UNIVERSITY OF ALBERTA

PREDICTING TIMES OF IRRIGATION WITH A SIMULATION MODEL

BY

BAREND JAN VAN DEN BROEK

A thesis submitted to the Faculty of Graduate Studies and Research in partial fulfilment of the requirements for the degree of MASTER OF SCIENCE.

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ABSTRACT

The increased competition between municipal, industrial and domestic water users for reliable good quality water supplies has put a strain on irrigated agriculture, i.e. less water availability. In The Netherlands much discussion centers around limited use of groundwater for irrigation purposes in certain parts of the country as groundwater tables are dropping and conflicts of interest arise for nature areas in close proximity of agricultural land. For some areas of The Netherlands legislation is currently being enforced prohibiting farmers any type of irrigation on grassland before a preset date.

The increased competition for the use of scarce groundwater for municipal, industrial, domestic and agricultural purposes require methods to assist farmers in making optimal use of irrigation water while maintaining or enhancing the environment. The principal objectives of this study were to investigate the use of a simulation model to predict the times of irrigation in the practical case of real time irrigation with limited crop, soil and forecasted weather data (collected by the farmer or easily accessible by the farmer) and whether such a model could be used in a farm management system to assist farmers in irrigation scheduling.

The field research was conducted on a potato crop as it is an intermediate drought resistant crop where soil water availability affects both yield and quality. The research was conducted over a two year period at two research sites. At each site three irrigation treatments were laid out: no irrigation (rainfed only); irrigation based on farmer's decision and irrigation predicted by the model based on the soil energy status in the root zone. During the two seasons (1986 and 1987, respectively a very dry and wet year) several crop and soil parameters were determined for model input and to compare simulation results with measured data.

The results obtained show that with easily accessible field data, predicting times of irrigation with a dynamic simulation model is possible providing water stress relations for the various growth stages are well understood as they affect both yield and quality. Simulation results compared favorably with measured field data on the

non-irrigated treatments whereas difficulties were encountered in simulating water infiltration into the ridged soil profile at the irrigation treatments. Representative soil physical data are required in the simulation model to adequately determine the available water supply to the plants and simulate the soil water flow through the profile. When using this simulation model in a farm management system, more decision criteria affecting crop quality must be included as well as a broader set of variables to account for: farm management decisions.

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LIST OF SYMBOLS

SYMBOL	DESCRIPTION	UNITS
a	crop dependent constant	(-)
b	crop dependant constant	(-)
c	crop dependant constant	(-)
C	differential soil water capacity ($d\theta/dh$)	(cm^{-1})
CR	crop water requirement	(-)
d	depth of water applied or stored in a profile depth	(cm)
E	actual soil evaporation	($cm\ d^{-1}$)
E_a	isothermal evaporation	($kg\ m^{-2}\ s^{-1}$)
E_I	interception evaporation	($cm\ d^{-1}$)
E_o	'open water evaporation'	($kg\ m^{-2}\ s^{-1}$)
E_p	potential soil evaporation	($cm\ d^{-1}$)
E_r	reduced potential soil evaporation	($cm\ d^{-1}$)
ET	actual evapotranspiration	($cm\ d^{-1}$)
ET_p	potential evapotranspiration	($cm\ d^{-1}$)
ET_r	reference evapotranspiration	($cm\ d^{-1}$)
f	relative humidity of air	(-)
g	acceleration due to gravity	($m\ s^{-2}$)
G	soil heat flux	($W\ m^{-2}$)
h	soil water pressure head	(cm)
h_l	pressure head in the leaves	(cm)
h_{lim}	minimum allowed h at the soil surface	(cm)
h_r	pressure head at the root surface	(cm)
h_s	actual soil water pressure head at the soil surface	(cm)
H	hydraulic head	(cm)
I	infiltration into the soil profile	($cm\ d^{-1}$)
Ir	irrigation	(cm)

k_c	crop coefficient	(-)
K	proportionality constant or hydraulic conductivity	(cm d^{-1})
K↓	global radiation flux	(W m^{-2})
K(h)	hydraulic conductivity as a function of h	(cm d^{-1})
L	column length	(cm)
LAI	leaf-area-index	(-)
M	molecular weight of water	(kg mol^{-1})
NS	water from natural sources	(-)
Pr	precipitation	(cm)
q	soil water flux; capillary rise (+)and infiltration (-)	(cm d^{-1})
q_s	potential flux (soil evaporation or infiltration)	(cm d^{-1})
Q_s	flow through bottom of subsoil, upward or downward	(cm)
Q_r	flow through bottom of root zone, upward or downward	(cm)
Q^*	net radiation flux	(W m^{-2})
R	universal gas constant	(J mol^{-1} K^{-1})
R_p	flow resistance in the plant	(d)
R_s	flow resistance in the soil	(d)
RAW	readily available water	(cm)
Ru	runoff	(cm)
s	slope of saturation water vapor pressure vs. temp. curve	(mbar K^{-1})
Sc	soil cover	(-)
S_{max}	maximum water extraction by plant roots	(d^{-1})
S(h,z)	root extraction as a function of pressure head and depth	(cm^3 cm^{-3} d)
t	consecutive days with t getting <10 mm rain per day	(d)
T	actual transpiration	(cm d^{-1})
T_a	air temperature	(K)
T_p	potential transpiration	(cm d^{-1})
TAW	total available water	(cm)
u	regression coefficient	(-)
v	regression coefficient	(-)
V	soil water storage in profile	(cm)

V_{in}	amount of water added to profile	(cm)
V_{out}	amount of water withdrawn from profile	(cm)
V_r	soil water storage in root zone	(cm)
V_s	soil water storage in subsoil	(cm)
w	regression coefficient	(-)
z	vertical coordinate with origin at the soil surface, directed positive upward	(cm)
Z	specific profile depth	(cm)
Z_r	depth of root zone	(cm)
$\alpha(h)$	dimensionless prescribed function of h	(-)
α	coefficient in the Priestley and Taylor formula	(-)
γ	psychrometric constant	(mbar K^{-1})
δ	soil dependent parameter	(-)
θ_m	gravimetric soil water content	(g g^{-1})
θ_v	volumetric soil water content	(cm^3 cm^{-3})
λ	latent heat of vaporization of water	(J kg^{-1})
ϕ_g	gravimetric potential	(-)
ϕ_m	matric potential	(-)
ϕ_t	total potential	(-)

1.0 INTRODUCTION

1.1 Irrigation: Global Overview

Since the ancient civilization of Mesopotamia, which thrived in the area of present day Iraq, the productivity of irrigated agriculture has been recognized. Major famines due to drought have been a part of man's history. For example, in the first half of the 19th century China experienced four massive famines when some 45 million people died (Jensen, 1991). Irrigation development has helped reduce the risk of famines.

Following 100 years of moderate expansion of world-wide irrigation, in the last forty years the world has witnessed an unprecedented growth and development of irrigated land. Some 250 million ha are currently under irrigation in the world, which is approx. 17 percent of the total cultivated land and from which 36 percent of the world's food production is derived (Field, 1990). Although this expansion has slowed down, as indicated in Figure 1, the world population is growing at approx. 1.8 percent annually (Stewart and Nielsen, 1990).

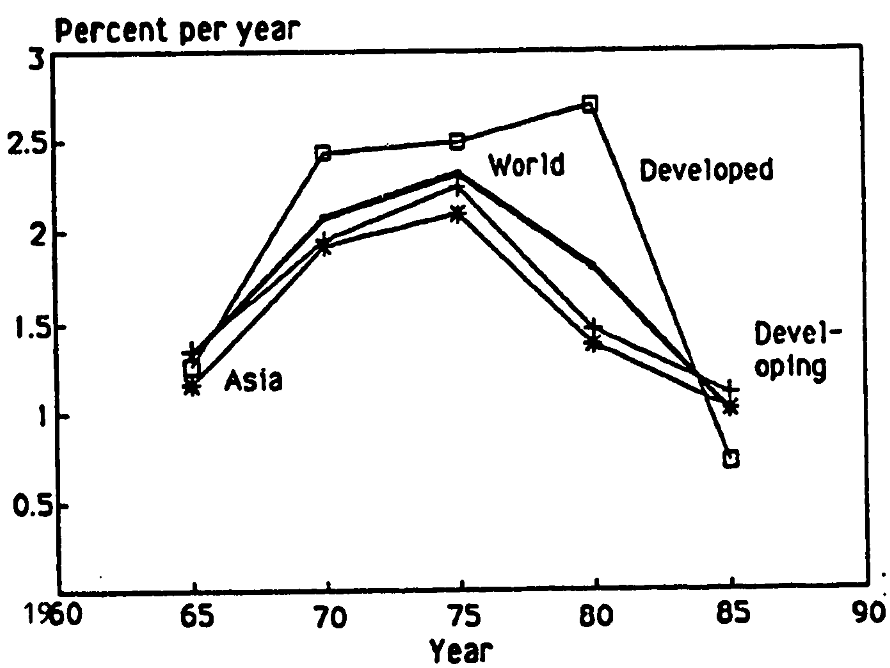

Figure 1. Rate of increase of irrigated land areas (adapted from Jensen, 1991)

Consequently, the increased demand for food will have to be met by increased production on both irrigated and non-irrigated land.

The rise in population and the development of industry and agriculture, are placing a substantial demand for fresh water. Groundwater plays an important role as a fresh water source because, when compared with surface water, it is often of better quality, better protected from possible contamination and pollution, and less subject to seasonal fluctuations. An overview of the importance of groundwater as part of the watersupply in various regions of the world is given by Zekster and Dzhamalov (1988). Although groundwater may offset some of the fresh water supply deficits, a fresh water deficit exists (Zekster and Dzhamalov, 1988) on 60 percent of the earth's land surface already slowing down development of industry and agriculture in certain countries.

