. Relative water content is usually calculated from:

$$RWC = \frac{\text{fresh mass} - \text{oven dry mass}}{\text{turgid mass} - \text{oven dry mass}}$$

The turgid mass is determined by rehydrating the sample. A relationship can often be established between dry mass and turgid mass. Relative water content is related to volumetric water content via the proportion of pore volume to total volume of sample (porosity):

$\theta_v$ = RWC . porosity,

$$\text{where porosity} = \frac{\text{volume of spaces within the sample}}{\text{total volume of sample}}$$

Water potential may be defined as the amount of useful work which would have to be performed to move the water in the system, reversibly and isothermally, to a reference state (usually pure water at 20 °C at atmospheric pressure), and can be expressed per unit mass, volume, weight or amount of substance (in this case, water). Plant physiologists use the symbol $\Psi$ for water potential, and usually define it on a volume basis ( $\Psi_v$), which leads to the familiar pressure units (kPa or MPa), although some workers use the mass basis ( $\Psi_m$) and others the molar basis ($\Psi_n$) (Savage 1978). Hydraulic engineers traditionally use the weight basis (hydraulic head, h). Interconversions can be performed:

$$\Psi_v = \Psi_w \rho_m = \Psi_n / \overline{V}_w = \rho_w g h$$

where $\rho_w$ is the specific density of water (approximately 1 000 kg m$^{-3}$ at 25 °C)

$\overline{V}_w$ is the partial molar volume of water (approximately 18 x 10$^{-6}$ m$^3$ mol$^{-1}$ at 25 °C) and

g is the acceleration due to gravity (approximately 9,8 m s$^{-2}$).

For example, a volumetric water potential of -1 MPa is equal to a number of alternate SI units and other equivalent and obsolete (*) units (Savage 1978, 1979):

Volume basis
-1 MPa = -1 MJ m$^{-3}$ = -1 MN m$^{-2}$ = -10$^6$ kg m$^{-1}$ s$^{-2}$ = -10 bar *
= -1000 mbars * = -9,869 atmospheres * = -10 dyne cm$^{-2}$*
= -0,0001450 lb in$^{-2}$* = -0,02089 lb ft$^{-2}$*

Mass basis equivalents
-1 MPa, -0,001 MJ kg$^{-1}$, -1 kJ kg$^{-1}$, -1 000 J kg$^{-1}$ water

Molar basis equivalents
-1 MPa, -18 J mol$^{-1}$

Weight (head) basis equivalents
-1 MPa, -101,98 m of water, -7,501 m of mercury

## THE ELECTRICAL ANALOGUE - R J Scholes

The idea of representing water movement in the SPAC as a chain of resistances between a source (the soil) and a sink (the atmosphere) is credited to Gradman (1928) and is now known as the Electrical Analogue (van den Honert 1948). Philip (1966) popularised the term 'Soil-Plant-Atmosphere Continuum' (SPAC) for this chain. The concept has subsequently been improved upon by other workers, such as Cowan (1972).

The principle of the electrical analogue is that water movement in the SPAC system is in response to a gradient of water potential. The mass flux density between two points in the system can be expressed in terms of the water potential difference between them:

$$I = \frac{\Psi_2 - \Psi_1}{r}$$

where $I$ is the mass flux density,
$\Psi$ is the water potential at points 1 and 2, and
$r$ is the resistance to flow.

| Quantity | Dimension | Unit |
|---|---|---|
| $I$ | $M\ T^{-1}L^{-2}$ | $kg\ s^{-1}\ m^{-2}$ |
| $\Psi$ | $M\ T^{-2}L^{-1}$ | $kg\ s^{-2}\ m^{-1}$ |
| $r$ | $M^0L^{-1}T$ | $s\ m^{-1}$ |

The mass flux density of evaporating water can easily be converted to energy flux density, often referred to as 'latent heat $\lambda E$', by multiplying $I$ by the specific latent heat of vapourisation of water (about 2,44 MJ $kg^{-1}$ at 25 °C).

If the 'resistance' $r$ is constant for all combinations of $\Psi$, then the flow of water in the SPAC is directly analogous to the flow of electricity in a circuit, as governed by Ohm's law - hence the term 'Electrical Analogue'. The theory of water movement in the SPAC, and its measurement and prediction, is dominated by this concept; there is an ubiquitous use of the terms potential, resistance, conductance and capacity. An Electrical Analogue representation of the SPAC is presented (Figure 2).

The advantages of the Electrical Analogue model are:

1. it allows a complex pathway to be reduced to unit steps with known behaviour;
2. if it is assumed that the system is in equilibrium (that is the reservoir volumes are not changing) then the mass flux densities at each step are equal, and the relative importance of each step in limiting the overall rate of water movement can be determined by measuring the water potential gradient across it (without necessitating the measurement of the flux density, which may be technically difficult); and
3. if the resistances are known, then the flux density can be inferred from the water potential gradient.

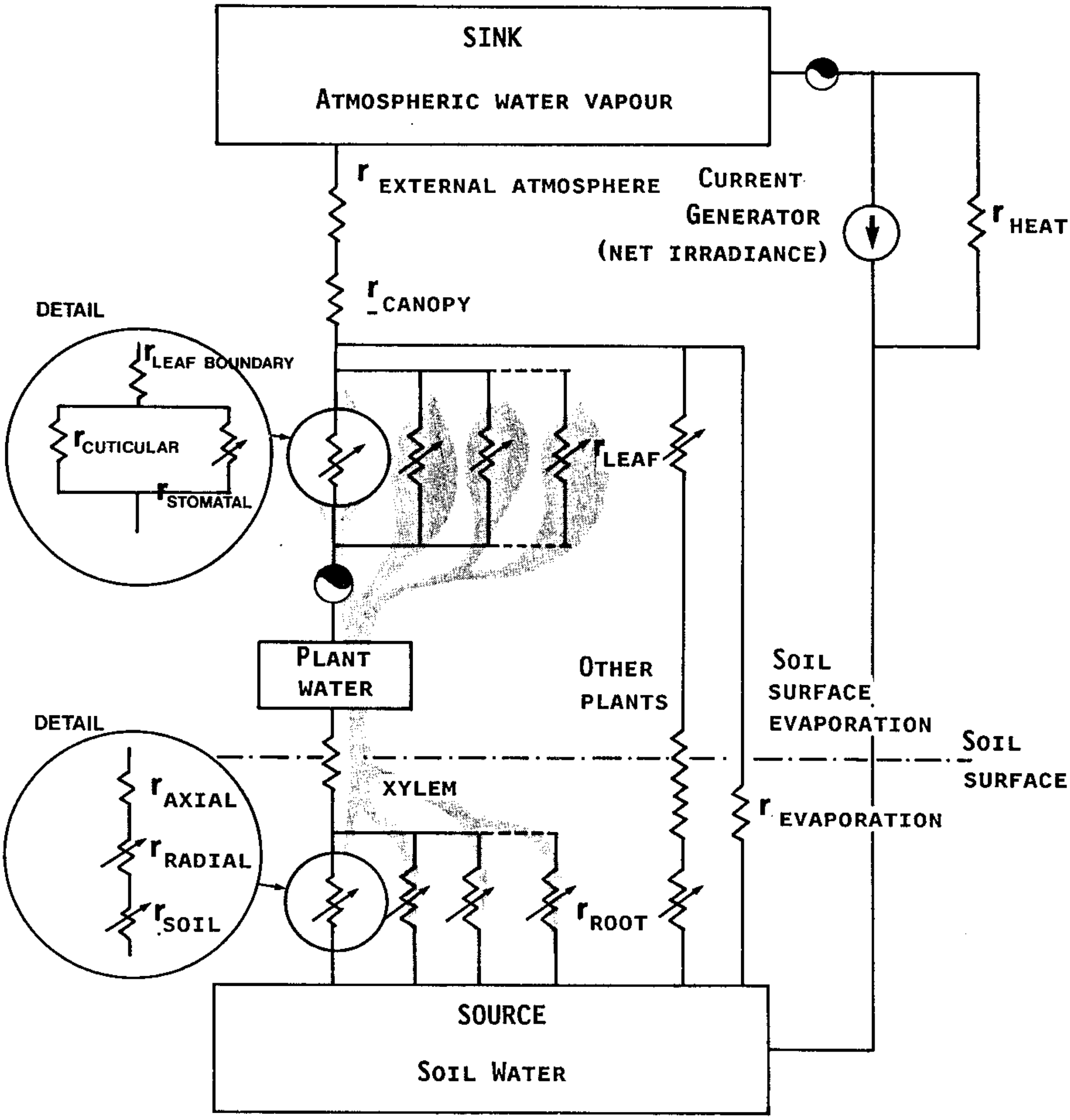

FIGURE 2. An electrical analogue diagram of water transport in the SPAC. Boxes represent significant capacitances. The water potential difference between the soil and atmosphere is maintained by a net downward irradiance, which is partially balanced by an upward flux density of sensible heat energy. Diagram adapted from Cowan (1972).

The disadvantages of the model are:

1. the assumption that resistances are linear (that is, constant for all values of water potential) is false. For example the soil, root and stomatal resistances are all highly non-linear. The assumption may be an adequate approximation over small water potential ranges;
2. in addition to resistances, there are also capacitances (reservoirs) in the system. Therefore 'quantity-intensity' relations such as the soil water retentivity curve, the plant pressure-volume curve and the relative humidity-saturation deficit function are necessary to relate the water potential to the water content for a given capacitance;
3. a phase change occurs at the plant-atmosphere interface. In the vapour phase, water moves down a partial pressure gradient rather than a water potential gradient as it is conventionally defined. This leads to some theoretical inconsistencies; and
4. there are circumstances under which the Electrical Analogue completely fails to explain the observed water movement in plants. It appears that water uptake by roots is not an entirely passive process as is suggested by the Electrical Analogue model.

The debate between Kramer, Passioura and Schulze (Plant, Cell and Environment 1988, Vol 11, 565-576) illustrates the differences of opinion which exist regarding the Electrical Analogue model. The current consensus is to use the Electrical Analogue approximation in the absence of a more appropriate model.

# PRECIPITATION, INTERCEPTION, RUNOFF AND INFILTRATION MEASUREMENT TECHNIQUES

**R E Schulze, D B Versfeld, H M du Plessis, P J Dye and D A Russell**

## THE MEASUREMENT OF PRECIPITATION - R E Schulze

Precipitation includes rainfall, fog, dew, snow and hail. A water balance model can only be as accurate as the measurement of precipitation. The South African standard rainfall gauge has a 127 mm orifice diameter mounted at 1,22 m above the ground. This standard usually underestimates the true rainfall. There are three sources of error: site errors, due to wind, turbulence and splash; gauge errors, due to gauge design and evaporation; and observer errors. De Villiers (1980) compared the rainfall "catch" of various rain gauge designs, while Ward (1975) includes estimates of errors associated with different rain gauge network densities and discusses the correct siting of rain gauges. The orientation of rain gauges for water balance modelling or catchment hydrology may differ from that for the weather station standard. For very accurate measurements windshields may be required. Evaporation from a standard gauge is about 0,5 mm day$^{-1}$. If a gauge cannot be regularly checked, or if rainfall intensity is required (eg for runoff or erosion studies) then a recording rain gauge is needed. Recording rain gauge data should be corrected for high intensity storms (Savage and McGee 1981). Dew is usually a minor component of the water balance (Monteith 1976), but fog (ground-level cloud) can be a major component (Schulze 1983). Fog interceptors give relative estimates of the fog contribution only. Areas receiving appreciable snowfall require snow gauges as well.

## DETERMINATION OF INTERCEPTION - D B Versfeld

Interception is the amount of precipitation which evaporates directly from the wetted surface of vegetation and litter and therefore does not reach the soil (Rutter 1975). It can be a large proportion of the gross precipitation, particularly for storms of low intensity, since it commences during the storm. The measurement of interception is always indirect:

interception = gross rainfall - (throughfall + stemflow),

where gross rainfall is the rainfall measured above the canopy,
throughfall is the rainfall measured below the canopy and
stemflow is the water running down the plant stem to the ground.

Interception studies require measurements of above-canopy microclimate (precipitation, wind speed, temperature and saturation vapour deficit), canopy architecture (surface storage capacity, percentage gaps, height), throughfall and stemflow. Rainfall should be recorded using a tipping-bucket gauge with 0,1 to 0,2 mm resolution. Throughfall is usually measured with troughs, but numerous (more than 20) 'jam tin' recorders are often superior. Splash and the wetting coefficient of the recorders are major sources of error. Litter storage capacity can be between 1 and 10 mm and therefore cannot be ignored; stemflow can also be considerable.

Sophisticated interception models are available. The Rutter model (Rutter et al 1971) has a 5 min time increment. For most purposes the Gash (1979) model with a one week increment is more appropriate.

## RAINFALL SIMULATION - H M du Plessis

It is often impractical to rely on the vagaries of natural rainfall when performing precise empirical studies on runoff, erosion, infiltration and interception. A variety of rainfall simulators and their use are reviewed by Bertrand (1965), and more recently by Peterson and Bubenzer (1986). Rainfall simulators can broadly be divided into drip and nozzle simulators depending on the method of drop formation. Drip simulators can combine large diameter drops (3 to 6 mm) with low application rates but it is difficult to simulate the impact velocity of natural rain. With nozzle simulators it is possible to obtain impact velocity and drop size comparable to natural rain only at high discharge rates. Nozzle simulators employing a rotating boom (Swanson 1965, used by the Directorate of Agricultural Engineering and Water Supply) or a rotating disc with variable slit sizes to reduce and control application rates (Morin et al 1966, 1967, used by the Soil and Irrigation Research Institute), are in use in South Africa. Both reproduce natural rain drop size and energy well, apply rain uniformly and near continuously, utilize a plot size sufficient for reproducibility and can apply rain for any desired duration. Only the rotating disc type, however, uses small enough volumes of water that deionized water can be used; this is an important factor when natural rainfall is being simulated. A description and results of the program to assess soil loss and runoff using the rotating boom simulator are given by McPhee et al (1983) and McPhee and Smithen (1985), while some initial results for South African soils using the rotating disc simulator have been published (du Plessis and Shainberg 1985).