Jensen (1991) summarized some of the major factors contributing to the declining expansion in irrigated agriculture: physical constraints like widespread waterlogging and soil salinity problems (mainly in semi-arid and arid regions in particular in the developing countries); increasing development costs; low commodity prices due to overproduction; availability of resources for continuing expansion and more conservative lending policies. Environmental concerns are also a major factor (e.g. water quality) contributing to the slow-down in development as public concern is mounting. The outcome is less water availability for irrigated agriculture due to the increased competition for renewable water supplies for municipal, industrial and domestic water use.

In the last ten years the focus has shifted from irrigation expansion to water and energy conservation and its influence on the environment (Stewart and Nielson, 1990). The scheduling of irrigation and its proper management have thus become key words in the world of irrigated agriculture. Reviews and other extensive works on crop water requirement, irrigation scheduling and management of farm irrigation systems are given by Jensen (1980) and more recently by Hoffman et al. (1990), Stewart and Nielsen (1990) and Anstey et al. (1991).

1.2 Water Management in the Netherlands

The Netherlands has a humid temperate climate strongly controlled by maritime influences. Although the mean annual precipitation is 750 mm and the mean annual evapotranspiration is 500 mm with shallow groundwater tables prevailing, many crops still experience some degree of water stress during the summer period. A precipitation excess exists in winter with a water deficit in summer (Figure 2). Under average climatological conditions, the net difference between total precipitation and total evapotranspiration from April 1 to September 1 is -100 mm. However, large temporal variations in rainfall result in significant deviations from this mean deficit.

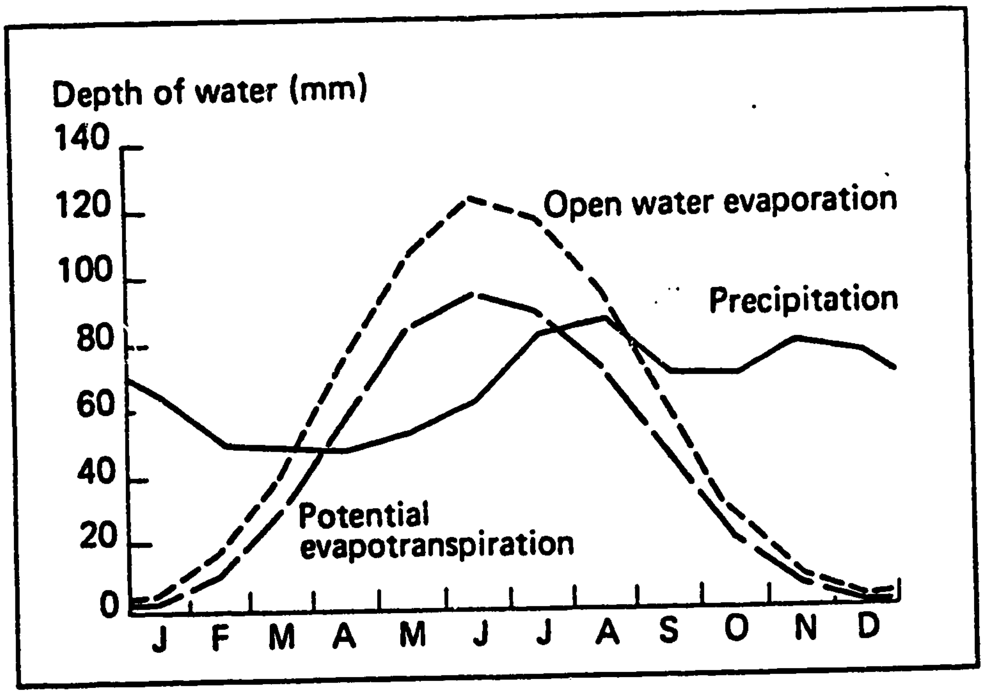

Figure 2. Mean monthly precipitation, open water evaporation and potential evapotranspiration over the year in the Netherlands (spatial averages derived from monthly weather reports KNMI) (adapted from Colenbrander, 1989).

The country, largely comprised of the deltas and former flood plains of the three main rivers; Rhine, Meuse and Scheldt, is divided in a 'low' and a 'high' region (see Figure 3) where the 'low' region, 25 percent of the total land area, lies below Mean Sea Level. In the absence of dunes and dikes, 65 percent of the country would be flooded at high tide and maximum river levels (Colenbrander, 1989).

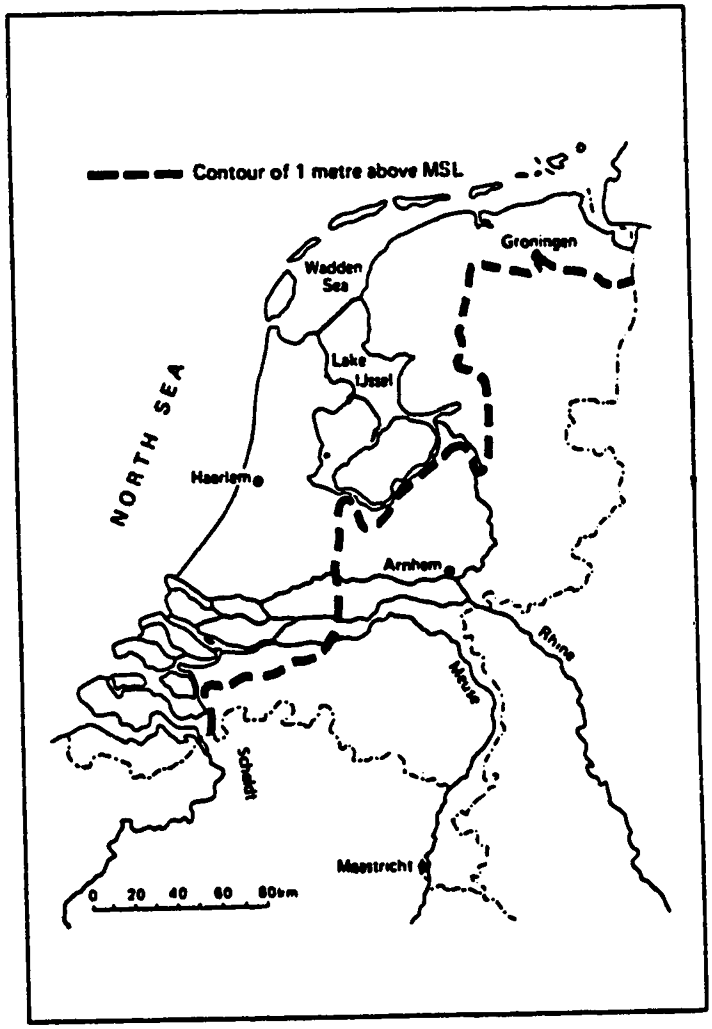

Figure 3. Division of the Netherlands in 'low' and 'high' regions (adapted from Colenbrander, 1989). The low regions are located to the left of the dotted contour line.

Precise water level control is essential in these 'low' areas whereas in the 'high' region of the country the channel system to transport surface water is limited. The provinces in the 'low' region have their irrigation water supplied mainly by available surface water, especially in areas where shallow salty groundwater levels are present.

The majority of irrigation water supplied in the 'high' region of the country comes from extractions.

During a survey in 1985 (Barendswaard, 1987), 18% of the total cultivated land area (excluding glasshouses) may be irrigated of which 40% is supplied by groundwater and the remainder through a combination of ground and surface waters. Groundwater in the higher parts of the country is fresh and of good quality and therefore an attractive source for public water supply and irrigation. However, unlimited and uncontrolled extraction of this precious groundwater, with its possible negative effect on agricultural production and nature areas could not and should not be allowed.

Certain crops are more drought resistant than others and continue to produce high yields even without supplemental water supplies. However, with increased competition for top quality products, a reliable and continuous supply of water is essential. Increased irrigation has contributed to the lowering of the groundwater levels in many regions of the country during the last thirty years, even to the extent that in some areas in the Netherlands legislation is being developed to decrease irrigation, in particular as a groundwater source.

During the late sixties attention focused on the conservation of water in dry periods (Colenbrander, 1989). It became evident that in some areas a substantial deficit could occur between the amount of water a crop demanded and the actual amount of water available in the root zone especially in the extremely dry year of 1976. Throughout the following years the potential for groundwater withdrawal as irrigation supply for crop growth and production was extensively studied at local and regional scales across the country (Ton, 1975; Van Boheemen and De Wilde, 1979; SWLT, 1980). As computers became more powerful in the seventies, large quantities of data obtained from these extensive research projects could be analyzed. Numerical crop water models were developed to simulate soil water flow, soil water availability, crop water demand and crop growth (Feddes et al., 1978; De Laat, 1980; Belmans et al., 1983).

1.3 Research Objectives

Bases for irrigation objectives may be maximizing crop production with an unlimited water supply or optimizing the use of a limited amount of water. Whatever the basis for irrigation, the amount of water a crop requires and the amount of water available in the soil root zone under the prevailing crop, soil and weather conditions must be known to determine a proper soil water balance.

Mathematical computations of observed data with the use of graphs, tables and nomographs to calculate the water balance hinders many farmers from using irrigation scheduling. This hindrance may be overcome with the use of computer software ranging from microcomputer programs (to meet the simplicity required by the farmer) to more sophisticated programs available to specialists of organizations supporting the farmers.

In 1985 a small working group including representatives from the extension service, research farms and institutes was set up to discuss the possibility of implementing a farm management system for sprinkler irrigation. This farm management system, to be run by an agricultural support organization, needed an effective tool to encourage the spread of practical irrigation scheduling. The discussion centred around the question of which available computer program or simulation model to investigate and eventually use in a farm management system to assist farmers with their irrigation, i.e. to promote a greater awareness in a more efficient use of irrigation water.

The objectives of this irrigation research were to assess:

- the ability of the program to predict the times of irrigation in the practical case of real time irrigation with limited crop, soil and forecasted weather data (collected by the farmer or easily accessible).
- the ability of the program to simulate soil water flow dynamically and compare the simulation results with measured field data.