A simple sprinkler infiltrometer used to determine the intake rate of irrigation systems is described by Reinders and Louw (1985).

Application rates vary between 60 and 120 mm $h^{-1}$ for rotating boom instruments and between 25 to 200 mm $h^{-1}$ in discrete increments for rotating disc instruments. The water composition depends on the available source for the rotating boom type; water for the rotating disc type can be deionised on site.

The main advantages of the use of rainfall simulators as opposed to field experiments are that:

1. they can be used in the field or the laboratory;
2. results can be obtained more rapidly; and
3. experimental conditions can be controlled and reproduced.

The disadvantages of rainfall simulation are:

1. instrumentation is fairly expensive;
2. trained operators are required; and
3. results have to be adjusted to compensate for plot length and surface storage when extrapolated to field conditions.

## RUNOFF AND INFILTRATION

Runoff is that part of net precipitation which fails to infiltrate the mineral soil and runs over the soil surface towards the nearest drainage channel. Its importance is as a loss to the field water balance and as a determinant of streamflow pattern and erosion. Since

runoff = net precipitation - infiltration,

it is obvious that runoff and infiltration are complementary measures of the ability of the soil to absorb applied water. However, they are often used in a subtly different sense: runoff usually refers to a large area, integrated over the period of a storm event or longer; infiltration measurements are usually obtained instantaneously on a fairly small area. There is also a relationship between the steady state infiltration rate ($i_{final}$) and the saturated hydraulic conductivity ($K_{sat}$), resulting in considerable overlap in techniques, and frequently a degree of confusion. Bottomland areas may experience runon from upslope areas.

### Determination of runoff - P J Dye

The principle of runoff plots is to contain runoff from an area of known size and hence measure the volume of water captured. Their shape is usually long and narrow, with walls 200 mm high, buried to 100 mm depth, made of galvanized iron, asbestos sheets, old conveyor belts or concrete. The choice of material depends on cost and whether the walls need to be lifted to apply treatments to the plots. The walls must be installed with the minimum of disturbance to the plot, and can be sealed with earth or putty. They are oriented with the long axis perpendicular to the contours. The length is usually arbitrary, but the longer the better. Dye (1980) found increases in effectiveness up to 80 m and greater. The standard runoff plot for erosion estimates is 22 m long. The principle design problem lies in capturing the large volumes of water yielded by the plots. The runoff collection system must be designed for the largest expected storms, since these are the ones which generate the most useful data. Some system of filters is essential to prevent the recorders from becoming clogged with debris. Collecting tanks are usually installed for erosion studies, to allow sediment loads to be sampled. To avoid excessively large collection tanks, sample splitters are often used. Some common types are the multiple notch, multiple hole, multislot and Coshocton wheel (the latter is prone to error). All must be precisely made, installed and calibrated. Tankless recording systems include flume and float recorders, tipping bucket gauges and direct metering using a flow meter. Design considerations are detailed by Hudson (1957).

## Infiltration measurement - D A Russell

Infiltration is the process by which water crosses the air-water interface into the soil. The curve of the infiltration rate (i, mm $h^{-1}$) versus elapsed time (t, h or min) shows an exponential decrease with time until an approximately constant rate ($i_{final}$) is maintained. This constant rate is often regarded as the saturated hydraulic conductivity ($K_{sat}$) of the rate limiting horizon in the profile. The cumulative infiltration (I, mm) is the depth of water that has infiltrated up to time t, and is therefore the integral of the infiltration rate curve (Figure 3). The term intake rate is synonymous to infiltration rate; infiltration capacity is obsolete. Amerman (1983) and various soil physics texts (Baver et al 1972; Hillel 1980) discuss details of the infiltration process. Two empirical equations are commonly fitted to the cumulative infiltration curve (Clemmens 1983):

$I = St^b$ $[\ i = Sbt^{b-1}\ ]$ Kostiakov power function

$I = St^b + At$ $[\ i = Sbt^{b-1} + A\ ]$ modified Kostiakov

where S, b, and A are constants, and

where b = 0,5 the modified Kostiakov function is equivalent to the physically derived Philip (1957) equation. In general, the empirical equations fit the data better (Bristow and Savage 1987), and are easier to use than the more rigorous physical equations such as the Green-Ampt equation.

The type of infiltrometer used depends on the objectives of the study. If infiltration under flooded conditions is being studied, then a ponded infiltrometer is appropriate (Bouwer 1986). These vary in size from 0,1 $m^2$ to several square metres; the water level inside the pond can be maintained at a constant level (constant head type), or permitted to drop (falling head type). Double ring infiltrometers have a buffer zone surrounding them, in which the water is kept at precisely the same level as the water inside the measurement ring. This requires a more sophisticated design, more care in operation and usually more water to perform the measurement. Single ring infiltrometers are adequate for relative measurements, but should be corrected for lateral flow (Baver et al 1972).

Measuring infiltration under rainfall or sprinkler irrigation conditions requires a sprinkler infiltrometer (Peterson and Bubenzer 1986). Many of the same conditions apply here as to rainfall simulators. In the use of both ponded and sprinkler infiltrometers, it is essential that the quality of the water used matches that of the process being studied: rainwater or deionized water for rainfall, irrigation water for irrigation.

The rainfall intensity in natural storms varies continually, unlike that from sprinkler infiltrometers, and the rainfall depth is usually well below that required for constant rate infiltration. Therefore the approach of concentrating on the initial part of the infiltration curve has some merit and is gaining in acceptance. The shape of the curve in this region is dominated by the first term of the Philip equation, which has a parameter (S) known as sorptivity. Sorptivity can quickly and easily be measured by ponded infiltration or by using an air-entry permeameter, which is preferable where the soil contains large pores or cracks (Green et al 1986). This approach can also be applied using the Green-Ampt equation (Bouwer 1986), but cannot be applied to a layered system (such as a strongly duplex soil) as a whole.

Infiltration rate is spatially and temporally highly variable. Methods of sampling in relation to variability are discussed by Sharma et al (1983), Gish and Starr (1983) and Warrick et al (1986). Streamflow data from small catchments can be used to yield an estimate of areal infiltration, but for large catchments the rainfall is usually too varied to support this approach.

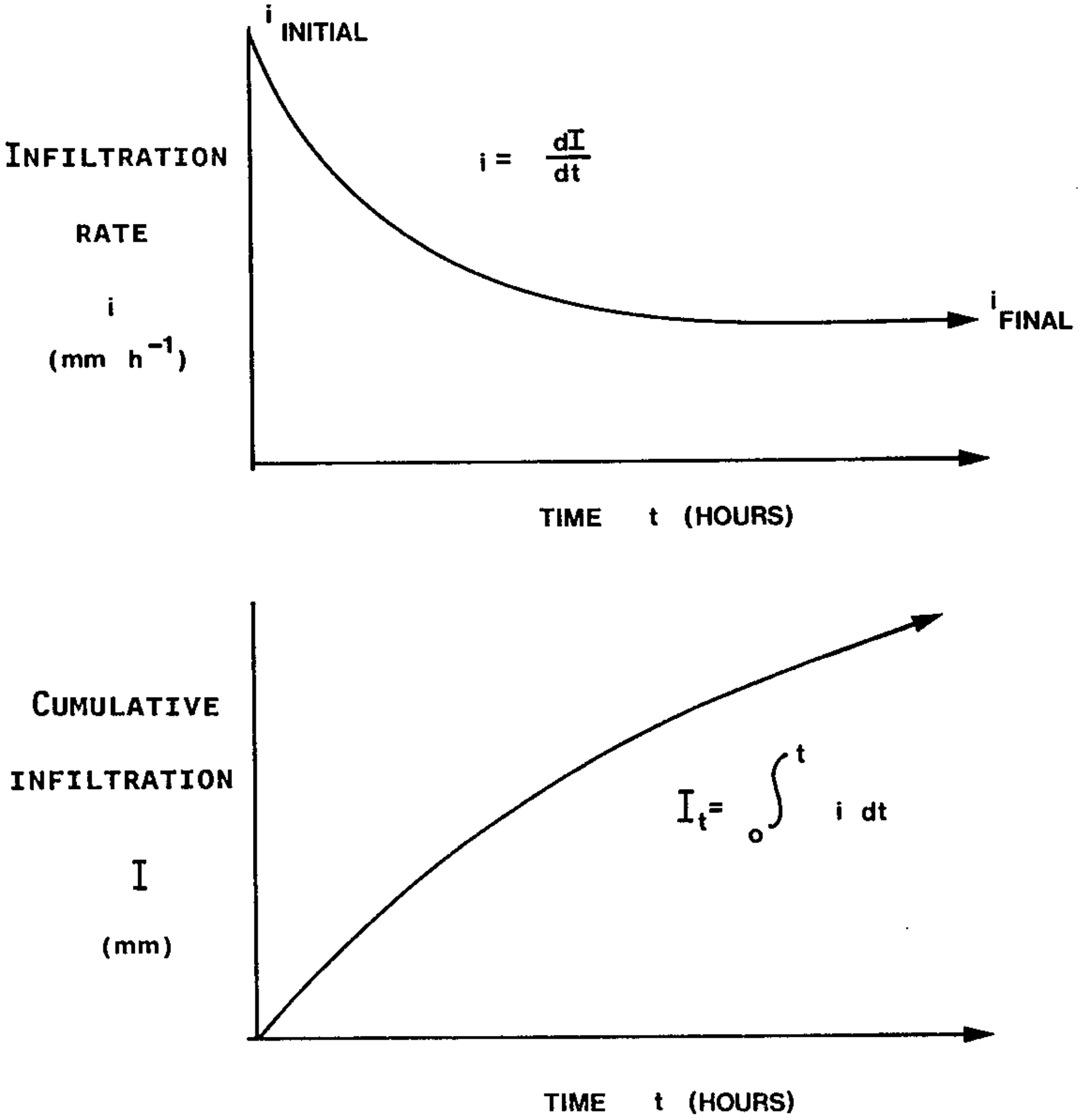

FIGURE 3. The relationship between infiltration rate, cumulative infiltration and time. During the initial phase, the infiltration rate is dominated by sorptivity, but during the steady-state phase it approximates $K_{sat}$.

# MEASUREMENT OF SOIL WATER STATUS

**HvH van der Watt, M A Johnston, R Mottram, M J Savage, R J Scholes and D A Russell**

The soil is the major water reservoir in the terrestrial portion of the hydrological cycle. Its measurement is central to most hydrological water balance models. Some information about the soil water availability to plants should accompany all work on plant water status. This can take the form of measurements of soil water content or potential, preferably at several depths and locations in the plant rooting zone. Soil water availability models, employing the concept of plant available water content, help to integrate these data in a biologically meaningful way.

## CONCEPTS OF SOIL WATER - HvH van der Watt

Two aspects of soil water are relevant to the SPAC: basic energy concepts such as water potential (Hillel 1971, 1980) and concepts relating to the amount of soil water available to plants (Ritchie 1981; Boedt and Laker 1985). Energy concepts are most appropriate for studies of water movement and water stress, while amount of water concepts are more appropriate for water balance and water use studies.

The components of the total soil water potential, viz the matric, gravitational and osmotic potentials, are adequately discussed in most of the more recent books on soil physics. The concepts of hydraulic head and gradient are essential when the movement and availability of water in a soil profile are considered.

Field capacity and permanent wilting percentage are the classic upper and lower limits of available soil water (Figure 4). However, both concepts have severe limitations under real field conditions (Ritchie 1981; Boedt and Laker 1985). For example, field capacity does not reflect an equilibrium condition but rather a dynamic one (Hillel 1980; Beukes 1984, 1986). A repeatable physical measurement, such as the water content at air-entry potential would be preferable. Field capacity has intuitive appeal, however, and remains in usage. It should be measured in the field (Cassel and Nielsen 1986) rather than approximated by the soil water content at -0,01 or -0,03 MPa matric potential. Similarly, the permanent wilting percentage, usually approximated by the water content at -1,5 MPa, is not very meaningful unless plant and atmospheric factors are also considered. A better approach is to measure it in the field, as recommended by Ritchie (1981).

In South Africa much attention has been given to the water-supplying capacity of entire soil profiles. The concept of profile available water capacity (PAWC) was developed by Hensley and de Jager (1982), and Hensley (1984) and further studied by Boedt and Laker (1985). Basically, PAWC is defined as the amount of water in the effective root zone between field-determined field capacity and first material plant stress.

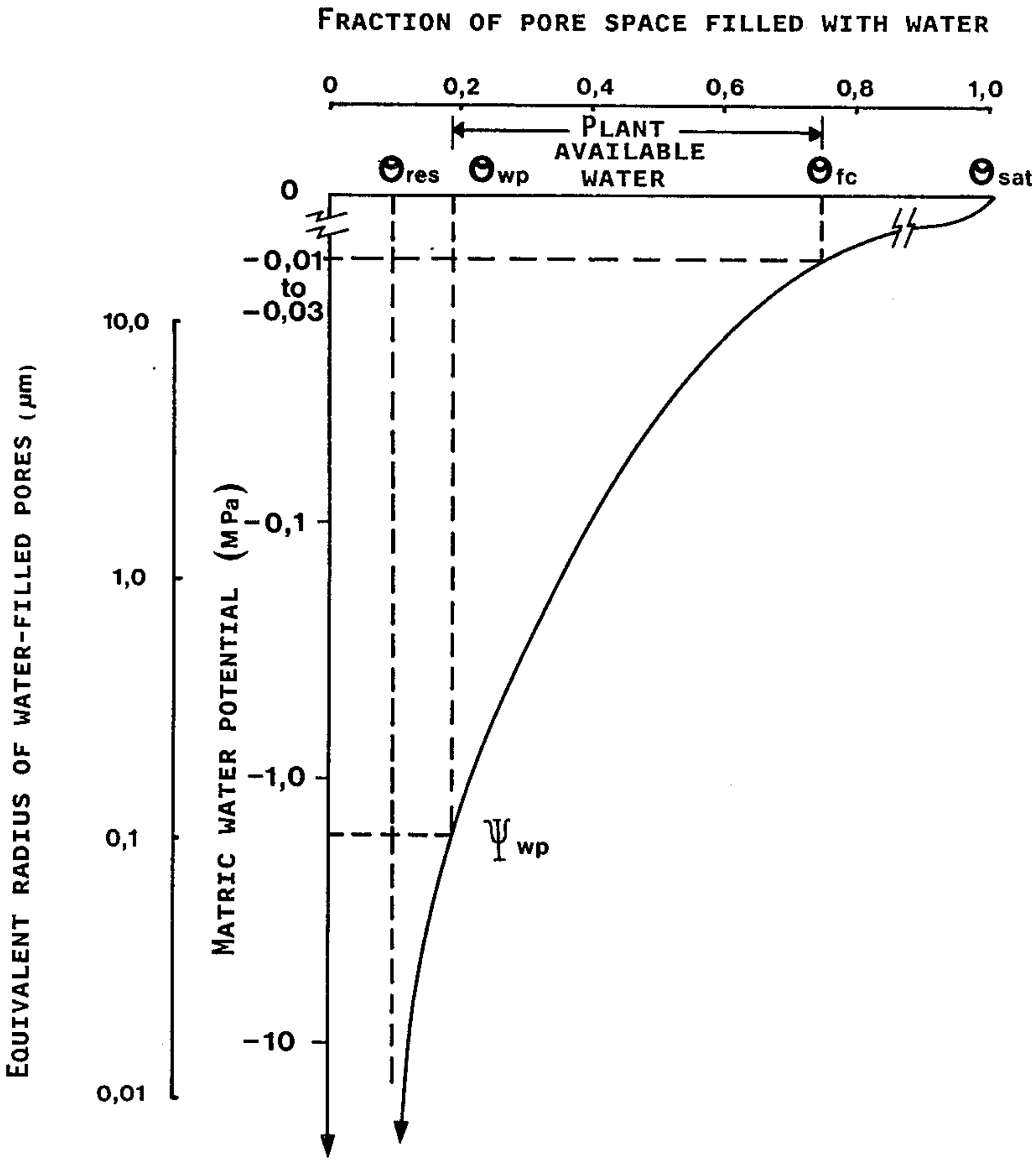

FIGURE 4. A hypothetical relationship between the water content and water potential of a clayey soil, illustrating the relationships between pore size, pore volume, soil water availability and residual soil water content ($\theta_{res}$) water content at wilting point ($\theta_{wp}$), field capacity ($\theta_{fc}$), saturation ($\theta_{sat}$) and wilting potential ($\Psi_{wp}$).

## THE SOIL WATER RETENTIVITY CURVE - M A Johnston

The soil water retentivity curve is the relationship between the water content of the soil and the soil matric potential. It is so fundamental to soil water behaviour that it is sometimes known as the 'characteristic curve'. The curve is hysteretic; that is, its shape differs when the soil is being wetted from when it is being dried out (Figure 5).

It is usually determined in the laboratory (Klute 1986b), but estimating it in the field (Bruce and Luxmore 1986), although laborious, avoids problems with sample disturbance, which may be critical in highly structured soils. Its measurement in situ can be combined with the in situ measurement of hydraulic conductivity.

Different types of pressure equipment are normally required to encompass the water potential range (0 to -10 MPa). A tension tray can be used for the 0 to -15 kPa water potential range (Avery and Bascomb 1974), a 5 bar pressure plate extractor for the 0 to -0,5 MPa range and a 15 bar pressure plate extractor for the -0,5 to -1,5 MPa water potential range. The Soil Moisture Equipment Company (Sunnyvale, California) also supply the Tempe cell for use over the 0 to -100 kPa range, and pressure membrane (as opposed to ceramic plate) apparatus which operates over the 0 to -1,5 MPa range. A pressure membrane apparatus is also marketed which covers the very low water potential range of -1,5 to -10 MPa. The principles of measurement which apply to all of the equipment mentioned are discussed by Klute (1986a). Results obtained using the different types of equipment are generally comparable. Normal accuracy of equipment is within approximately 5%.

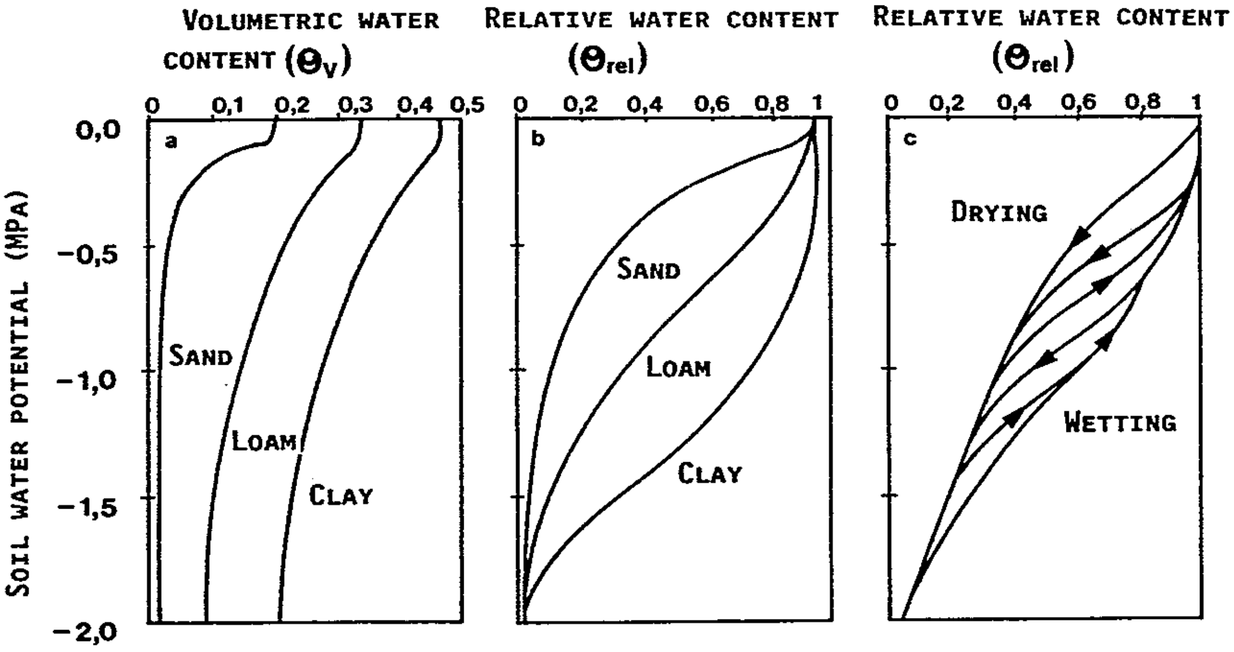

FIGURE 5. Soil water retentivity curves: a) as a function of volumetric water content, showing increasing water retention at a given water potential as the soil texture becomes finer; b) as a function of RWC, showing the suddenness of water loss in sands; and c) curves for a loamy soil showing hysteresis between wetting and drying phases.

It is important to use undisturbed soil cores for the 0 to -0,5 MPa range, and sampling devices are described by Avery and Bascomb (1974) and Loveday (1974). It is less important, yet desirable, to use undisturbed cores for water potentials less than -0,5 MPa.

Regression equations based on easily-measured soil parameters can be used to estimate selected points on the retentivity curve (Hutson 1986; Hall et al 1977; Bruce and Luxmore 1986). These equations may be adequate within the soil types from which they were derived, but extrapolation to other soil types is not recommended.

## PARTICLE SIZE DISTRIBUTION - M A Johnston

The behaviour of water in the soil is largely a function of the size distribution of the soil pores. This is in turn related to the size distribution of soil particles. Hence the most basic soil information relating to the SPAC is its texture. Given the percentages of sand, silt and clay, some crude estimates of water holding capacity and hydraulic conductivity can be made.

Particle size distribution of the sand fraction (0,05 to 2,0 mm) is normally determined by dry sieving, whilst the silt (0,002 to 0,05 mm) and clay (< 0,002 mm) fractions are determined using a sedimentation procedure, measurements being taken using a pipette or hydrometer.

Chemical pretreatment for removal of cementing agents is described by Klute (1986a) and Loveday (1974). Suitable dispersing agents for different soil categories are outlined by Loveday (1974). Physical agitation using mechanical stirrers and the ultrasonic probe is adequate for all soils, whereas end-over-end shakers or ultrasonic baths can only be recommended for soils with a moderate to low degree of aggregation.

The pipette method for clay and silt determination is described by Klute (1986a), while the hydrometer method is described by Bouyoucos (1951) and Klute (1986a).

| Method | Advantages | Disadvantages |
|---|---|---|
| Pipette method | More accurate (± 1 % clay, excluding error of pretreatment). Pretreatment quicker (uses smaller sample). | Slower (procedure is speeded up if electronic balance is available) |
| Hydrometer method | Quicker | Less accurate (± 3 % clay excluding error of pretreatment). Calibration problems. |

## SOIL WATER POTENTIAL

The choice of technique for measuring soil water potential depends on the range in which the measurement is to be taken, the funds that are available and whether or not the system is to be automated. The available choices are summarized (Table 1).

TABLE 1. Methods of soil water potential measurement.

| Method | Range (MPa) | Accuracy | Comments |
|---|---|---|---|
| 1. Hygrometry | | | Direct and accurate measurement over indicated range. |
| a) Psychrometry | -0,05 to -6 | ±0,025 MPa if calibrated | Sensitive to temperature gradients. Costly to |
| b) Dew-point | -0,05 to -6 | ±15 % if uncalibrated | automate. Increased sensitivity in the wet range. |
| 2. Tensiometry | 0 to -0,08 | | Direct measurement, but only in the wet range. Relatively cheap, but expensive to automate. Requires upkeep. |
| 3. Resistance blocks | | | Easy to automate. Indirect measurement. Errors due |
| a) Gypsum | -0,1 to -4 | ±5 % calibrated | to hysteresis, sensor aging and salinity effects. |
| | | ±10 % uncalibrated | Dry range, saline soils. Wet range, acid soils. |
| b) Nylon | 0 to -1,5 | | Indirect measurement. Requires calibration. |
| 4. Heat dissapation | 0 to -0,1 | ±0,01 MPa | Nonlinear and hysteretic. |
| 5. Filter paper | -0,1 to -10 | < 10 % | Cheap, but slow and cannot be automated. |

### Tensiometry - R Mottram

A tensiometer consists of an airtight water-filled tube with a porous ceramic cup at the bottom and a vacuum gauge or manometer near the top. The porous ceramic cup has pores which allow water to flow in and out but which, because of their very small radius prevent air from entering the wetted cup. The unit is installed with the porous ceramic cup in firm contact with the soil. As the soil dries out water flows out of the ceramic cup and a vacuum is created in the system which is monitored by the vacuum gauge or manometer. When the soil becomes wet, water moves back into the unit through the pores in the cup.

The tensiometer gives a direct measure of matric potentials greater than -0,08 MPa. Thus the tensiometric water potential range encompasses the soil water potential range required for most shallow rooted and quick growing vegetable crops such as potatoes, tomatoes, cole crops and some orchard crops. Where grain crops and forages such as lucerne are grown, resistance blocks may be required to extend the soil water potential range for most efficient monitoring of the water content. If equilibrium has not been established then small deviations from the true soil water potential may be expected, depending on the permeability of the tensiometer cup and the surrounding soil. For coarse grained soils and a coarse filter cup this effect is usually negligible. If, on the other hand, the material of the filter cup contains fine pores, the vacuum registered by the gauge/manometer will include the contribution by osmotic potential.

Design and installation aspects are considered by Cassel and Klute (1986). Comparisons with gypsum block and neutron probe data have been performed (Tollner and Moss 1985). An analysis of air bubble errors is discussed by Towner (1983). An envelope of fine-grained material placed around the tensiometer cup can improve liquid continuity and so reduce the response time (Cass and Campbell 1982); these workers also found that the enhanced contact also expanded the range of water content over which the tensiometers provided a reliable measurement of soil water potential.

### Hygrometry - M J Savage

Hygrometry is the general term used to describe the measurement of water potential using a thermocouple placed in a chamber wherein the atmospheric water vapour pressure is in equilibrium with that neighbouring the substance being measured. Hygrometers therefore sense both matric and osmotic effects of soil, plant or other material. There are two basic technical variants: thermocouple psychrometry operates on the same principle as a wet and dry thermometer, at a microscopic scale; while dew point thermometry measures the dew point temperature, which is related to the water potential. The dew point method is more sensitive, especially in the wet range and for temperatures greater than 15 °C, but is more complicated to use (Savage 1982). The principle sources of error are failure to equilibrate, the presence of thermal gradients and the use of dirty thermocouples. Hygrometry is the method of choice for high precision work where continuous monitoring is required, but technical expertise is required for its reliable use.

General details on the design, calibration, installation and use of hygrometers, are discussed by Rawlins and Campbell (1986) and Savage and Cass (1984a).

### Resistance blocks - R J Scholes

These devices operate by measurement of the electrical resistance between two electrodes imbedded in a matrix, the water potential of which is in equilibrium with the water potential of the surrounding soil.