The program chosen, meeting the objectives of this research, is an extensively tested and applied numerical water balance simulation model. This model SWATRE (Soil Water Actual TRanspiration Extended) describes the dynamics of the soil-water-atmosphere system quantifying processes in the unsaturated-saturated soil profile using crop, soil and weather data. This model was developed by Feddes et al. (1978) and further extended by Belmans et al. (1983) and has been used in many hydrological situations.

Potatoes were chosen as the crop for this study as they are an intermediate drought resistant crop according to a Dutch classification system (Vos and Groenwold, 1988) and also potato quality is affected by soil water availability (Carr, 1989). Therefore, irrigation scheduling for potatoes is always aimed at maintaining optimal soil moisture regimes throughout the period of growth. The irrigation scheme chosen should be designed to maximize yields per unit land area rather than to spread a limited water supply over a large area, i.e. the aspect of optimization of water use will not be considered perse, but much more the timing of irrigation.

The field research was conducted over a two year period (1986 and 1987) at three research farms, respectively situated in the 'high', 'low', and polder areas of the country. At each research site three irrigation treatments were laid out: no irrigation (rainfed); irrigation based on the farmer's decision and irrigation predicted by the model based on a critical soil water status in the root zone. After the experiments were conducted, two research sites were chosen for full data analysis because the third site in the polder area did not supply enough relevant information.

Some preliminary results of this research have been published by Ouwerkerk (1987), Dekkers (1988) and Wesseling and Van den Broek (1988). Other aspects concerning fertilizer usage, detailed crop yield measurements and various quality aspects of the potato crop were reported by Mol (1988) and Van der Schelde (1988).

2.0 PLANT-SOIL-ATMOSPHERE SYSTEM

Plants require large amounts of water, removing it from the soil and transpiring nearly all of it into the atmosphere. For the production of 1 kg of dry matter, depending on climate, plant type and fertility, from 300 to 2000 litres of water may be required (Wesseling, 1976). Water is an important component of the plant accounting for 60 - 95 percent of its fresh weight (James, 1988). It also acts as a carrier for mineral nutrients and gases entering the plant through the roots to the various plant tissues where they are used. After the transport of nutrients, the water leaves the plant via the tiny openings in the leaves (stomata). Besides this transport function, the evaporation process, called transpiration, absorbs heat, cools the plant and as such prevents a heat accumulation which may injure the plant. When there is a shortage of water in the soil, the water intake by the roots cannot equal the water loss through the leaves, the stomata will close and the rate of transpiration is then reduced. With this closure, the rate of photosynthesis is also reduced and may eventually lead to reduced crop yields.

When air near the leaves is warmed up by either direct heat from the sun or radiation from the soil surface and the air's vapor pressure remains lower than the vapor pressure at the leaf surface (i.e. a vapor pressure gradient), vapor transport takes place, providing a supply of water exists to the evaporating leafsurface, called transpiration.

Pressure head forces like adhesion, cohesion and osmosis exist in the soil in contact with the roots. Similarly there are pressure head forces present in the plant. Pressure head gradients between the soil and the plant roots tend to draw water and plant nutrients into the roots, through the plant and into the atmosphere. If a critical pressure head is reached in the soil, plants stop removing enough water and crop growth will eventually cease. Therefore, the root zone must have sufficient water available to meet the requirements of high yields under optimum soil fertility and good cultural practices.

The irrigation requirement of a crop is thus defined as the total amount of water that must be supplied by irrigation to a disease-free crop, growing in a large field with adequate soil water and fertility, and achieving full production potential under the given growing environment (Doorenbos and Pruitt, 1977). Simply speaking, irrigation requirement includes crop water requirement (CR), but does not include water from natural sources (NS) that crops can effectively use. This is expressed as:

$$Ir = CR - NS \tag{1}$$

These terms, CR, commonly called evapotranspiration, and NS, are made up of infiltration into the soil profile, capillary flux into the root zone and the amount of water actually stored in the root zone, are described in the following sections.

Water is continuously moving in the soil, either as a liquid or a vapour. In irrigation studies, the flow of water is of particular interest in the upper part of the soil profile where the plant roots are present, the so-called root zone. It is in this root zone that water moves downward following rain or irrigation, and upward to evaporate from the soil surface, or move into plant roots and eventually into the atmosphere through transpiration by the leaves. Within the root zone, acting as the transport medium between the atmosphere above and the subsoil below, many important processes take place: physical, chemical, and (micro)biological. Of these processes, the flow of water is a complex dynamic phenomenon dependent on plant and soil properties and meteorological conditions. The plant needs the water, the soil stores the water needed by the plant and the atmosphere supplies the energy needed by the plant to extract water from the soil.

2.1 SOIL WATER DYNAMICS

2.1.1 Soil Water Content

The soil system is composed of solids, air and water. The size and distribution of soil particles and pores determine how much water a soil can hold. When all pores are completely filled with water, the soil is in a saturated state. Conversely, when the pores are partly filled with water and air the soil is considered unsaturated. The amount of water present in the pores is referred to as soil water content. The choice of definition of soil water content often depends on convenience. The definitions used in this study are:

A: gravimetric soil water content

$$\theta_m = \frac{\text{mass of water}}{\text{dry mass of soil}} \tag{2}$$

θ_m ($g\ g^{-1}$) is also called water content on mass basis and is the most commonly used expression (Warrick, 1990).

B: volumetric soil water content

$$\theta_v = \frac{\text{volume of water}}{\text{total volume of soil}} \tag{3}$$

θ_v ($cm^3\ cm^{-3}$) is often termed water content on a volume basis as this definition is particularly useful when considering a volume of water stored in a specific volume of soil. This value will always be positive (or zero) as it is a fraction of total soil volume.

C: depth of water

$$d = \theta_v Z \tag{4}$$

where: θ_v = volumetric soil water content ($cm^3\ cm^{-3}$),
Z = specific profile depth (cm), and
d = depth of water applied or stored in a profile depth of Z (cm).

This definition is very useful in irrigation application or drainage amounts.

2.1.2 Soil Water Potential

To describe the dynamics of water flow in soil it is necessary to understand the basics of the energy status of water. Water in the soil is subject to adhesive forces between the solid particles and water molecules, cohesive forces between water molecules themselves, and the gravitational force causing water in the larger pores to move downward in the soil, called 'free water'.

The existence of these forces gives water at any point in the soil system an energy status or potential. This so-called soil water potential is the work necessary to move a unit quantity of water from a reference state to a situation of interest. This reference state of water may be taken as pure water at standard atmospheric pressure at an elevation equal to zero. Soil water potential consists of several components whose sum equals the total potential. In most hydrological situations, these components are: soil matric; elevation; the presence of solutes; liquid and air pressure; and soil temperature. However, in reality this total potential is simplified by disregarding the osmotic potential (influence of salts), assuming the air pressure in the pores is equal to atmospheric and assuming no soil temperature gradients.

The total potential ϕ_t remains the sum of two components, soil matric ϕ_m and elevation ϕ_g described as:

$$\phi_t = \phi_m + \phi_g \tag{5}$$

In hydrology, potential is usually expressed as energy per unit weight of soil water, with the dimensions of length, i.e. cm. Potential is then denoted as 'head' with matric head 'h' arising from local interacting forces between soil and water and gravitational head (elevation) 'z' arising from the gravitational force. These two heads give a total (hydraulic) head 'H' written as:

$$H = h + z \tag{6}$$

Taking the soil surface as the reference level, the vertical coordinate z will always be positive above the soil surface (in the upward direction) and negative below the soil surface. The matric head h, or soil water pressure head, has its reference level at the phreatic surface (water table), i.e. where the atmospheric pressure is equal to zero. The soil water pressure head will be negative for unsaturated conditions and zero or positive for saturated conditions.

2.1.3 Soil Water Retention

The relationship between soil water pressure head and soil water content is one of the most important characteristics of the soil-water system. This relationship is called the soil-water retention curve, the soil-water characteristic curve or the pF curve. pF (by analogy with the pH acidity scale), introduced by Schofield (1935) as cited by Hillel (1982), is defined as the logarithm of the negative soil water pressure head in centimeters of water expressed as:

$$pF = {}^{10}\log |-h| \tag{7}$$

Soil-water retention curves for different soil texture and soil structure are presented in Figures 4a and 4b respectively.

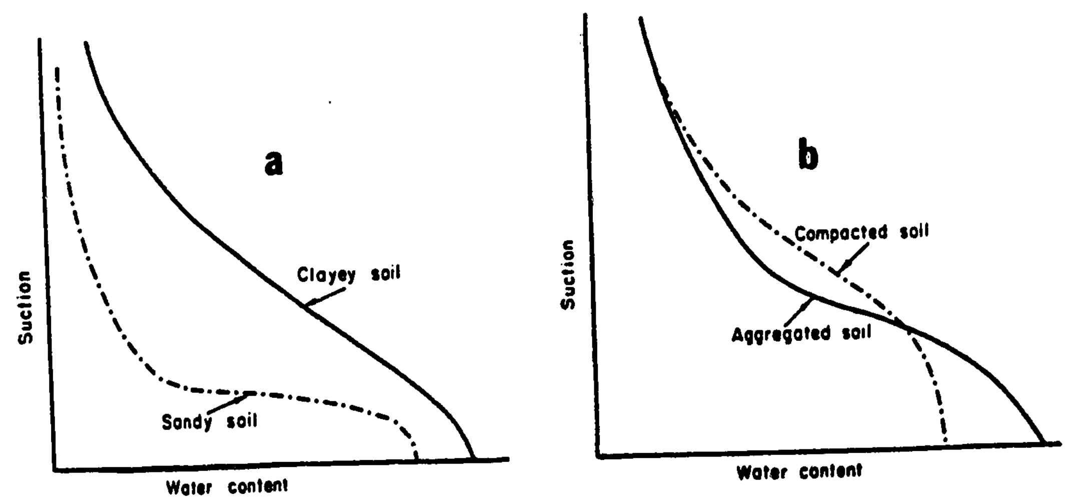

Figure 4. The effect of texture (a) and structure (b) on soil water retention (Reprinted with permission from Soil and Water: Physical Principles and Processes, c. 1971. Published by Academic Press, NY)

The amount of water a particular plant can extract from the soil is determined by an upper and lower limit on the soil-water characteristics curve. When a soil is completely saturated, water in the larger pores will move downward in the soil due to gravitational forces. After this downward flow of 'free water' is reduced to a negligible value, the remaining soil water content and corresponding soil water pressure head is referred to as 'field capacity' (FC), i.e. the upper limit. As the soil dries out further, less and less water is extracted till plants eventually start to wilt. Once plants remain wilted for a 24 hour period, 'wilting point' (WP) is reached, i.e. the lower limit. The amount of water stored between FC and WP is referred to as 'total available water' (TAW). However, this does not mean that plants do not encounter difficulty extracting water till WP is reached. Between FC and WP lies a critical limit separating TAW into 'readily available water' (RAW) and 'decreasingly available water'. Between FC and the critical limit, the water extraction by plant roots is at a potential rate as determined by the climatological demand while below this critical point, plants will extract water at a reducing rate until WP is reached.