Gypsum resistance blocks were developed by Bouyoucos and Mick (1947). The nylon variety, which are more sensitive in wet soil but less accurate in dry soil, was developed by Bouyoucos (1949). Details of the design and manufacture of the blocks and the performance of various materials are presented by Perrier and Marsh (1958), of hysteresis problems by Bourget et al (1958), the correction for temperature sensitivity by Slavik (1974) and improved circuitry for the measurement of the blocks by Goltz et al (1981).

An example of the calibration, installation and use of resistance blocks under southern African conditions is presented by Hussein (1981).

Resistance blocks are cheap and amenable to automatic datalogging. However, they have limited accuracy, are hysteretic (measurements differ between wetting and drying soils) and it is not uncommon for breakdown of gypsum blocks to occur in acid soils. The sensor measurement range is 0 to -1,5 MPa for nylon blocks and -0,1 to -4,0 MPa for gypsum blocks. The measurement accuracy is ±5 % for individually calibrated gypsum blocks and ±10 % for individually calibrated nylon blocks.

### The filter paper method - R J Scholes

The water content of porous material such as filter paper, will equilibrate with the water potential of a soil sample, sealed in the same chamber. The method is described by Fawcett and Collis-George (1967), Al-Khafaf and Hanks (1974), Hamblin (1981) and Campbell and McGee (1986) following its original development by Gardner (1937) and subsequent work by McQueen and Miller (1968). This laboratory method is cheap and simple but requires constant temperature control for accurate results (Campbell 1987).

### Heat dissipation method - R J Scholes

Heat dissipation through a porous medium is a function of its water content. The rate of dissipation of a heat pulse is measured in a standard material whose water potential is in equilibrium with the water potential of the surrounding soil. The method is not widely used since the sensors are not freely available. It is described by Phene et al (1971a,b) and Campbell and McGee (1986). The method is only suitable for the wet range, where the accuracy is similar to that of resistance blocks. The metering is more difficult than that for resistance blocks, but the heat dissipation sensors have the advantage of being insensitive to salinity, and probably have a greater sensing life than gypsum blocks.

## SOIL WATER CONTENT

The standard reference method of determining soil water content remains the gravimetric method in which a weighed soil sample is dried in an oven at 105 °C until constant mass is achieved, and then reweighed (Gardner 1986).

$\theta_m$ = (wet mass - oven dry mass)/oven dry mass

A quick field estimate of soil water content can be obtained by the acetylene generation method (the 'speedy water meter'). For repeated, nondestructive measurement, the neutron water meter (neutron probe) is the method of choice. The gamma ray attenuation method (Nofziger 1978; Gardner 1986) has a finer spatial resolution, but is not in general use. A new technique which shows considerable promise, especially for the measurement of water in heterogeneous materials at considerable depths, is time-domain reflectometry (TDR) (Topp and Davis 1985).

## Neutron water meter - R Mottram

A source of fast neutrons (typically $^{241}$Am mixed with beryllium) is lowered down an access tube into the soil. The fast neutrons are slowed down by collision with nuclei in the soil, particularly those of hydrogen atoms. The density of these slow (or thermal) neutrons is detected by a scintillation counter mounted just above the fast neutron source. Since water is the main source of hydrogen atoms in the soil, the scintillation count is directly proportional to the soil water content. Other sources of hydrogen atoms are clay lattices and soil organic matter. Large amounts of cadmium, chlorine or boron also absorb fast neutrons, but otherwise the neutron water meter is independent free of temperature, salinity and pressure. Since soil bulk density influences attenuation of the fast and slow neutrons, the meter needs to be calibrated for each soil type. Most modern instruments have built-in density estimation which partially corrects this error, and for routine work the manufacturer's calibration is adequate. Precise work nevertheless requires separate calibration, which can be carried out in drums packed to a known bulk density with soil of known water content; alternatively, calibrations can be performed in the field. The latter is the preferred method. For measurements in the 0 to 300 mm depth range, a separate instrument (surface probe) is required. Procedures for use and calibration are given by Carniero and de Jong (1985), Chanasyk and McKenzie (1986) and Gardner (1986). A note on calibration in stony soils is provided by Stocker (1984). Analyses of the errors inherent in the method are given by Schudel (1983), Haverkamp et al (1984), Hauser (1984) and Vauclin et al (1984). Details on the installation and removal of access tubes are presented by Watt and Jackson (1981) and Wesley and Adams (1983). Data capture from the neutron water meter is addressed by Hulsman (1985).

The advantages of the neutron water meter are that it is nondestructive and a relatively large volume of soil is sampled. Approximately the same volume is sampled each time, which reduces variability (to attain the same precision as one neutron measurement, approximately seven 200 ml gravimetric samples would be required). The disadvantages are that the sample volume is not accurately known, the calibration is critical, and accurate measurement is time consuming (relative to water potential measurements). Health precautions must be observed. Gardner (1986), indicates that the radius of the sphere of influence (accounting for 95 % of the neutron flux which would be obtained in an infinite medium) is given by a reciprocal linear function of the soil water content.

## HYDRAULIC CONDUCTIVITY

Hydraulic conductivity (K) describes the conductivity of soil to the flow of water. The value of K increases exponentially with increasing water content, reaching a maximum, known as the saturated hydraulic conductivity ($K_{sat}$) when the soil is saturated (Figure 6). In drier soil, reference is made to unsaturated hydraulic conductivity, denoted $K(\theta)$ to indicate the dependence on water content. After the soil water retentivity curve, the hydraulic conductivity versus water content curve is the most useful information about soil water behaviour, and $K_{sat}$, which is often taken to represent the final infiltration rate, is one of the easier soil parameters to determine. Since $K(\theta)$ is difficult to determine, one of the

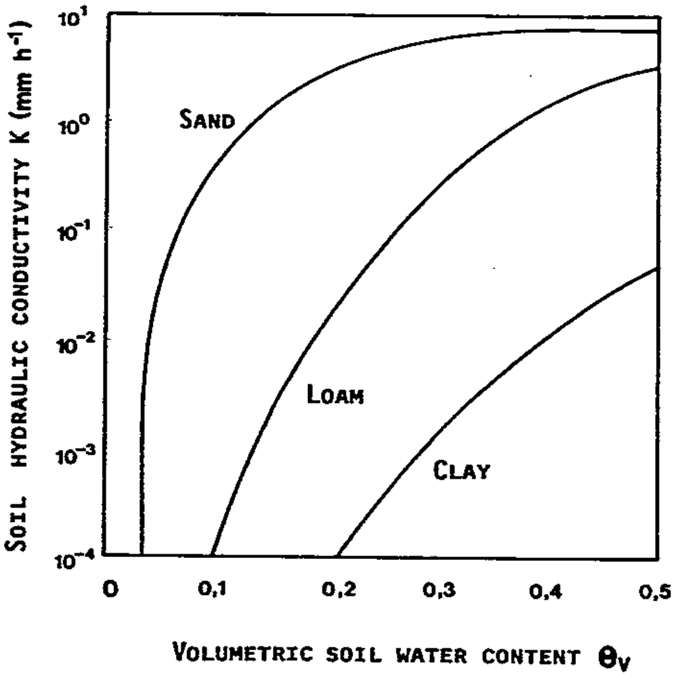

FIGURE 6. Examples of the relationship between hydraulic conductivity (K) and water content ($\theta$) for soils of different textures. Note that hydraulic conductivity is depicted on a $\log_{10}$ scale.

principal uses of $K_{sat}$ is as a matching factor for the calculation of K($\theta$) from other soil data. Since the hydraulic conductivity curve and the water retentivity curve are both functions of pore size distribution, many attempts have been made to find a common system of functions to describe them (Mualem 1976, 1986).

## Saturated hydraulic conductivity - D A Russell

Saturated hydraulic conductivity ($K_{sat}$) may be measured in the field (Amoozegar and Warrick 1986), in the laboratory (Klute and Dirksen 1986) or estimated from other soil parameters (Hutson 1983; Campbell 1985). The last method should only be used to expand on known data, or where no other approach is feasible.

Field measurements are theoretically the best, but can be expected to exhibit order-of-magnitude variability in $K_{sat}$. Where the horizon for which the conductivity is being measured is below the water table (ie groundwater studies), then well-pumping (piezometer) methods can be used. More often the soil in question is above the water table, and single or double ring infiltrometers are used. A recent development, which is simple, portable, uses little water and is apparently reliable, is the constant head well permeameter. Details of one design, the "Guelph permeameter" are given by Reynolds et al (1983) and Reynolds and Elrick (1986).

Laboratory measurements are relatively simple, but must be performed using undisturbed samples obtained using a special core sampler. There is always some doubt as to how representative such measurements are of field conditions, particularly in highly structured soils. Stony soils cannot be sampled without disturbance.

## Unsaturated hydraulic conductivity - HvH van der Watt

For an understanding of the principles and problems involved in the measurement of the unsaturated hydraulic conductivity ($K(\theta)$) of soil, the general equation of flow (Richards' equation) should be considered first. The derivation and explanation of this equation is given in most modern soil physics texts (eg Hillel 1971, 1980). A description of laboratory methods is given by Klute and Dirksen (1986), field methods by Green et al (1986) and calculation methods by Mualem (1986).

The difficulties encountered in the measurement of $K(\theta)$ stem from the fact that in unsaturated soil the flow rate of water is very low. For example, in the case of a sandy soil at a matric potential of -10 kPa (wet condition) $K(\theta)$ is of the order of 0,5 mm $day^{-1}$.

The methods that have been used for the determination of K are many and varied. The trend in the preferred methods has been from laboratory methods to model calculations to field methods. The most frequently used methods are:

### 1. Laboratory methods

Use of disturbed samples or repacked soil columns cannot be recommended in any of these methods:

(a) columns - steady state conditions (Klute 1965; Hillel 1971);
(b) columns - infiltration measurements (Youngs 1964);
(c) cores - evaporation measurements (Arya et al 1975); and
(d) pressure plate outflow data (Gardner 1956; Passioura 1977).

### 2. Calculations based on capillary models

Various workers discuss such calculations (Marshall 1958b; Millington and Quirk 1961; Jackson 1972; Maulem 1976, 1986; Beukes 1986).

The accuracy of predictive methods using capillary models or retentivity functions is uncertain, even when matching factors are used (Russell 1982; Beukes 1986).

### 3. Calculations using water retentivity functions

For such calculations, the reader is referred to Campbell (1974, 1985) and Hutson (1983).

### 4. Field methods

Most of the field methods are very time-consuming:

(a) infiltration method (Hillel and Gardner 1970);
(b) internal drainage (instantaneous profile) method (Watson 1966; Hillel et al 1972). This method has been widely preferred, although somewhat time-consuming;

(c) plane of "zero flux" (Arya et al 1975). More rapid than the internal drainage method;

(d) the θ, flux, CGA and other simplified, newer methods (Libardi et al 1980; Chong et al 1981; Jones and Wagenet 1984). These methods are simple and usually of acceptable accuracy if soil spatial variability is considered (Jones and Wagenet 1984).

## DEEP DRAINAGE - D A Russell

Deep drainage, defined as the flow of water below the rooting zone, is nearly impossible to measure directly. Some large-scale estimates can be obtained from borehole recharge data, and lysimeters provide estimates on a small scale. In general deep drainage is either calculated by measuring all the other components in the field water balance equation, or by modelling water movement in the deep soil layers. Both approaches have many sources of error. Since deep drainage is usually only a small fraction of rainfall input in South Africa, the errors tend to be large relative to the mean value for drainage. If possible more than one approach should be employed. At soil depths greater than about 4 m the rainfall pulses have been damped out. In such a case flow is approximately steady-state, and equal to the hydraulic conductivity at the particular water content. A relatively simple modelling approach, which ignores unsaturated flow, uses a knowledge of the infiltration parameters and the root zone water deficit to give an estimate of the proportion of applied water percolating below the root zone (Bishop et al 1967). The water content of deep soil horizons is usually measured using a neutron water meter. Special precautions, such as the use of a dummy probe and an oversize, fully lined access tube, must be observed to avoid the loss of the probe.

Another simple procedure for relating drainage to the soil water content is described by Ritchie (1981), developing a procedure by Black et al (1969).

### Porous cup (tensioned) lysimeters

Simply, porous cup lysimeters are tensiometers modified to extract a sample of soil solution. They are used to monitor changes in the in situ soil solution, but can also be used to give qualitative estimates of deep drainage. Variants such as porous plates and tubes sample from a more definable volume, but are less easy to install and alter the soil water flow regime in a way which is difficult to predict. They are often used to prevent water-logging in the bottom of weighing lysimeters.

Commercially available porous ceramic cups (about 50 mm diameter) are most commonly used (Reeve and Doering 1965). Modifications have, however, been introduced for specific purposes: glass filter (Long 1978), Teflon (Morrison 1982) and micro-ceramic (6 mm diameter, de Jong 1976). "Plugging" of pores decreases cup conductivity and hence the radius of influence of an extraction unit. Thus, much less than previously predicted flow disturbance (relative to unextracted soil), is found to occur in the vicinity of the cup (Talsma et al 1979). The retention and release of nutrients by ceramic cups have been investigated by Nagpal

(1982) amongst others. A device to control the extracted volume is described by Chow (1977). An useful vacuum extractor made of porous ceramic tubing within a trough has been developed by Duke and Haise (1973) to measure deep percolation both quantitatively and qualitatively and used by Montgomery et al (1987).

The advantages of porous cup tensioned lysimeters are that they:

1. obtain in situ soil solution sample with minimal soil disturbance;
2. are relatively cheap;
3. are easy to operate and maintain; and
4. operate in soil water content range where most water flow occurs (0 to -0,03 MPa).