The soil-water retention characteristics of a given soil vary temporally and spatially, and, therefore, the general concepts of FC and WP are approximations in a particular situation. A generally accepted definition for FC and WP is the soil water content of a soil sample at 1/3bar and 15 bar pressure respectively using the Richards pressure plate apparatus (Gardner, 1988). Jury et al. (1991) stated that this definition neglects the evidence that water retention in a profile depends on the water transmission properties of the entire profile and on the hydraulic head gradient rather and considers only the energy state of water at a particular point in the profile. In irrigation studies, it is important to know what these approximate limits are, either as soil water content or soil water pressure head values, to estimate how much water can be extracted without stressing the crop.

The relationship between soil water pressure head and volumetric soil water content may be determined by either removing water from an initially wet soil sample by applying an increasing pressure (desorption curve) or by adding water to an initially dry soil sample while reducing the pressure (adsorption curve). For a given soil type, one then obtains two different curves, the wetting and the drying curve, a phenomenon called hysteresis. At the same soil water pressure head, the soil water content in the drying cycle (desorption curve) is greater than in the wetting cycle (adsorption curve) caused by various combinations of pore-space geometry, entrapped air, thermal gradients and shrinking and swelling soils as shown in Figure 5. Hillel (1982) and Feddes et al. (1988) reviewed some of the research on hysteresis. Besides hysteresis, soil temperature also has its effect on the soil water retention curve. For practical purposes, however, both phenomena are not used as they cannot easily be determined by field measurements or laboratory tests on undisturbed soil samples. Therefore, when calculations of water flow in the unsaturated zone are made, the influence of hysteresis and soil temperature are often ignored as was the case during this research.

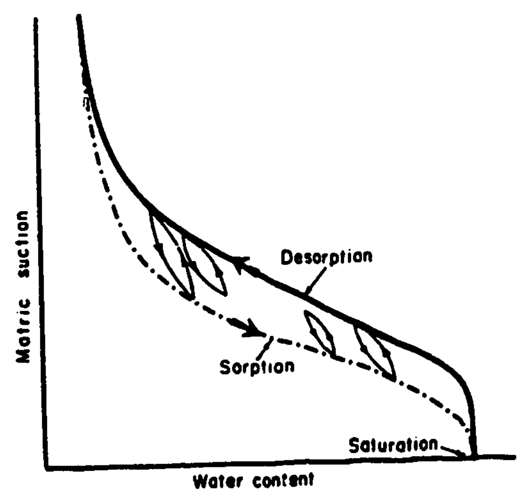

Figure 5. The suction-water content curves in sorption and desorption. The intermediate loops are 'scanning curves', indicating transitions between the branches. (Reprinted with permission from Soil and Water: Physical Principles and Processes, c. 1971. Published by Academic Press, NY).

2.1.4 Soil Water Movement

Flow through soil pores is limited by numerous constrictions or necks and occasional dead-end spaces (Hillel, 1971). As the actual geometry and flow pattern of a typical soil type is too complicated to be described in microscopic detail, the flow through this complex porous medium is described in terms of a macroscopic flow velocity vector. This vector is the overall average of the microscopic velocities over the total volume of soil as found by Henri Darcy (Hillel, 1971), for saturated flow. Darcy's equation looks as:

$$q = -K\left(\frac{\Delta H}{L}\right) = -K\left(\frac{\partial H}{\partial z}\right) \qquad (8)$$

where:
- q = specific discharge ($cm\ d^{-1}$),
- K = proportionality constant ($cm\ d^{-1}$),
- H = hydraulic head (cm),
- L = column length (cm), and
- z = distance (cm).

Darcy's law indicates that the flow of a liquid through a porous medium is in the direction of, and at a rate proportional to, the driving force acting on the liquid ($\partial H/\partial z$) and the ability of the conducting medium to transmit the liquid (K) (Hillel, 1971). The negative sign in front of K signifies that water flows in the direction of head loss, i.e. from a high potential to a low potential.

K is strongly affected by texture and structure. A highly porous fractured soil yields a much higher K than a dense and compacted soil. However, K does not only depend on total porosity, but primarily on pore size and its distribution. For saturated flow, the total pore space is available for water flow and K is constant. With unsaturated flow, however, when part of the pore space is filled with air K is no longer constant but dependent on soil water pressure head h as $\theta = f(h)$. Thus $K = f(\theta)$ or $K = f(h)$. Figure 6 shows generalized K(h) curves for various soil types.

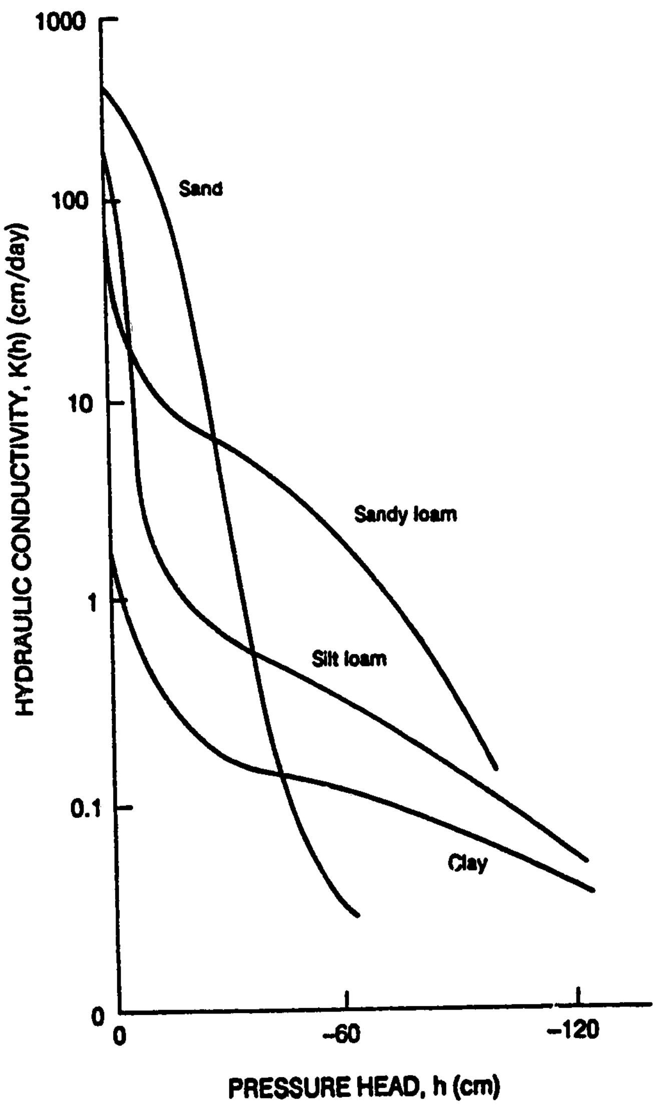

Figure 6. Examples of K(h) relationships for several soils. (Reprinted with permission from Ground Water Models: Scientific and Regulatory Applications, c. 1990 by the National Academy of Sciences. Published by National Academy Press, Washington, DC.)

Darcy's law, originally intended for saturated flow only, was extended by Richards (1931) to unsaturated flow with K being a function of h and when written for one-dimensional vertical flow:

$$q = -K(h)\left(\frac{\partial h}{\partial z} + 1\right) \tag{9}$$

where:
- q = soil water flux (positive for capillary rise; negative for infiltration (cm d^{-1}),
- $K(h)$ = hydraulic conductivity as a function of h (cm d^{-1}),
- h = soil water pressure head, negative in unsaturated zone (cm), and
- z = vertical coordinate with origin at the soil surface, positive upward (cm).

From Richards (1931) and continuity, where $\partial\theta/\partial t = \partial q/\partial z$, the general one-dimensional flow equation for steady-state and transient flow in unsaturated soil is obtained:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left[K\left(\frac{\partial h}{\partial z} + 1\right)\right] \tag{10}$$

To avoid the problem of the two dependent variables θ and h, the derivative of θ with respect to h is introduced, known as the differential soil water capacity (C). C $= d\theta/dh$ writing:

$$\frac{\partial \theta}{\partial t} = \frac{d\theta}{dh}\frac{\partial h}{\partial t} \tag{11}$$

yielding the one-dimensional or Richards' equation for water flow in heterogeneous soils:

$$\frac{\partial h}{\partial t} = \frac{1}{C(h)}\frac{\partial}{\partial z}\left[K(h)\left(\frac{\partial h}{\partial z} + 1\right)\right] \tag{12}$$

Calculating steady-state or stationary conditions means that soil water pressure head and soil water content values will not change over time: $\partial\theta/\partial t = 0$. Then equation 12 yields a relationship between flux, q, soil water pressure head, h, and the vertical coordinate, z:

$$z_2 = z_1 + \frac{h_2 - h_1}{-1 - \frac{q}{K(h)}} \tag{13}$$

This equation states that at any flux, q, be-it percolation ($q < 0$) or capillary rise ($q > 0$), soil water pressure head profiles, h, and height of capillary rise, z, can be calculated, providing K(h) relationships are known.