However, they have certain disadvantages:

1. possible disturbance of water flow pattern in vicinity of cup;
2. possible nitrate screening and phosphate adsorption; and
3. limited soil water range.

The bubbling pressure of such units varies. As low as about -0,2 MPa is possible, but a normal operating range is 0 to -0,08 MPa

### Pan (tensionless) lysimeters - R J Scholes

Pan lysimeters are trays or troughs inserted horizontally into the soil to intercept downward flux density of soil water and direct it to a sample bottle. They are simple in design, manufacture and maintenance, but difficult to install. Their main disadvantage is their interruption of the flow path, causing flow into the sample bottle to be erratic, and therefore an underestimation of the true downward flux densities. An example design is given by Jordan (1978).

## EVAPORATION FROM THE SOIL SURFACE - R J Scholes

Evaporation from the soil surface is difficult to measure, since it varies with soil water distribution, soil surface conditions (roughness, reflection coefficient, litter and plant cover) and micrometeorological conditions (irradiance, wind speed profile, temperature and saturation deficit). Soil surface evaporation is one of the largest components of the water balance, of similar magnitude to transpiration (Ritchie 1972), and therefore warrants careful measurement. The theory of evaporation from the soil surface is discussed by Hanks and Ashcroft (1980), Hillel (1982) and Campbell (1985). Boast (1986) presents methods for its measurement. The possible approaches include modelling on the basis of micrometeorological measurements, remote sensing of soil reflection coefficient and temperature, water balance calculations and lysimetric methods. The latter include evaporimeters for measurement of the evaporation rate during the first (constant rate) phase of evaporation, and microlysimeters which are especially useful during the subsequent falling rate phase. Lysimetry is the recommended approach, but some level of modelling appears inevitable to apportion evapotranspiration between the soil and plant components in a vegetated system.

## QUANTIFICATION OF ROOTS - R J Scholes

The finest roots (less than 2 mm in diameter) are responsible for the majority of water and nutrient uptake. Fine root distribution in the soil can be expressed in terms of mass (kg $m^{-3}$), length (m $m^{-3}$), surface area ($m^2$ $m^{-3}$), volume ($m^3$ $m^{-3}$) or relative proportion (%). Most plant root uptake models require either the relative distribution of roots in the profile or the absolute root lengths per unit soil volume in each soil horizon (referred to as the root length density). For uptake studies, root mass or volume is inappropriate, and it is difficult to convert mass units to length units, since the mean root diameter is usually unknown. The profile wall method is a rapid technique for obtaining relative distribution data (Böhm 1979). Coring is the most efficient way of obtaining fine root length data. Corer designs are given by Welbank et al (1974) and Foale and Upchurch (1982). If the cores break easily, the core break technique (Drew and Saker 1980) avoids the necessity to extract the roots. Otherwise, a root washer such as that described by Smucker et al (1982) is required, and the length of the washed roots is determined by the intercept method (Newman 1966, improved by Tennant 1975), which can be automated. Automation requires that the sample be very carefully sorted to remove debris. Root uptake activity can be directly measured by monitoring the change in soil water content using a neutron water meter (van Bavel et al 1968), or by using various radioactive tracers (Baldwin et al 1971). These methods are laborious and include several sources of error.

### Root uptake models

Root water uptake models are functions which relate the rate of water uptake from the soil (or a given soil horizon) to the soil water content, root length, atmospheric water demand and plant water status. A recent review of root uptake models, most of which are based on the electrical analog, is given by Molz (1981).

The partitioning of the total soil-plant resistance into different components is described by Feddes and Rijtema (1972). The soil, soil-root contact, radial root and axial root resistances are the most important. Oosterhuis (1983) presented a review on the relative importance of the different resistances in the soil-plant system.

The water uptake process can be studied using a single root microscopic approach (Taylor and Klepper 1978) or a macroscopic whole root system approach. For the microscopic approach, it is necessary to measure or calculate the soil water potential at the soil-root interface. It can be measured using micropotometric methods (Rowse and Goodman 1981) or can be calculated (Gardner 1960).

The soil resistance only becomes significant when the soil water potential is lower than -1,5 MPa (Reicoscky and Ritchie 1976). The major resistances seem to be located in the soil-root contact zone (rhizosphere) and in the radial pathway through the roots (Newman 1969). The resistance or conductance for the combined soil-root pathway is a function of the rooting density (Ehlers et al 1981).

# MEASUREMENT OF PLANT WATER STATUS

M J Savage, R J Scholes, R Mottram and P J Dye

## PLANT WATER STATUS

Plant water status is the degree to which physiological processes are limited by the availability of water to the plant. It is usually expressed in terms of water potential, but can equally be expressed by relative water content, or even some other index such as leaf temperature or leaf angle. Water content is easily measured if the sample can be sacrificed, but for continuous measurements, water potential (by hygrometry) is preferable. Water potential has the additional advantage of having a thermodynamic interpretation (unlike leaf temperature) but there is little evidence that it correlates better with the rate of physiological processes than RWC does. Leaf water potential and RWC can be related by determining a pressure-volume curve. A plant water status index should be chosen to suit the study objectives and equipment available.

## PLANT WATER POTENTIAL - M J Savage

### Hygrometry

As in soil hygrometry there are two measurement techniques: thermocouple psychrometry and dew-point thermometry. The sample chambers are identical but the electronic circuitry is different. Thermocouple psychrometry is simpler, but requires a chart recorder for accurate work. Hygrometry can be performed in situ (Campbell and Campbell 1974), or on tissue samples cut from the plant. The latter technique is destructive, but has the advantage of being able to differentiate the turgor and osmotic components of total water potential, following destruction of the cell walls by immersion of the sample chamber (including leaf sample) in liquid nitrogen (Walker et al 1983, 1984). It is also much easier to perform, since interfering thermal gradients can be eliminated by equilibrating the sample chambers in an insulated box. In situ hygrometry provides continuous data and avoids errors due to cutting the leaf, but requires diligent precautions to minimize thermal gradients in the instrument block. The necessary modification of commercially available units and the application of the technique are presented by Savage (1983), Savage et al (1983, 1984), Savage and Cass (1984a,b) and Savage et al (1986).

Hygrometry is the most precise way of determining plant water potentials (absolute accuracy within 0,025 MPa over the range -0,05 to -6 MPa; relative accuracy is within about 0,015 MPa), but the sensors (especially the in situ type) and necessary electronics are expensive. Great care is required to obtain the best performance from the instruments, especially for field work. Potential sources of error include thermal gradients, faulty calibration, dirty sensors, salt exudation by the plant (Klepper and Barrs 1968) and failure to allow enough time for thermal and water potential equilibration.

### Pressure chamber

The principle of the pressure chamber (previously known as the 'Scholander bomb', Scholander et al 1965) is analogous to that of the soil pressure chamber. If a leaf or twig is cut from a plant the xylem fluid recedes up the xylem in the cut part. When the leaf is placed in a sealed chamber with only the cut end exposed to the atmosphere, and gas is introduced into the chamber under pressure, the fluid is forced back to the surface of the cut, which it reaches when the applied pressure exactly balances the xylem water potential at the time of excision. The technique has been used for leaves, twigs, roots, fruits and tubers. Its popularity is due to its rapidity and intuitive simplicity, but accurate results require careful attention to measurement techniques (Ritchie and Hinckley 1975; Brown and Tanner 1981; Savage et al 1983; Turner 1987). Measurements in the range 0 to -6 MPa can be obtained using standard instruments, and down to -12 MPa using specially designed equipment. Accuracy can be to within 0,05 MPa. Sources of error include poorly defined endpoints, failure to protect the excised twig from evaporation losses (Turner and Long 1980), crushing the xylem when sealing the chamber and excessive haste when increasing the chamber pressure. Although not usually recommended, some workers have stored plant material for long periods of time prior to measurement (Karlic and Richter 1979).

### The J14 press

The J14 press is similar in principle to the pressure chamber, but the pressure is applied mechanically instead of by pressurized gases. This means that the instrument is portable, safe and quick to use, and by defining different endpoints, osmotic and total potential can be measured on the same sample. It is less accurate than the other methods (Bristow et al 1981, Grant et al 1981), and is biased relative to measurements taken with the pressure chamber or hygrometers.

## PLANT WATER CONTENT - R J Scholes

Plant water content is not usually used as a field measurement of plant water stress in South Africa, but should be considered as a simple and low cost alternative to plant water potential where appropriate. The procedures for determining the relative water content (RWC) of a tissue sample are presented by Slavik (1974). They involve finding the wet mass, the turgid wet mass following equilibration in a saturated atmosphere, and the mass following drying at 80 °C.

RWC = (wet mass - dry mass)/(turgid mass - dry mass).

The RWC can be monitored continuously and nondestructively by measuring changes in leaf dimensions, using a Beta gauge or a micrometer (Burquez 1987).

## INFRARED THERMOMETRY - R Mottram

Infrared thermometry is a technique for the remote sensing of the surface temperature of foliage, to an accuracy of about 0,2°C. Since plant leaf temperature is normally less than air temperature, due to the latent heat of evaporation of transpired water, the leaf-air temperature difference is used as an indication of plant water stress (Tanner 1963). The index has been refined into 'Stress-Degree-Day' concept by Idso et al (1981). The subject is reviewed by Kirkham et al (1983). Dippenaar and Weyers (1984), Berliner et al (1984), Mottram et al (1983) and Torman (1986) give examples of applications. Errors due to wind (O'Toole and Hatfield 1983) and viewing angle (O'Toole and Real 1984) must be considered.

## POROMETRY - P J Dye

A porometer is a device for measuring the rate of movement of a gas through a system of pores. In this case the gas is water vapour, and the pores are the stomatal apertures in the leaf surface. Porometer measurements are traditionally expressed as stomatal resistances (s $m^{-1}$). Expressing the data as stomatal conductance (1/resistance; mm $s^{-1}$) instead (Incoll et al 1977) avoids problems with very large numbers when the stomata close. The units can also be expressed in quantity terms; $m^2$ s $mol^{-1}$ and mol $s^{-1}$ $m^{-2}$ for resistance and conductance respectively. With some instruments the measurements are indicated directly in transpiration units (mg $s^{-1}$ $m^{-2}$). These are not true transpiration flux densities since the instrument cuvette alters the boundary layer around the leaf. The stomatal resistance (or conductance) is an index of plant water status which can in theory be directly related to plant water use (and photosynthesis, since $CO_2$ must diffuse in through the same stomatal apertures), but in practice its high variability between parts of the canopy and over short periods of time (for instance, when the sun is obscured by clouds) makes it very difficult to integrate over a whole plant or day (Leverenz et al 1982). Also, each stomate is independent of each other stomate (Lange et al 1971). Leaf water potential is much less variable. The main advantage of porometers is the rapidity and simplicity of the measurement. Useful precautions in the calibration and use of porometers are presented by Morrow and Slatyer (1971).

Many designs of porometers have been reported, with design improvements culminating in the continuous flow (steady state) instruments now in general use (Beardsell et al 1972). These devices are accurate and easy to use, and avoid the problems of calibration and humidity drift associated with transient porometers. The choice of porometer depends more on the suitability of the leaf chamber, convenience and cost considerations than on considerations of accuracy.

## PRESSURE-VOLUME CURVES - M J Savage

The pressure-volume curve is a graphical plot of the leaf water potential versus the relative water content (Figure 7). Several variants are possible (Tyree and Richter 1981), but one of the axes is usually plotted as a reciprocal so that the curve is linear once turgidity is lost (Richter 1978). An alternative form, containing the same information, is the Höffler (1920) diagram.

The curves summarize a great deal of information about the plant water use strategy: 1) they allow the calculation of water potential from water content and vice versa to be performed; 2) the osmotic and turgor components of the total potential and the apoplasmic and symplasmic components of leaf water are indicated; 3) they allow the calculation of the bulk modulus of elasticity; 4) they enable the breakdown of leaf tissue due to drought damage to be determined (Turner 1976, Kyriakopoulos and Richter 1981).

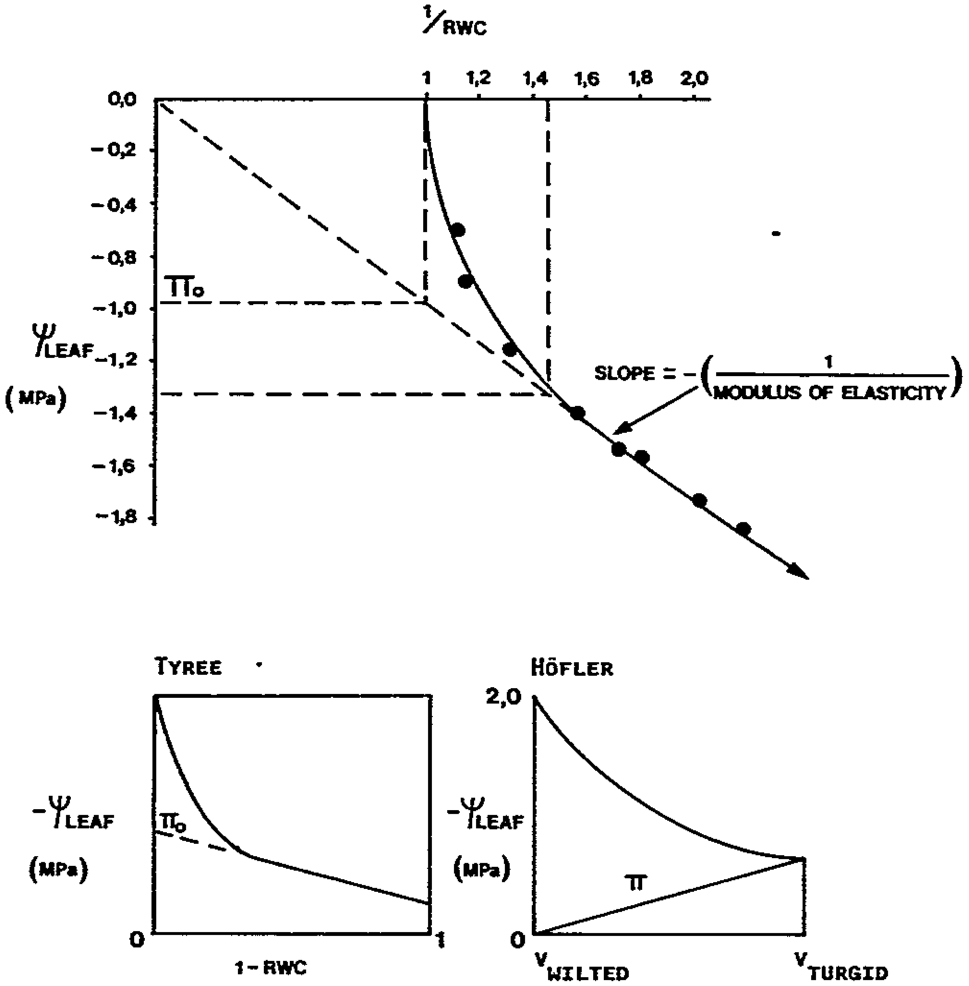

FIGURE 7. Pressure-volume curves for plant tissues drawn in various ways. Cell osmotic potential ($\pi_o$) is determined by extrapolation to the point of full turgidity where RWC = 1.