In case of transient or non-stationary flow, $\partial\theta/\partial t \neq 0$ and equation (12) is valid as a second-order, non-linear, partial differential equation. It is non-linear because C(h) and K(h) are highly nonlinear functions dependent on h. A solution of this equation is only possible with analog or numerical methods.

2.1.5 Determination Soil Hydraulic Properties

Soil water retention and hydraulic conductivity curves are essential to characterize soil hydraulic behaviour and thus serve as key parameters in complex simulation models. Lack of accurate soil hydraulic functions is often considered to be a major obstacle (Van Genuchten et al., 1989). These properties are difficult to obtain because most measurements are tedious, laborious, and restricted to a limited measurement range.

Various laboratory methods to determine the $h(\theta)$ relationship are described and reviewed by Klute (1986). These methods are often not applicable under field conditions. In situ measurements based on simultaneous monitoring of soil water content and soil water pressure head are preferable. However, field and laboratory methods are slow, laborious and expensive. Consequently, other ways were looked for to predict water retention data from more easily determined and routinely available soil components (texture, structure, bulk density, organic matter and particle-size distribution). Klute and Dirksen (1986) and Green et al. (1986) reviewed various methods. These indirect methods are mainly statistical regression models based on analytical equations with soil component data as input (Haverkamp and Parlange, 1986; DeJong and McKeague, 1987).

As K(h) relationships are much harder to determine than h(θ) curves, numerous attempts have been made to approximate K(h). These methods can be divided in two groups: direct and indirect.

Direct methods to measure K(h) are based on the solution of the inverse problem, i.e. the Darcy equation or the one-dimensional unsaturated flow equation, in simplified form, is inverted such that K will be directly measurable. The steady-state and transient state can be measured in the laboratory and the field. Various laboratory and field methods are described and reviewed by Wösten et al. (1990), Klute and Dirksen (1986) and Green et al. (1986).

Indirect methods to determine unsaturated K were reviewed by Vereecken et al. (1990) who outlined three different approaches. The first approach consists of estimating relevant data points of the curve from basic soil properties (physical, mechanical, or morphological). The second approach consists of estimating hydraulic conductivity from the soil water characteristics curve using theoretical developed models. The hydraulic conductivity is then calculated by numerically integrating the h(θ) curve. The third approach is based on estimating the parameters of functions fitted to measured K(θ) or K(h) points and trying to relate these parameters to nonhydraulic soil properties.

2.2 SOIL WATER BALANCE

2.2.1 General

To evaluate the field water cycle as a whole and to quantify the contributing incoming and outgoing processes over time, it is necessary to consider the soil water balance. The water balance is simply a statement of the law of conservation of matter, i.e. matter can neither be created nor destroyed but can only change from one state or location to another. The water content of a given soil volume cannot increase without addition of water (as by infiltration or capillary rise), nor can it diminish unless water is transported to the atmosphere by evaporation or to deeper zones by drainage (Hillel, 1971).

The water balance is used to estimate the incoming and outgoing fluxes of a soil profile. If the outgoing fluxes exceed the incoming fluxes, a water deficit may occur in the soil to the point where growth is constrained and, in extreme cases ceases. The water balance equation stated in its simplest form in a given volume of soil over a certain period is:

$$\Delta V = V_{in} - V_{out} \tag{14}$$

where: ΔV = change in soil water storage in profile (cm),
V_{in} = amount of water added (cm), and
V_{out} = amount of water withdrawn (cm).

The terms of a water balance are generally expressed in units of volume per unit area, i.e. depth of water in cm. A water balance may be calculated over any volume of soil; the root zone (maximum rooting depth), subsoil (any depth below the root zone with or without groundwater present) or any profile depth. The water balance of the root zone in the one dimensional vertical direction, i.e. no lateral flow, may be expressed as:

$$\Delta V_r = Pr + Ir \pm Q_r - ET_p \tag{15}$$

where:
ΔV_r = change in soil water storage in root zone (cm),
Pr = precipitation (cm),
Ir = irrigation (cm),
Q_r = flow through bottom of root zone, upward or downward (cm), and
ET_p = evapotranspiration (transpiration and soil evaporation) (cm).

The component Q_r, either percolation (downward flow out of the root zone) or capillary rise (upward flow into the root zone), is difficult to evaluate properly and therefore often not taken into consideration. However, the presence of a groundwater table in the subsoil may influence the water status in the root zone remarkably, i.e. the fluxes in and out of the root zone can be described much more precisely if the distribution and movement of water inside the profile (root zone and subsoil) is considered. The change in soil water storage in a subsoil is then expressed:

$$\Delta V_s = \pm Q_s \pm Q_r \tag{16}$$

where:
Q_s = flow through bottom of subsoil, upward or downward (cm), and
Q_r = flow through bottom of root zone, upward or downward (cm).

In equation (16) the component Q_s is either deep percolation (downward flow out of the subsoil) or seepage (upward flow into the subsoil).

Adding equation (15) and equation (16), yields the water balance for a soil profile:

$$\begin{array}{llcl}
\text{root zone} & \Delta V_r & = & Pr + Ir + Q_r \qquad\quad - ET_p \\
\text{subsoil} & \Delta V_s & = & \qquad\qquad - Q_r + Q_s \\
\hline
\text{profile} & \Delta V & = & Pr + Ir \qquad\quad + Q_s - ET_p
\end{array} \tag{17}$$

2.2.2 Evaluating the Soil Water Balance

The water balance equation (17) is relatively simple but solving for one unknown may in practice prove rather difficult as some components are not easily measured. For instance, not all of the water from precipitation and irrigation (Pr + Ir) will infiltrate into the soil. Some is intercepted by the leaves and surface residue to evaporate as interception evaporation (E_i), and some may temporarily accumulate on the soil surface and move downslope as runoff (Ru). The net amount of water infiltrating (I) into the soil thus becomes:

$$I = Pr + Ir - E_i - Ru \qquad (18)$$

Interception evaporation takes place at plant and soil surfaces at a rate similar to that of free water. The amount that evaporates depends on the frequency and amount of rainfall/irrigationand the characteristics of the intercepting surfaces. Measuring interception evaporation, E_i, is difficult. E_i =zero if the crop canopy is dry. When the canopy is wet, E_i can be derived from measured interception - precipitation curves (Feddes, 1971; Von Hoyningen-Huene, 1981).

The amount of runoff generally is (or at least should be) small in agricultural fields for well designed sprinkler systems, so that it may be regarded negligible in comparison with the major components of the water balance (Hillel, 1982). In our case study, precipitation and irrigation are treated equally, where runoff is calculated by the model depending on maximum possible infiltration capacity of the soil at the current soil water status.

The largest 'negative' term of equation (17) is generally evapotranspiration, ET_p. Hillel (1971) states that from a physical point of view, evapotranspiration can be viewed as a stream flowing from a source of limited capacity and of variable potential, namely the reservoir of soil water, to a sink of virtually unlimited capacity (though of variable evaporative potential) - the atmosphere. At this point the concept of "potential evapotranspiration", ET_p, is introduced. ET_p represents the atmospheric 'demand' for water depending primarily on the energy supplied to the field by solar radiation. Thus, ET_p depends primarily on meteorological conditions (radiation, air temperature, vapor pressure, cloudiness, wind speed, etc.) at different locations, latitude, season, slope, etc. Hillel (1982) mentioned several other conditions on which ET_p depends: atmospheric advection (related to the size and orientation of the field and the nature of its upwind 'fetch' or surrounding area); surface roughness (type and structure of crop); and soil thermal properties. The last two characteristics vary in time and, as described by Van Bavel and Hillel (1976), indicate that ET_p does not entirely depend on meteorological conditions but also on transient properties of the field itself.

Potential evapotranspiration is a composite term, made up of potential transpiration, T_p, and potential soil evaporation, E_p, hence:

$$ET_p = T_p + E_p \qquad (19)$$

Transpiration is the major contributor to most evapotranspiration estimates. It takes place directly at the interface between the water supply (internal leaf surfaces) and the atmospheric evaporative demand (surrounding air of the leaves). Depending on climatic conditions and soil water regimes, T_p may be highly variable.

Soil evaporation, where water vapor moves directly from the soil surface into the atmosphere, is the next largest source of evapotranspiration for a vegetated surface with an incomplete soil cover. The rate may vary from a maximum atmospheric demand for a very wet soil to almost zero for an extremely dry soil. Soil water moving from deeper in the soil profile up to the soil surface may also evaporate, but this rate decreases as the soil dries out and the hydraulic conductivity is reduced.

In the case of limited soil water, the atmospheric demand may not be met such that evapotranspiration will be less than ET_p. This is the actual evapotranspiration, ET, and thus a fraction of ET_p. A fully grown crop, with a closed canopy and well supplied with water, will in general exhibit an ET value close to ET_p. As a composite term, ET then becomes the sum of actual transpiration, T, and actual soil evaporation, E.

Thus, when there is no shortage of water in the soil profile, evapotranspiration is mainly governed by climatological factors, but if the water stored is gradually depleted by evapotranspiration of the crop, there is a need for it to be replenished in time with the approximate amount of (irrigation) water. A delay in supply or an inadequate amount will result in restricted crop growth or in the worst case even a crop failure. The calculation or estimation of this complex process is vital in irrigation studies.

The upward flow from the water table into the root zone (capillary rise) may play an important role in irrigation studies to help replenish the soil reservoir. This supply of water is often disregarded but may constitute 10% or more of the total water balance (Robins et al., 1954; Nixon and Lawless, 1960; Rose and Stern, 1967 a, b; as cited by Hillel, 1982; Torres and Hanks, 1989). Alternatively, water also flows out of the soil profile, called deep percolation or natural drainage.

Having briefly looked at the various water balance components, one can rewrite equation (17) in terms of the actual amount of water flowing in and out a vertical soil profile in its integral form with all components summed over time as :

$$\Delta V = I \pm Q_s - ET \tag{20}$$

2.3 CROP WATER REQUIREMENT

2.3.1 General

Crop water requirement is defined as the depth of water needed to meet the water loss through evapotranspiration of a disease-free crop, growing in large fields under non-restricting soil conditions including soil water and fertility and achieving full production potential under the given growing environment (Doorenbos and Pruitt, 1977). Another expression often used is consumptive use. Consumptive use includes water used in all of the plant processes rather than just evapotranspiration. Thus, consumptive use exceeds evapotranspiration by the amount of water used for digestion, photosynthesis, transport of minerals and photosynthates, structural support and growth. Since the difference is usually less than one percent, consumptive use is used synonymously with evapotranspiration (James, 1988). Evapotranspiration is an essential component of the soil water balance and needs to be estimated for irrigation studies to determine how much irrigation water a crop requires in times of water shortage.

Crop evapotranspiration can be determined by direct measurements or calculated from crop and climate data. Most direct measurement techniques involve isolating a part of the crop from its surroundings to determine actual evapotranspiration, as described by James (1988) and Hatfield (1990). Many methods with different data requirements and levels of sophistication have been developed for estimating evapotranspiration with crop and climate data. Extensive reviews on various methods to estimate evapotranspiration are given by Brutsaert (1982) and Hatfield (1990).

2.3.2 Reference Evapotranspiration

The complexities of estimating potential evapotranspiration, ET_p, have led to the development of the concept of reference evapotranspiration, ET_r (Hatfield, 1990). ET_p from a well-watered agricultural crop is estimated as the product of reference evapotranspiration, ET_r, from a standard surface and an appropriate

empirical crop coefficient, k_c. The former depends on local meteorological conditions, whereas the latter also depends on crop specific characteristics.
The methods for estimating ET_p involve the following equation:

$$ET_p = k_c \, ET_r \tag{21}$$

where: ET_p = potential evapotranspiration for a specific crop (cm d^{-1}),
k_c = crop coefficient, and
ET_r = reference evapotranspiration (cm d^{-1}).

Reference evapotranspiration, ET_r, is preferred over potential evapotranspiration, ET_p, since ET_p varies from crop to crop due to differences in aerodynamic roughness and surface reflectance and from location to location because of differences in the amount of sensible and latent heat transferred into the area (James, 1988).

Crop coefficients, k_c, are often determined experimentally with lysimeter studies, and reflect the physiology of the crop, the degree of crop cover, the location where data were collected, and the method used to calculate ET_r, (James, 1988). Specifics on the use of crop coefficients were presented by Doorenbos and Pruitt (1977). Wright (1981) briefly reviewed the nature and origin of commonly used coefficients and outlined the conditions under which they can be appropriately applied.

The selection of methods for calculating evapotranspiration often depends on available data and level of accuracy required. The methods described here are commonly used in irrigation studies due to their simplicity and are directly related to empirical or statistical methods. These methods include the 'combination method' involving the solution of the energy balance (Penman, 1948) and other methods using routinely measured meteorological data: radiation (Priestley and Taylor, 1972) and temperature (Blaney and Criddle, 1950).

2.3.3 Combination Methods

One widely used combination method is the equation developed by Penman (1948), combining the aerodynamic formulas for the vertical transfer of sensible heat and water vapour (Dalton's equation) and the surface energy balance formula, resulting in:

$$\lambda E_o = \frac{s(Q^* - G) + \gamma \lambda E_a}{s + \gamma} \tag{22}$$

where:
λ = latent heat of vaporization of water (J kg^{-1}),
E_o = 'open water evaporation' (kg m^{-2} s^{-1}),
s = slope of the saturation water vapour pressure vs. temperature curve (mbar K^{-1}),
Q^* = net radiation flux (W m^{-2}),
G = soil heat flux (W m^{-2}),
γ = psychrometric constant (mbar K^{-1}), and
E_a = isothermal evaporation (kg m^{-2} s^{-1}).

(To convert λE_a from W m^{-2} to mm d^{-1} multiply λE_a by 86400 sec d^{-1}/λ = 0.0352 at 20°C)

Penman was one of the first to recognize the significance of (net) radiation for the evaporation process and developed this formula to describe the water loss of an evaporation pan he used during his experiments. Penman assumed the soil surface to be horizontally uniform, such that advection effects can be ignored. He also considered the case that the air at the soil surface is saturated making this equation not only a proper description of evaporation from open water but also from a wet land surface, i.e. the surface being covered with a thin layer of water. This equation became known as the Penman open-water equation. Numerous variations of the Penman combination equation appeared with the primary difference being the variations on how Q^* and E_a are evaluated.

The main limitations with the energy balance approaches are the need for elaborate instrumentation and the collection of accurately measured data for several parameters, in particular the aerodynamic resistance terms. These limitations have prompted the development of empirical approximations.

Penman equations were modified by replacing the aerodynamic resistance term with a wind function to estimate reference evapotranspiration based on either the open-water equation or on a reference crop like alfalfa or grass. These modified equations are widely used today, the most common ones of which were given by Allen (1986) and Allen et al. (1989). Research in the late 1960s and the 70s found that for short well-watered crops, the available energy (Q^*-G) in equation (22) primarily determined evapotranspiration resulting in a shortened variation of the Penman equation. This equation indicates low advective transport of heat, i.e. it was assumed that the vapour pressure deficits at the surface and in the air are equal which may occur under large areas with non-advective conditions and a wet surface. This led to the formula by Priestley and Taylor (1972):

$$\lambda ET_p = \alpha \frac{s}{s + \gamma} (Q^* - G) \qquad (23)$$

where α is the coefficient of value for specific sites depending on surface vegetation and microclimatic conditions. In general for wet surfaces with α set at 1.26, the combined term $\alpha[s/(s\gamma)]$ is approximately 1 at air temperatures near 24 ^oC and therefore evapotranspiration is approximately equal to the available energy. Flint and Childs (1991) reported values for α from 0.72 for forest conditions to 1.57 for crop conditions under strong advection. Mukammal and Neumann (1977) as cited by Flint and Childs (1991) found α = 1.29 for a grass surface with the soil at field capacity. Hatfield (1990) reviewed several studies, where α ranges from 1.20 to 1.30. In the Netherlands, Buishand and Velds (1980) found α = 1.26 was satisfactory for the summer months (May - September) when using 24-hour average temperature and radiation values. Brutsaert (1982) confirmed this formula for Dutch conditions. Many authors found this equation more operational than the Penman model because of the simplicity of input (Heermann, 1988; Hatfield, 1990).

2.3.4 Evaporation Research in the Netherlands

De Bruin (1987) gave an overview on evaporation research in the Netherlands. Since 1956 the Royal Netherlands Meteorological Institute (KNMI) publishes daily reference evaporation values based on the Penman open-water equation, i.e. evaporation from a hypothetical water surface. The introduction of many variations of the Penman equation has not always led to improvements in accuracy of these values. Instead much confusion arose about which Penman method was best suited, which led researchers in the Netherlands to search for another more simplified method. From 1987 onward this new method is the so-called Makkink (1957) reference crop evapotranspiration based on short grass well supplied with water. From extensive evaporation studies of grassland in the Netherlands, it was found that G is negligible (on a daily basis), and that Q^* for grass is about one-half the incoming short wave radiation in summer time. This led to the use of the following formula by Makkink (1957):

$$\lambda ET_r = 0.65 \frac{s}{s + \gamma} K\downarrow \tag{24}$$

where: $K\downarrow$ = global radiation flux (W m^{-2}).

Research done by De Bruin and Holtslag (1987) indicated, that the Priestley-Taylor formula and the related Makkink formula described the evapotranspiration of well watered short grass on a regional scale for the summer months (May - September). These equations hold valid during the summer months when radiation is the main driving force, while in winter they do not because the physical basis for these formulae is not reliable. In a comparison of evapotranspiration methods, Jensen (1973) found that the Makkink equation of 1957 could be recommended for coastal areas. Aslyng and Hansen (1982) also used the Makkink equation successfully in Denmark where the climatic conditions are not very different from the Netherlands.

Another great advantage for choosing Makkink's formula as the new reference crop evapotranspiration is the simple input data requirement of global radiation and air temperature (to calculate s in equation 24). These latter parameters are directly measured by many meteorological stations in the Netherlands, whereas net radiation Q^* is not always directly measured but often determined semi-empirically.

The determination of the crop coefficients k_c associated with the Penman and Makkink equations was extensively described by Feddes (1987) for many arable and horticultural crops. Some are listed in Appendix 1.

2.4 IRRIGATION SCHEDULING

2.4.1 General

Irrigation scheduling is the process of planning when to irrigate and how much water to apply based on the understanding of each individual crop's requirement and the practicality of irrigation. Proper scheduling requires knowledge of soil water available to the plant and the expected change in levels for individual fields over the succeeding five to ten days (Heermann et al., 1990). Thus, proper scheduling is essential for the efficient use of water, energy, and other inputs, such as fertilizer. The immediate aim of irrigation scheduling is to apply the water before the soil becomes dry enough to adversely affect the crop.

2.4.2 Irrigation Scheduling Objectives and Requirements

Scheduling Objectives

Cavazza (1985) gave two main objectives:

- maximization of yields, i.e. requiring that irrigations be scheduled to maintain a non-stressing soil water status for much of the growing season, and
- optimization of water use when its allocation is limited, i.e. assure adequate water supplies at critical growth stages. This may not produce maximum yield but often contributes to maximum water use efficiency.