The curves are usually determined using a pressure chamber and applying the overpressurization method, where the volume of water exuded at each pressure increment is determined by collecting it on filter paper or in a capillary tube. The method takes about 2 h to perform. An alternative is the leaf drying method (Grant et al 1981; Richter 1978), in which the leaf is allowed to transpire between successive measurements of leaf potential, using either a pressure chamber or hygrometer. The same leaf need not be used in each case to obtain the curve of water content *versus* leaf potential. If the same leaf is used in conjunction with a pressure chamber, the pressurizing gas should be nitrogen to avoid membrane oxidation. A third method is the equilibration method, in which leaves are equilibrated above salt solutions of known osmotic potential, following which their water content is determined.

# TRANSPIRATION MEASUREMENT

R J Scholes and G C Green

## GAS ANALYSIS - R J Scholes

In gas analysis, the plant or plant part is enclosed in a chamber (the cuvette) and the increase in humidity due to transpiration is measured. The design principle is very similar to that of transient or continuous flow porometers (and the transpiration rate is usually expressed as a stomatal resistance). The difference is that gas analysis machines simultaneously measure the decrease in $CO_2$ due to photosynthesis in the same sample. This usually means that the cuvette is attached to an infrared gas analyser (IRGA) for the $CO_2$ determinations. Other methods of measuring $CO_2$ have been described (soda-lime traps, $^{14}C$ radioactive tracers) but are less convenient. In theory the IRGA is able to monitor the humidity increase as well, as is done in some benchtop setups, but in field systems the humidity is monitored by a capacitance sensor (as in porometers), and the air is dried before passage through the IRGA. A general discussion of gas analysis system design considerations is presented by Slavik (1974). The currently available field systems are all of the closed system transient type; therefore attention must be paid to sealing the cuvette against leaks, matching the cuvette volume to the IRGA sampling rate, and the duration of time for which plant parts are enclosed in the cuvette. Whole plant cuvettes integrate the rates over the whole canopy, but if larger than about 5 litres they tend to overheat unless they are coupled to sophisticated cooling systems.

These instruments are considerably more expensive, complicated and delicate than porometers, and if stomatal resistance is the only measurement required, porometers are probably more accurate. They are uniquely suited to studies linking water use and productivity. Several models are available; the choice should be based on convenience and suitability of the cuvette for the plants being studied.

## LYSIMETRY - G C Green

A lysimeter intended for studying water dynamics in the SPAC may be defined as a volume of soil (usually undisturbed but sometimes disturbed) with clearly defined boundaries, facilitating measurement and control of inputs and outputs of liquid water, and measurement of changes of water content. This enables the soil water balance equation to be solved for the evapotranspiration component over a time interval which depends on the resolution of the system.

Weighing lysimeters have been in common use since approximately 1960. References to publications describing the design and performance of several early installations, both in South Africa and overseas, are given by Green et al (1974) and Hutson et al (1980). Modern weighing lysimeters generally have electrical sensors to make them amenable to automatic data logging.

Two types, employing different weighing principles, are in common use. The first uses a mechanical lever system and a single electronic load cell

(Hutson et al 1980), while the second determines the mass directly using an arrangement of load cells in parallel (Green et al 1974, Green and Bruwer 1979).

The advantages of the mechanical lever type are the following:

1. simple, precise mechanical taring is possible;
2. a single low capacity load cell can be used for the entire measuring range;
3. extremely high accuracy and resolution can be achieved, making hourly evaporation measurements entirely feasible; and
4. electronics are simple and maintenance costs low.

The main disadvantage is that lysimeters of this type are limited in size due to escalating costs associated with larger mechanical weighbridges.

The main advantage of the direct measurement type is the cost advantage in large systems (from say 20 000 to 60 000 kg or more), while the disadvantages are the large proportion of dead mass and utilization of only a small part of the operating range of the load cells. Furthermore, the most acceptable resolution is only achievable with the use of the highest precision load cells and the most sophisticated electronics. Both lysimeter types give rise to potentially high maintenance costs. Resolution adequate for hourly evaporation measurements is not easily attainable.

To best simulate the natural root zone conditions and typical soil water regimes, the lysimeter should ideally be designed for a soil monolith and use a sophisticated suction drainage system. In practice, carefully repacked disturbed soil does stabilize with time and thereafter resembles the natural undisturbed soil. However, drainage conditions similar to those in natural soils are rarely simulated. This leads to anomalous soil water and plant root distributions in the lysimeter tank, the anomalies being most serious in shallow (less than 1 m deep) lysimeters and under conditions of developing water stress. The effect of these anomalies on several aspects of plant water relationships are described by Berliner and Oosterhuis (1987).

## Usefulness of weighing lysimeters

1. Weighing lysimeters are more useful for irrigation research than for dryland agricultural or ecosystem research because of the wetter soil water regimes under irrigation.

2. When close representation of natural field conditions is required, the use of lysimeters for studying plant responses to climate and other factors is limited to soil water regimes which permit evapotranspiration to take place at potential rates.

3. If strict representation of field conditions is not an issue, lysimeters can be most useful for investigating water use and related physiological processes associated with soil water deficits.

4. Lysimeters have proved to be most useful systems for providing comprehensive "special case" data sets for the validation of dynamic soil water and evapotranspiration models.

## HEAT PULSE METHOD - G C Green and B W Olbrich

The heat pulse method, as applied to the measurement of sap flux density, involves measurement of time elapsed between the release of a heat pulse applied to the stem and the occurrence of the maximum temperature at various positions at fixed distances downstream. The theory (Marshall 1958a) is based on the solution of the convective heat-diffusion equation in two dimensions. Suitable equipment for trees and its calibration have been described by Cohen et al (1981).

For thin-stemmed plants, methods based on concepts described by Stone and Shirazi (1975) will have to be developed.

Besides the accurate measurement of temperature and time intervals, it is necessary to obtain data on the thermal diffusivity, density and specific heat capacity of the live wood. The thermal diffusivity is easily determined by monitoring the travel time of a heat pulse under conditions of zero sap flow at night. The other parameters are easily obtained by conventional means.

Sap flux density declines radially with depth beneath the bark. In order to arrive at total sap flow rate, flux densities calculated at each measurement depth beneath the bark have to be integrated over the entire stem cross-section, requiring accurate measurements of cross-sectional dimensions of the stem.

Extensive calibration of the heat pulse method for several species has revealed that theoretically predicted sap flow consistently under estimates transpiration by approximately 45 %. For a given species, *Citrus sinensis*, empirically corrected field measurements of sap flow using the heat pulse technique have been found to be accurate within 5 %.

The theory developed by Marshall (1958) assumes conditions of idealised heat transfer within the sapwood. Swanson and Whitfield (1981) showed that the wound caused by drilling holes to insert the heat pulse probes was the major source of departure of practice from theory. It is thus necessary to correct for the size of this wound and to adjust for the specific probe material used. Taking the above factors into account, heat pulse measures of water use have been shown to correspond well with lysimetry, transpiration or whole tree potometer readings for a variety of tree species including *Pinus radiata, Nothofagus solandri, Populus tremuloides* (Swanson 1983) and apple (Green and Clothier 1988).

The <u>main advantages</u> of the heat pulse method are:

1. it is very sensitive and has proved to be accurate in several applications;
2. it can be automated and is amenable to routine use; and
3. there is no need to measure the canopy leaf area.

<u>Disadvantages</u> are:

1. The rates obtained should be verified by some other technique, especially in large-vesselled plants such as vines.

## CUT SHOOT METHOD - R J Scholes

The mass loss of an excised shoot is accurately determined over a short period of time (about 5 min) and is assumed to represent the pre-excision transpiration rate. It is usually expressed per unit leaf area or leaf dry mass of the cut shoot. Weighing must be rapid and accurate. A battery-powered digital balance accurate to 0,01 g, shielded against the wind, is most suitable. Between weighings the shoot should be exposed in the same position and orientation as it occupied before cutting. Some species show a sharp increase in transpiration rate immediately after being cut; all species show a gradual decline in rate as the shoot dries out. A pilot run, weighing every minute for 15 minutes, should be performed to determine the most suitable interval for the species under consideration. The method is simple, rapid and cheap. Accuracy is within about 10 %. Considering the errors inherent in extrapolating from a small sample to a whole plant (or field), which apply to this method as well as to more sophisticated techniques such as porometry, this method is probably as accurate as any other field technique. The disadvantages are that it is destructive, and the leaf water potential is altered by cutting the xylem. On the other hand, the leaf external environment is not altered as it is with porometers.

## MICROMETEOROLOGICAL METHODS

Transpiration may be estimated by measurement of the water vapour gradient above a transpiring surface. This technique is theoretically attractive, since the plant environment is not interfered with, but in practice is only suitable for large areas of homogeneous vegetation, such as extensive, flat grain fields. High-precision micrometeorological instruments and a multichannel datalogger are required, as well as a computer to perform the calculations. The main problems are turbulence, instability and advocating and ensuring sufficient upwind fetch for the models to be valid. The method is not yet ready for general application. The theory is presented by Thom (1975), and a South African example by Bristow and de Jager (1981).

# MICROMETEOROLOGICAL AND MODELLING ASPECTS OF SOIL, PLANT AND ATMOSPHERE WATER RELATIONS

**M J Savage, D R Morrey and W J van Zyl**

A minimum set of micrometeorological measurements and soil water determinations is an essential accompaniment to any work on plant water status, since the plant water status at any given moment is a function of atmospheric water demand and soil water supply. This set should include radiant flux density, air temperature, wind speed and relative humidity. Measured or calculated potential evapotranspiration integrates these factors in a biologically meaningful way.

## RADIATION MEASUREMENT* - M J Savage

The energy source that drives water in the SPAC is solar radiation (Figure 8). Apart from being an essential measurement to accompany measurements of soil and plant water status, solar irradiance may be used for the calculation of potential evapotranspiration and as an input to some models relating to the SPAC. Radiation measurement is deceptively simple, but large errors often occur due to ignorance of the necessary conditions, precautions and calibrations. Radiation can be measured and expressed according to three different systems; the photometric, radiometric and quantum systems. Interconversion between the systems can only be done by approximation. The photometric system refers to radiant energy that is visible to the human retina. Only this segment of the radiation spectrum may properly be called 'light'. The system is used by lighting engineers and photographers, but apart from historical comparisons, has no place in plant physiology or meteorology.

The quantum system, centered around the term photosynthetic photon flux density (PPFD), involves the measurement of the number of photons (in Avogadro units) incident on a plane over a given time period. Since the energy content of a photon (a quantum of radiant energy) is a function of its wavelength, the system is said to be wavelength dependent. Photochemical processes such as photosynthesis are controlled by the number rather than the energy content of the photons intercepted (provided their energy is within the action spectrum of the process), making the quantum system particularly suitable for photosynthetic work. There is no international standard for the Photosynthetic Active Radiation (PAR), but the 400 to 700 nm waveband is generally accepted (McCree 1981). The term photosynthetic photon flux density (PPFD), with SI units of mol $s^{-1}$ $m^{-2}$ is the accepted measurement of PAR, replacing the einstein $s^{-1}$ $m^{-2}$. The sensor is a silicon diode quantum sensor with a spectral response approximating that of a photosynthesising leaf. The sensors are robust and relatively inexpensive.