With the maximization of yield objective, only the time of application is determined whereas with the water use optimization objective, the time of application and amount to be applied are determined. The former tends to be mainly suitable for yield control and not necessarily to water saving, whereas for the latter, control of water application depths and efficiency are also needed.

Other scheduling objectives may be: soil salinity control; control of damages from excess water use; integration of the irrigation program with other agronomic practices and optimization of the management of the distribution network and irrigation equipment.

Irrigation scheduling methods should meet certain requirements as listed by Cavazza (1985). Four main requirements are:

- the method should give satisfactory information to determine the time and, when required, the depth of application which requires data from plant, soil and atmosphere.
- the accuracy of the method does not only depend on the precision of the instruments used but also on the choice of variables to be observed and the fitting of functions.
- the resolution of scale required for a scheduling method is that of a field. Problems may arise when instruments used have a smaller or larger resolution.
- the timing of the appropriate signal obtained from the method must never be too early (too frequent water application) or too late (insufficient irrigation). This depends on response time of instruments and variables chosen to be observed.

Other requirements may be: nature and distribution of the errors of estimate from the method per se; the reliability of a method; the versatility of the method and the simplicity of application and practicality of the method.

2.4.3 Irrigation Scheduling Components and Criteria

Scheduling Components

To determine and satisfy crop-water needs requires applying knowledge of the plant-soil-atmosphere system as well as the water system conveyance processes. The volume of water needed for a specific irrigation then determines the combination of specific flow rate and the duration (Replogle, 1986). Knowledge of the crop and soil is closely related to the farm operator problem, i.e. the physical arrangements of his fields may be limited by the ability of the irrigation system. For irrigated crop production, water delivery to the field crop is a function of three basic components of an irrigation schedule categorized according the restraints placed on them. The duration.

- Flow rate: This may be continuous and/or seasonally modified. If the irrigator is dependent on the water authority, the flow rate may be negotiable. However, fixed flow rates do not necessarily limit production. Delivery flow may be by surface spreading, sprinkling or drip systems.
- Frequency: The delivery frequency, like flow rate, can vary widely. Water can be delivered periodically or with a repeated cycle. If water is passed on from user to user, the cycle may vary as the use varies.
- Duration: The length of time that an irrigation system is allowed to operate can vary from continuous flow throughout the season to varying time per irrigation cycle.

A restraint on one of these three components may for specific situations be offset by more flexible schedules of the remaining two. Replogle described these three system components in detail as well as the many restraints and numerous intermediate combinations possible. He also detailed the scheduling terminology used. The most flexible schedule is the so-called 'demand-system' which allows an irrigator to simply irrigate when he wants and how much he wants. This schedule was available at both research sites during this study.

Scheduling Criteria

Related to the irrigation components as described above are the irrigation scheduling criteria. The primary objectives of irrigation scheduling are to apply irrigation water at the right time and the right amount. Therefore, two scheduling criteria are time and depth as described by Raes et al. (1988).

Some time criteria are:

- fixed interval: irrigation is applied at predetermined intervals. The decision to irrigate is taken independently of the water content in the root zone.
- allowable fraction of 'readily available water'(RAW): irrigation is applied whenever the soil water depletion, relative to RAW, drops below a predetermined level.
- allowable depletion amount: irrigation is applied whenever a predetermined amount of water below field capacity (FC) is depleted out of the root zone.

specified depth in the root zone.

Some depth criteria are:

- back to FC: the soil water content in the root zone is brought back to FC.
- fixed depth: a predetermined amount of water is applied.

Predetermined values of the time and depth criteria listed above may vary between crops depending on their sensitivity to water shortages. A list of the sensitivity to water shortages for various crops was given by Brouwer et al. (1989), while Taylor and Ashcroft (1972) provided a list with critical soil water pressure head values below which transpiration reduction takes place. These parameters may vary depending on the crop growth period sensitive to a water shortage, i.e. flowering and yield formation as well as on atmospheric conditions: radiation, windspeed and humidity.

During the research reported here, the combination of time/depthcriteria as simulated by the model is a predetermined soil water pressure head value at a specified depth in the root zone with a fixed depth of irrigation water applied.

2.4.4 Irrigation Scheduling Techniques

GENERAL

The appropriate technique or technology is a function of the irrigation water supply, technical abilities of the irrigator, type of irrigation system, crop value, crop response to irrigation, the cost of implementing technology and personal preference (Heermann et al., 1990). Crop response to irrigation applies particularly to the potato crop as used in this research. Wright and Stark (1990) reviewed the irrigation management of potato. In the past, growers have principally irrigated from experience, using either a schedule based on the calendar or visual observation of crop and the soil water status. While this approach has served skilled irrigators well for years, it is prone to problems, especially with potatoes. Growers frequently irrigate excessively to prevent the detrimental effects of deficit irrigation. Excess irrigation usually results from applying too much water at a given irrigation rather than from irrigating too frequently. But over-irrigation increases fertilizer requirements to compensate for N leached out from the root zone and also increases energy inputs. Therefore the irrigation management scheme needs to be oriented towards maximizing the percentage of top grade tubers. This requires irrigation management to maintain optimum soil water contents to meet the crop water requirement. Such a management program includes:

- regular quantitative monitoring of soil water content,
- scheduling irrigations according to crop water use and soil water holding capacity, and
- a water supply and irrigation system capable of providing the needed irrigation on schedule.

The many techniques available to schedule irrigation are listed below with their primary advantages and disadvantages listed (some methods are still in development while others may not be very practical at the farm level).

PLANT - SOIL - WATER BALANCE

Many techniques and technologies can forecast the date and amount of irrigation water to apply. Much has been published on crop water requirements, scheduling techniques and numerous methods are discussed in detail (Jensen, 1980; Cavazza, 1985; James, 1988; Bailey, 1990). Thorough reviews of these subjects were given by Haise and Hagan (1967) and very recently by Heermann et al. (1990) and Anstey et al. (1991).

Irrigation scheduling methods include observations, measurements and various techniques listed as:

- plant observations,
- soil observations, and
- water balance techniques.

Plant based observations and indicators

Monitoring the plants is the most direct method of determining when to irrigate, as the primary objective of irrigation is to supply the plants with the water needed. However, plants are often too late by showing water stress conditions. Several plant observations are:

- Appearance and growth. These visual indicators like leaf wilting, curling and colour changes have simplicity as their primary advantage and observations can be made directly. Their disadvantage is that yield is usually affected before these changes are observed.
- Leaf temperature. A rise in leaf temperature related to air temperature is associated with reduced transpiration rates. The lower the leaf temperature with respect to that of the air, the less need plants have for water. Methods are the hand-held infrared thermometer and remote sensing from the ground, aircraft or possibly satellites.
- Leaf water potential. This destructive, time consuming measurement of leaf water potential is an indicator of the plant's need for water. The more negative the potential, the greater the need for water.
- Stomatal resistance. This is related to the degree of stomatal opening and the rate of transpiration and as such an index to the need for water. In general, high resistances indicate significant stomatal closure, reduced transpiration rates and the need for water.

Soil based observations and indicators

With soil-based irrigation scheduling, one must determine the current water content or pressure head of the soil compared to a predetermined minimum water level or pressure head and then irrigate to maintain the water content or pressure head above this minimum level. Campbell and Campbell (1982) as cited by Anstey et al. (1991) pointed out that it is often not the amount of water in the soil in deciding when to irrigate but the rate at which the soil water changes. Continuous measuring methods are therefore most useful. Campbell and Mulla (1990) gave an in depth overview of various soil water content measurement techniques.

Several soil observations are:

- Appearance and feel. Experienced irrigators may be able to judge the soil water content by the appearance or feel of the soil.

- Gravimetric soil water sampling. This is a direct method to measure the water content of the soil, but is very time consuming.
- Porous blocks. These blocks come in contact with the moist soil and equilibrate with the soil water. A water content change in the blocks, changes thermal conductivity and electrical resistance: calibration curves are required.
- Neutron scattering. Neutron moisture gauges or neutron probes are used to measure the volumetric water content. The technique involves an access tube, a source of high energy or fast neutrons (usually americium which is radioactive), and a detector. Fast neutrons are emitted and dramatically slowed down if they collide with hydrogen atoms. In most soils the only source of hydrogen is water. Therefore, when a soil has a high water content, the gauge readings will be high.
- Time Domain Reflectometry. There exists a relationship between the apparent dielectric constant measured with TDR and the volumetric soil water content. This TDR method works independently of soil type, density, temperature and soluble salt content. This method was originally proposed by Topp et al. (1980).

Besides the gravimetric method, tensiometers were also used during this study to monitor soil water status. Soil water pressure head is measured with a tensiometer buried in the soil at the required depth of measurement. A tensiometer consists of a ceramic cup filled with water connected through a water-filled tube to a vacuum gauge which is situated above soil level. Water moves in and out of the porous cup depending on changes in soil water content. As the soil dries out, water is drawn through the porous cup into the soil, causing a partial vacuum in the tube which is measured by the gauge. The soil water pressure directly read from the gauge is a fundamental parameter affecting soil water flux. Soil water characteristic curves may be used to convert soil water pressure values to volumetric water content values. Tensiometers may be successfully used to monitor soil water potential and are more applicable to potato production than to some other crops because of the need to keep the soil relatively wet and thus within the tensiometer range of from 0 to about -800 cm. A useful practice is to place them in the potato hill at various depths and use them in sequence as the root system develops.

The principal disadvantages of tensiometers are the installment requirements, the frequency of readings and service and the requirement for multiple sites. A limitation is the restricted range at which they reliably operate, from saturation to -800 cm. Irrigation scheduling using tensiometers of different types and complexity is practiced worldwide (Poulton, 1985; Lok, 1989). Jet-fill tensiometers have a tiny water buffer at the very top of the water-filled tube with which the tensiometer can be filled and de-aired. Phene et al. (1981) used tensiometers with microcomputers to automatically schedule irrigation. A recent development is the dielectric tensiometer as described by Hilhorst and De Jong (1988).