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* Based on a paper by Savage (1988)

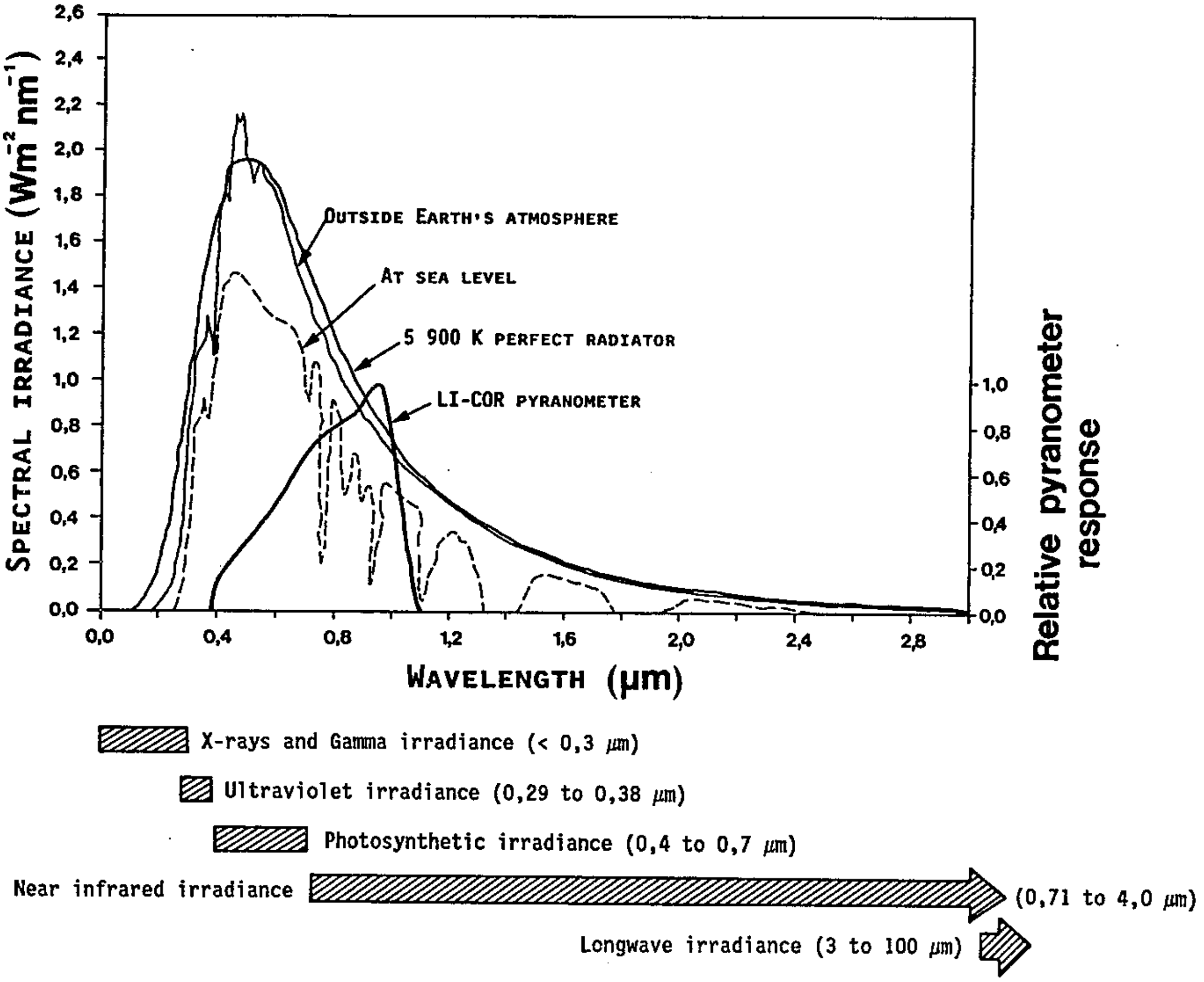

FIGURE 8. The solar radiation spectrum in relation to biologically important wave bands. Wavelengths greater than 0,4 µm contain most of the energy responsible for water transport in the SPAC. Ultraviolet irradiance is involved in photomorphogenesis and shorter wavelengths are responsible for genetic damage.

The radiometric system gives equal weight to all types of radiant energy, irrespective of wavelength. It is the appropriate system to use in energy balance studies such as micrometeorological models (for example, potential and actual evapotranspiration, SPAC models). Irradiance or radiant flux density has SI unit W $m^{-2}$ (J $s^{-1}$ $m^{-2}$). Integrated over time this becomes radiant density (J $m^{-2}$). Irradiance should always be totalled, and not averaged. The general term for the sensors is radiometer; those specifically designed for measuring direct solar irradiance are called pyrheliometers and those measuring total solar irradiance are called solarimeters. Thermopile radiometers operate by detecting the temperature difference between black- and white- (or silver-) painted pads exposed to the sun. They are extremely accurate, but may have a slow response time. They may be shielded with various filters in order to measure a specific portion of the spectrum. Those covered with polished glass domes allow for the measurement of solar irradiance (short wavelengths between 295 to 2 800 nm). Infrared irradiance (wavelengths greater than 700 nm but less than 2 800 nm) can be measured with the same instrument, fitted with a red filter. Therefore photosynthetic irradiance (PI) can be approximated as the difference between solar and infrared irradiance (Table 2). Net radiometers are covered with a thin polyethylene bubble which is rather fragile under field conditions. Usually net irradiance is calculated from empirical relations to solar irradiance (Szeicz 1974). The standard shortwave radiometer is a Kipp solarimeter, which should be calibrated against a Linke-Feussner pyrheliometer. A second Kipp solarimeter, stored in a dark place, is useful for routine calibration checks. Tube solarimeters are less expensive, and are useful for canopy interception studies, where their long sensing element integrates patchy sunflecks. They should ideally be oriented north-south in the early morning and late afternoon, and east-west near noon. For studies of sunflecks, a silicon diode sunfleck ceptometer has a finer resolution and more rapid response than a tube solarimeter. Silicon diode radiometers, referred to as silicon pyranometers, are calibrated for direct sunlight, and so they should never be used in growth chambers, beneath plant canopies, for reflectivity or diffuse radiation measurements or on very overcast days unless they have been specifically recalibrated for that purpose. Quantum silicon photodiodes may be used for the measurement of photosynthetically active radiation (that is PPFD) in growth chambers provided the lamps used do not have thin spectral lines. Kipp solarimeters or tube solarimeters can be used in growth chambers with the same proviso and can also be used for reflection coefficient measurements.

Commercially available integrators or dataloggers allow irradiance to be integrated. Daily total radiant density, in MJ $m^{-2}$, is the integral (or the summation for the discrete case) of solar irradiance over time of day. Note that irradiance is integrated or totalled but not averaged.

A summary of sensors and their uses is presented (Table 2).

TABLE 2*. Some plant physiological processes for defined wavebands, radiation terms, instrumental details and units (for instantaneous and integrated measurements) associated with various thermoelectric and photodiode sensors. Manufacturers addresses are listed at the base of the table.

| Waveband (nm) and processes | Radiation term | Instrument (sensor cover) | SI Unit | |
|---|---|---|---|---|
| | | | Instantaneous | Integrated |
| **THERMOELECTRIC SENSORS** | | | | |
| 250 to 2 800; water movement; canopy temperature | Solar irradiance $I_s$ | Moll-Gorczynski or Kipp or Eppley (from Science Associates) solar radiometer/pyranometer (glass) | W m$^{-2}$ | MJ m$^{-2}$ |
| 250 to 2 800; water movement; canopy temperature | Direct beam irradiance | Linke-Feussner pyrheliometer | W m$^{-2}$ | MJ m$^{-2}$ |
| 400 to 700; photosynthesis (energetic) | Photosynthetic irradiance PI, PI = $I_s$ - IR | By subtraction of measurements from a Delta-T Devices unfiltered and an infra-red filtered thermopile radiometer (glass; infrared filter) | W m$^{-2}$ | MJ m$^{-2}$ |
| 700 to 2 800; flowering, fruiting, seed germination | Infrared irradiance IR | IR filtered thermopile radiometer (glass and infrared filter) | W m$^{-2}$ | MJ m$^{-2}$ |
| 250 to 100 000; partitioned into sensible and latent energy | Net irradiance $I_{net}$ | Net radiometer of thermopile type (usually polyethylene for the non-ventilated type) | W m$^{-2}$ | MJ m$^{-2}$ |
| **PHOTODIODE SENSORS** | | | | |
| 400 to 700; photosynthesis (energetic) | Photosynthetic irradiance PI | Didcot integrating PAR silicon sensor, Decagon silicon ceptometer, Delta-T Devices energy sensor type ES | W m$^{-2}$ | MJ m$^{-2}$ |
| 400 to 700; photosynthesis (quantum) | Photosynthetic photon flux density PPFD | Li-Cor quantum or line quantum silicon photodiode sensor | mol s$^{-1}$ m$^{-2}$ | mol m$^{-2}$ |
| 400 to 1 100; water movement; canopy temperature | Solar irradiance $I_s$ | Silicon diode pyranometer | W m$^{-2}$ | MJ m$^{-2}$ |
| 660 and 730 only; phytochrome and biomass research | Ratio of sensor response to two wavelengths | Skye silicon photodiode | - | - |
| 780; flowering, fruiting, seed germination | Near infrared irradiance | Silicon photodiode; narrow bandwidth, typically 70 nm | W m$^{-2}$ | kJ m$^{-2}$ |
| 290 to 385; ultraviolet effects on plants, humans and animals; atmospheric pollution research | Ultraviolet irradiance | Selenium photodiode with glass filter from Middleton Instruments | W m$^{-2}$ | kJ m$^{-2}$ |

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* Taken from Savage (1988)

Manufacturers addresses in order of appearance in the table: Science Associates, P O Box 230, Princeton, New Jersey, USA 08540; Delta-T Devices Ltd, 128 Low Road, Burwell, Cambridge, CB5 0EJ, United Kingdom; Didcot Instrument Co Ltd, Station Road, Abingdon, Oxon, OX14 3LD United Kingdom; Decagon Devices Inc, P O Box 835, Pullman, Washington, 99163 USA; Li-Cor, P O Box 4425, Lincoln, Nebraska, 68504 USA; Skye Instruments Ltd, Unit 5, Ddole Industrial Estate, Llandrindod Wells, Parys LD1 6DF, United Kingdom.

## ATMOSPHERIC EVAPORATIVE DEMAND - W H van Zyl

Atmospheric evaporative demand (AED) is the upper limit of evaporation from natural vegetation (de Jager and van Zyl 1989). AED is defined as the water vapour transfer to the atmosphere required to sustain the energy balance of a given vegetative surface (crop) in a given growth stage when its roots are supplied with adequate soil water to permit unhindered transpiration and the surface soil has a given water content.

Potential evapotranspiration ($E_p$), reference evapotranspiration ($E_o$), maximum evapotranspiration ($E_m$) and basal evapotranspiration ($E_v$) are specific cases of AED. The relevant definitions are:

- Potential evapotranspiration, $E_p$, is defined as evaporation from an extended surface of a green crop which fully shades the ground, exerts little or negligible resistance to the flow of water and is always well supplied with water (Rosenberg, Blad and Verma, 1983).

- Reference evapotranspiration, $E_o$, is defined as the rate of evapotranspiration of an extended surface of an 80 to 150 mm tall green grass cover of uniform height, actively growing, completely shading the ground and not short of water (Doorenbos and Pruitt 1977).

- Maximum evaporation, $E_m$, is defined as the rate of evaporation from an incomplete healthy vegetative cover under which the root zone soil is adequately supplied with water and the soil surface is wet to field capacity or above (de Jager and van Zyl, 1989).

- Basal evapotranspiration $E_v$, is defined as the rate of water loss from an incomplete cover of healthy vegetation with its roots well supplied with water, but for which the soil surface is dry, so that no evaporation occurs from it (Wright 1981).

AED can either be measured with a lysimeter or calculated from weather elements and an appropriate formula:

$$AED = E_pF$$

where F is a normalized crop factor (de Jager, van Zyl, Bristow and van Rooyen, 1982) which takes into account surface wetness and leaf area index. Methods of measuring $E_p$ are discussed below.

## POTENTIAL EVAPOTRANSPIRATION - R J Scholes

Potential evapotranspiration ($E_p$) is quoted in mm day$^{-1}$ or mm h$^{-1}$. Potential evapotranspiration can be measured using a well-watered lysimeter planted with the defined vegetation, but since lysimeters are expensive and clumsy, it is usually calculated from meteorological data. The available methods are reviewed by Rosenberg et al (1983), and in more detail, including practical instructions, by Doorenbos and Pruitt (1977). The reference method is the Penman-Monteith combination formula (Thom, 1975), which has an elegant physical basis. It requires a knowledge of net irradiance (usually approximated from solar irradiance), soil heat flux density (heat flux plate, but is frequently ignored as insignificant on a daily basis), air temperature, water pressure deficit (calculated from relative humidity, air temperature and pressure) and wind speed. Various modifications have been made to replace certain of the measurements with others, or to allow for the effects of wind, advection and different crop surfaces. Very few weather stations record all the data necessary for this calculation. Where less detailed data are available, empirical models which relate $E_p$ to air temperature, irradiance, humidity and various combinations thereof have been developed. Many are reasonably accurate for time periods longer than a week, and within the geographical region for which they were developed. The Linacre (1977) equation is currently the most acceptable general temperature-based equation. Evaporation from a small water body such as an evaporation pan is a crude index of $E_p$ and is usually abbreviated by $E_{pan}$. Pan evaporation has many shortcomings, not least of which is observer error, but may be the only data that are available. Various other evaporimeter designs, such as the Piché or carborundum evaporimeters, can be used in place of the aerodynamic term in the Penman-Monteith equation (Stanhill 1962; van Zyl and de Jager 1987).

The available methods for the estimations of potential evaporation from a vegetated surface are summarized (Table 3).

## MODELLING PRINCIPLES - D R Morrey and M J Savage

Some level of modelling is essential when studying a subject with as many interacting variables as energy and water movement through the SPAC. Models vary in complexity from the conceptual type, which can be expressed in words (such as the electrical analog), through statistical (empirical) models to mechanistic, physically-based models. The level of complexity should not exceed that which is supportable by the resolution of the data or is warranted by the objectives of the study. Statistical models require no a priori knowledge of mechanisms or processes in the system. It is a summary of the system processes, and as such is often not sufficiently robust to apply to a similar system with different ranges of values. A mechanistic model requires assumptions or knowledge about system processes, and if successful, should be adaptable to similar systems. For predictive purposes an empirical model often fits the data better than a rigorous physical model, but the physical model is more satisfying to the scientist, since it involves an explicit and testable hypothesis. Its failure to match observations contains the information needed to generate further hypotheses. With this in mind, models should be exposed to rigorous statistical tests on independently collected data that has not been used to formulate the model. Statistics for model testing are discussed by Wilmott (1980). Modelling should be approached as a process rather than an end result. Very few models are currently used for prediction, extrapolation and decision making. Mostly they are an aid to experiment design and hypothesis generation, as well as facilitating understanding of structure and function. By requiring precise definition of processes, models highlight areas of insufficient data or knowledge. The steps involved in modelling are outlined below:

1. Construct a conceptual model (words, or box-and-arrow);
2. Generate hypotheses and function equations;

TABLE 3. Methods of estimating potential evapotranspiration ($E_p$) from a vegetated surface.

| Method | Requirements | Comments |
|---|---|---|
| I Climatological models | | |
| 1. Based on air temperature | Mean air temperature on a daily, weekly, monthly or annual basis depending on the resolution required.<br>Various formulas also require other inputs. | Minimal data requirements. Accurate in the regions for which they were developed and for periods greater than one week. Data widely available. Thornthwaite (1948) requires daylength, but is unsuitable in the tropics and for periods of less than one month. Blaney-Criddle (1950) also needs daylength and an empirical crop factor. Hargreaves (1974) needs latitude and RH*. Linacre (1977) needs latitude, altitude and either RH or daily temperature range to provide an estimate accurate to 1,7 mm daily, but 0,3 mm/day on a yearly basis. Bailey (1979) requires the air temperature range but is only suitable for annual estimates. |
| 2. Based on radiation | Solar irradiance<br>Various formulas require other inputs as well. | This data is more difficult to obtain than air temperature. Makkink (1957) gives good results in cold, wet climates, but poor results in hot dry climates. Jensen and Haise (1963) also requires air temperature and gives a daily estimate, but underestimates under advective conditions. Caprio (1974) is not widely tested. Idso et al (1975, 1977) needs soil surface temperature, and is suitable for remote sensing. |
| 3. Combination | Net irradiance, soil heat flux density, air temperature, surface temperature, RH and wind speed | This is the reference method and has a sound physical basis. It is applicable to intervals of a few minutes to months, but has high data requirements. Several variants are possible, with slightly different data requirements. Underestimates under advective conditions. Widely used in research applications. Original reference is Penman (1948), but the Thom (1975) form is most used. Also see Slayter & McIlroy (1961), van Bavel (1966) and Priestley & Taylor (1972). |
| II Micrometeorological methods | | |
| 1. Mass transport | RH at two heights<br>Wind speed at one height | Simple to calculate, and accurate for open water bodies once calibrated. Underestimation when plants are stressed. Dalton (1802), Rohwer (1931), Penman (1948) and Harbeck (1962). |
| 2. Aerodynamic | Air temperature and RH at two heights. | Requires very accurate measurement of water vapour pressure and stability correction. If the Bowen-Ratio-Energy-Balance approach is used (Bowen 1926), the intrumentation need not be as responsive. |
| 3. Resistance | Canopy resistance and RH at one height. | Monteith (1963) and Brown & Rosenberg (1973). |
| 4. Eddy correlation | Vertical wind speed and water vapour pressure fluctuations. | Theoretically attractive, but expensive. |
| III Direct measurement | | |
| 1. Lysimeters | Lysimeter | This is a reference method, but is expensive to install and service. |
| 2. Pan evaporation | Standard pan | These data are widely available, but prone to error. |
| 3. Atmometers | Piché or similar | A promising approach if used to estimate the aerodynamic component of the Penman-Monteith combination equation (van Zyl & de Jager 1987). |

* RH - relative humidity (equivalently, water vapour pressure)

3. Determine values for the important parameters;
4. Perform a sensitivity analysis, and return to 2 or 3 if necessary;
5. Verify that the model reproduces the observed data. If not return to 1, 2 or 3;
6. Validate the model against independently collected data not used to formulate the model; and
7. Use the model to solve practical problems.

The simulation of ecological processes is discussed by de Wit and Goudriaan (1978); mathematical models of plant water loss and plant water relations are discussed by Hall (1982); crop simulation models in agronomic systems are reviewed by Whisler et al (1986); and Campbell (1985) discusses the modelling of soil physical systems.

## Applicable models

In modelling, there is always a danger of reinventing the wheel. Wherever possible existing, proven models should be used as components or tools in the modelling process. A list of readily available models relevant to the SPAC is presented (Table 4, taken mainly from Whisler et al 1986).

## MINIMUM DATA SET - M J Savage

The International Benchmark Sites for Agrotechnology Transfer (IBSNAT) Project has defined the minimum data set required to execute and validate a crop model for a given location. The requirements of their models are broadly representative of most models in the SPAC. The IBSNAT minimum data set includes daily weather data, soil profile data, soil nitrogen dynamics data, initial condition soil profile data, irrigation management data, nitrogen fertilizer management data, crop management data, genetic coefficient data and crop specific coefficient data. In general, the shorter the timestep of the model, the more detailed are the data requirements. The minimum weather data set for hourly measurements, for example, includes soil and air temperature, solar irradiance (W $m^{-2}$) and rainfall. For a daily model, mean temperatures, total daily radiant density (MJ $m^{-2}$) and total daily rainfall are sufficient. Of particular note is that wind speed and atmospheric water vapour pressure are not part of the minimum data set used by IBSNAT; most of the IBSNAT models rely on the soil evaporation model of Ritchie (1972) which uses the wind speed and vapour pressure-independent Priestly and Taylor (1972) calculation for potential evaporation. Other information such as the soil surface reflection coefficient (sometimes incorrectly referred to as the "albedo") and also that of full canopy vegetation is required for the partitioning of so-called evapotranspiration into soil evaporation and plant evaporation. The minimum data set for the soil profile data includes the lower limit of plant available water and the drained upper limit ("field capacity").

TABLE 4. Details of readily available models for the description of mass and energy transport in the SPAC (adapted from Whisler et al, 1986, the additions being marked by the superscript[1]).

| Research group | Institutions | Model name | Species | Processes treated |
|---|---|---|---|---|
| Acock B, V R Reddy, F D Whisler, D N Baker J M McKinion, H F Hodges and K J Boote | USDA-ARS, Mississippi State U, and U of Florida | GLYCIM | Soybean | Photosynthesis, respiration, transpiration, growth, and morphogenesis. Incorporates RHIZOS |
| Allen J and J H Stamper | U of Florida | CITRUSIM | Citrus | Photosynthesis |
| Angus J F and H G Zandstra | CSIRO (Australia) and International Rice Research Institute | IRRIMOD | Rice | Growth, phasic development, soil water flow, soil nitrogen, transpiration and evaporation |
| Arkin G F, J T Ritchie and R L Vanderlip | Texas A & M U, USDA/SEA and Kansas State U | SORG | Sorghum bicolar | Photosynthesis, respiration, transpiration and evaporation |
| Baker D N, J R Lambert and J M McKinion | USDA/SEA (Mississippi) and Clemson U | GOSSYM | Cotton | Photosynthesis, respiration, growth and morphogenesis. Incorporates RHIZOS |
| Baker D N, D E Smika, A L Black, W O Willis and A Bauer | USDA/SEA (Mississippi, Colorado and North Dakota) | WINTER WHEAT | Wheat | Photosynthesis, respiration, transpiration, growth and morphogenesis. Incorporates RHIZOS |
| Bristow K L | CSIRO, Townsville, Qld Australia | SWASV2 | Bare soil, mulches | Energy and water movement in fallow soils |
| Brown L G, J D Hesketh, J W Jones and F D Whisler | Mississippi State U | COTCROP | Cotton | Photosynthesis, respiration, transpiration, runoff, drainage, nitrogen uptake, denitrification, leaching, organogenesis, partitioning and growth |
| Childs S W, J R Gilley and W E Splinter | U of Nebraska | Unnamed | Maize | Photosynthesis, respiration, transpiration, growth, soil evaporation and soil water flows |
| Curry R B, G E Meyer, J G Streeter and H L Mederski | Ohio Agriculture Research and Development Centre | SOYMOD OARDC | Soybean | Photosynthesis, respiration, translocation and evaporation |
| de Jager et al[1] | U of Orange Free State, Bloemfontein | PUTU | Maize | Photosynthesis, transpiration, soil water balance |
| de Wit C T et al | Netherlands Agricultural U (Wageningen) | PHOTON and BACROS | Any crop | Photosynthesis, respiration, transpiration, reserve utilization, water uptake and stomatal control |
| Duncan W G | U of Florida and U of Kentucky | SIMAIZ | Maize | Photosynthesis, processes involved in setting seed number and seed size |
| Duncan W G | U of Florida and U of Kentucky | MIMSOYZ | Soybean | Photosynthesis, nitrogen fixation, assimilate redistribution, processes for setting seed number and seed size |

(continued)

**TABLE 4. (continued)**

| Research group | Institutions | Model name | Species | Processes treated |
|---|---|---|---|---|
| Duncan W G | U of Florida and U of Kentucky | PEANUTZ | Peanuts | Photosynthesis, nitrogen fixation, processes for setting seed number and seed size. |
| Fick G W | Cornell University | ALSIM | Alfalfa | Photosynthesis defined as crop growth rate and partitioning |
| Furnis P R[1] | Botanical Research Institute, Pretoria | DRIVER | Any crop | Simulation shell suitable for various ecophysiological processes |
| Holt D A, G E Miles, R J Bula, M M Schreiber, D T Doughtery and R M Peart | Purdue University and USDA/SEA | SIMED | Alfalfa | Photosynthesis, respiration, growth, translocation and soil water uptake |
| Jones C A and J T Ritchie | USDA/SEA (Texas) and IFDC, Alabama | CERES-MAIZE | Maize | Phasic development, morphogenesis, growth, biomass accumulation and partitioning, soil water balance and plant-soil nitrogen status |
| Keig G and J R McAlpine | CSIRO Div of Landuse Research, Canberra, Australia | WATBAL | Natural vegetation or crop | Weekly water balance |
| Kercher J R | Lawrence Livermore Laboratory | GROW1 | General | Photosynthesis, transpiration, translocation |
| Lieth H[1] | | | Any crop | Primary productivity |
| Lambert J L, D N Baker and J M McKinion | Clemson U and USDA/SEA (Mississippi) | RHIZOS | Soil | Infiltration, uptake, capillary redistribution, evapotranspiration, nitrogen transformation, nitrogen fertilizer applications |
| Loomis R S and E Ng | U of California-Davis | POTATO | Potato | Photosynthesis, respiration, transpiration, water uptake, growth, development and senescence |
| Loomis R S, J L Wilson, D W Rains and D W Grimes | U of California-Davis | COTGRO | Cotton | Photosynthesis, respiration, transpiration, water uptake, growth, development, flowering, fruit development, senescence and heat flux density |
| Loomis R S, G W Fick W A Williams, W H Hunt and E Ng | U of California-Davis | SUBGRO | Sugar beet | Photosynthesis, respiration, transpiration, water uptake, growth, plant development and senescence |
| Marani A | The Hebrew U of Jerusalem | ELCOMOD | Cotton (Acala) | Photosynthesis, respiration, growth, morphogenesis, evapotranspiration, nitrogen uptake and gravitational soil wetting |
| McCree et al[1] | Texas A and M University | MCSORGSIM | Sorghum | Photosynthesis, respiration, growth and translocation |

(continued)

TABLE 4. (continued)

| Research group | Institutions | Model name | Species | Processes treated |
|---|---|---|---|---|
| McMennamy J A and J C O'Toole | International Rice Research Institute | RICEMOD | Rice | Photosynthesis, respiration, growth |
| Orwick P L, M M Schreiber and D A Holt | Purdue University | SETSIM | Setaria | Carbon flow, photosynthesis, respiration, growth and translocation |
| Ritchie J T and S Otter | USDA/SEA (Texas) | CERES-WHEAT | Wheat | Phasic development, morphogenesis, growth biomass accumulation and partitioning, soil water balance, plant nitrogen status |
| Ryle G J A, N R Brockington, C E Powell and B Cross | Grassland Research Institute (Hurley, Berkshire, England) | Unnamed | Uniculum barley | Photosynthesis, assimilate distribution and synthetic and maintenance respiration |
| Schulze R E[1] | University of Natal, Pietermaritzburg | ACRU | Maize, wheat and sugar cane | Water flow, evapotranspiration and other agrohydrological processes |
| Stockle C and G S Campbell[1] | Washington State University, Pullman | CORN | Maize | Water flow, evapotranspiration, predicting effect of water stress on yield |
| van Keulen H | Netherlands Agricultural U (Wageningen) | GRORYZA | Rice | Gross assimilation and respiration |
| van Keulen H | Netherlands Agricultural U (Wageningen) | ARIDCROP | Natural vegetation in semiarid regions | Photosynthesis, respiration, transpiration and water uptake |
| Wagenet R J and J L Hutson[1] | Agronomy Department, Cornell University | LEACHM, WATFLO | Any crop | Water flow, nitrogen chemistry, pesticide chemistry, inorganic chemistry |
| Weir A H, P L Bragg, J R Porter and J H Rayner | Rothamsted Experimental Station, Letcombe Laboratory, U of Bristol | ARCWHEAT1 | Wheat | Photosynthesis phenology, respiration and dry matter partitioning |
| Wilkerson G G, J W Jones, K J Boote, K T Ingram and J W Mishoe | U of Florida | SOYGRO | Soybean | Photosynthesis, respiration, growth, senescence, phenology, infiltration, drainage, transpiration |
| Williams J R et al[1] | USDA,ARS: Grassland, Soil and Water Research Laboratory, Temple, Texas | EPIC | Any crop | Erosion and productivity |

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