Water balance techniques

Many different water balance techniques are available to determine the timing and amount of irrigation. The techniques chosen in practise differ as to: observed variables; formulae used; degree of sophistication; and the objectives to be reached (application time only or time and depth). The successful use of soil water balance techniques for irrigation scheduling requires accurate and timely data from the field. These include the amount of rainfall, meteorological data to estimate evapotranspiration, the soil water status and crop conditions. The amount and frequency of meteorological data input depends on the accuracy required. In most real-time irrigation applications, meteorological data are collected with automatic weather stations for a general region representative of the irrigated area being scheduled. Other approaches use long-term average climatic data provided by various services.

In general, water balance techniques range from manual water balance sheets (checkbook method) to process-oriented, physically based simulation models. Two main water balance technique groups are distinguished:

- Checkbook. This method introduces irrigators to the concept of simplified water budgeting. This water budget approach allows the irrigator to maintain a current balance of plant-available water in the soil profile. A simple budget consists of soil water content as the initial balance, evapotranspiration as debit and rainfall and irrigation amount as credit. The checkbook system may utilize weekly or monthly information on consumptive use and rainfall data provided by government agencies. Available water holding capacities, allowable root zone depletions and estimates of upward flow from the groundwater for various soil types (Martin et al., 1990) can be used as initial guides in scheduling irrigations for deep, uniform soils. Maulé and Chanasyk (1987) described two methods to determine the drainage component of the water balance. However, irregularities in the soil profile can greatly affect the water holding capacity and consequently the soil water balance. The irrigator is responsible for maintaining the water balance to avoid over-irrigation or excessive soil water depletions. The calculated depletion may become negative due to large rainfalls or irrigation. The excess water is then assumed to drain below the root zone or runoff. These techniques can provide a reasonable guideline for managing irrigation systems depending on the accuracy required, the basic assumptions made and the climatic variation in the area. Drawbacks of these techniques are compacted layers, the presence of a water table or other obstructions to water flow affecting the soil water holding capacity. An example of checkbook irrigation scheduling was given by McKenzie and Chanasyk (1986).

- Computers. With the increased availability and relatively low cost of computers, simulation of the hydrological cycle provides a useful technique. With the help of water balance models, in which a number of empirical indicators are adjusted to local conditions, the water input (rainfall and irrigation) and water output (evapotranspiration and drainage) are computed. Simple applications are the correlation-based models which can only be applied under the same conditions as those for which the regressions were established. In these models, crop water use is represented as a function of two or more meteorological variables by regression calculations without considering the physical processes involved. With the understanding of today's theory of the movement of water in the plant-soil-atmosphere system, process-oriented physically based models describing the dynamics of this system have become more applicable. Processes in the unsaturated and saturated root zone may by quantified using soil hydraulic properties, crop information and meteorological data. A validated water balance crop growth model is a useful tool for determining irrigation management. The basis for their usefulness is their ability to predict results under any sequence of weather conditions, and any soil characteristics, i.e. experiments can be simulated under various conditions. These models vary widely in dynamics of water transport, root growth and crop production. The more sophisticated models require many measurements and qualified people for data processing and appear to be more suitable for information services in aiding irrigators with scheduling. Anstey et al. (1991) listed literature on these models.

2.4.5 Forecasting Scheduling

Water balance techniques as listed above may use real-time climatic data to provide a current estimate of the soil water status. An irrigation can be started when the current estimated soil water depletion reaches a point where irrigation management is still sufficient. With this technique, the management of an irrigation system requires that water be available on demand and that the system capacity is large enough to irrigate the area intended. However, it is much more desirable to forecast a schedule of future irrigation times and amounts for the areas being managed. The water balance techniques may be extended into the near future (the next couple of days), by using forecasted ET_r rates and rainfall amounts. Heermann et al. (1990) discussed some forecasting options for ET_r and rainfall.

ET_r forecasting

One option is to use the real-time weather forecast for future ET_r rates. However, weather forecasts often only include temperature and precipitation while forecasted radiation is very limited. Another option is to assume the current actual ET rate or to use average actual ET rates of the previous couple of days, for the coming days, i.e. before the next irrigation. However, one should keep in mind that in general the crop coefficients k_c change during the growing season, increasing during crop development and decreasing as the crop matures. One can also use climatic average ET_r data providing it is available. The effect of ET_r variation on irrigation scheduling and crop yield is dependent on the type of irrigation system, soil type and climatic conditions. Stockle et al. (1991) state from their irrigation scheduling research that a 30% under prediction of ET_r may give a corn yield reduction up to 27%.

Beside the many methods on how to forecast ET_r, the question also arises when to update with real-time climatic data for the next forecast. Most weather forecasts used for irrigation scheduling are projected for a 3- to 5-day period (Fleming, 1988; Heermann et al., 1990) at which interval real-time climatic updates should take place.

Rain forecasting

Local rainfall forecasts are often made as a probability of occurrence in a general area and not as an amount. Depending on the climatic conditions, heavy showers may vary from one location to the next, making it very hard for farmers to use rainfall forecasts in their schedule. One option to forecast the next irrigation date is to enter different amounts of rainfall and evaluate the effect of these on the scheduling operation. Another option is to use historical normal rainfall amounts. With a high rainfall probability, it is advisable to manage the irrigation system such that the soil profile will not be filled to a predetermined level, but have a buffer for the expected rain. This management decision is difficult to make as it is highly dependent on how reliable the rainfall probability is and how much rain will fall.

This decision is even more difficult to make during the periods when the crop is sensitive to water shortages and next to impossible if the irrigator does not have a flexible schedule like the 'demand system', when at any time an unlimited amount of water is available.

Irrigation scheduling may not only be influenced by the type of irrigation system but also by local climatic conditions, i.e. arid or humid climate. Irrigation in humid areas may often be economical even though annual rainfall exceeds evapotranspiration. However, the annual rainfall distribution does not coincide with the evapotranspiration distribution, such that irrigation is necessary to supplement the rainfall during the brief periods of water shortage. Many of these humid areas are affected by a maritime climate, like the Netherlands, where rainfall distribution may be erratic and higher rainfall probabilities must be considered in the decision process. Therefore, the decision when to irrigate becomes more complex as increased rainfall can cause deep percolation and leaching of fertilizers. This problem is particularly true for soils with a low water-holding capacity where the margins for error are small when applying water.

Although rainfall may not be easily forecasted in maritime climate conditions, ET_r forecasting on the other hand is much easier. Rainfall may then frequently refill the root zone, requiring fewer long periods of accurate ET_r estimates because accumulated errors are reset to zero after heavy rains (Heermann et al., 1990). Large variations in ET_r are not expected and in simplified budgeting techniques are even assumed constant during periods within the growing season. Formulas to estimate ET_r may thus be simplified to functions of temperature and radiation like the equation of Makkink (1957) used in this study.

With forecasted ET_r and rainfall, a simulation model offers a means to provide decision-making information. The improved predictions possible from computerized irrigation scheduling allows the irrigator to lengthen the period between field monitoring and reduces the uncertainty of the soil water balance. However, the schedule is no better than the data used or the ability to decipher the scheduling information.

3.0 SIMULATING PLANT-SOIL-ATMOSPHERE SYSTEM

3.1 General

De Wit (1982) defined systems, models, and simulation. A system is a limited part of reality that contains interrelated elements. A model is a tool designed to represent a simplified version of the system and simulation is the art of building mathematical models and the study of their properties in reference to those of the system. A mathematical model consists of a set of equations that are known to govern the system's behaviour. According to France and Thornley (1984) as cited by Lascano (1991) models can be divided into:

- Empirical models based on observed qualitative relationships set out principally to describe.
- Mechanistic models based on known principles and attempting to give a description of the system.
- Static models that do not contain time as a variable.
- Dynamic models that simulate a process during a change in time.
- Deterministic models producing a unique outcome for a given set of events, i.e. do not have random variables and make definite predictions. However, due to spatial variability of the processes, for example soil hydraulic properties, a certain degree of uncertainty may be associated with the results.
- Stochastic models containing some random elements or probability distribution to accommodate spatial variability and may quantify the degree of uncertainty.

Models can be solved by either analytical or numerical techniques.

- Analytical models are ones in which all relationships are expressed in closed form so that the equations can be solved by the classical methods of analytical mathematics.
- Numerical models are ones in which the governing equations are solved by means of step-by-step numerical calculations.

Since the 1960s and 70s, when high-speed digital computers became more available, a dramatic change took place from analytical solutions to numerical analysis. With the current numerical techniques, more realistic situations can be obtained providing good field data are available. Various modeling techniques ranging from the strategy of model building to the use of different mathematical and numerical approaches and how they are solved are extensively discussed by Mercer and Faust (1981), Wang and Anderson (1982), and Lascano (1991).

Numerous models have been developed to describe the plant-soil-atmosphere system, using the general equation of water flow as a basis. These models vary widely in their coverage of water transport in the saturated-unsaturated zone, root development, soil water extraction and the dynamics of crop growth and production. Reviews of these models were given by Molz (1981), Malik et al. (1986), Milly (1988), and Lascano (1991).

According to Ritchie and Johnson (1990), most of these models are deterministic and physically based, providing a mechanism of estimating actual evapotranspiration giving a more complete description of the interacting process like energy exchange in the plant-soil-atmosphere system. These models may be further divided in mechanistic and functional models. Mechanistic models are usually based on dynamic rate concepts incorporating basic mechanisms such as Darcy's law and the continuity equation. The more functional models treat these processes in a more simplified manner, reducing the amount of input required. An important difference between the two is their primary usefulness: the former in research for better understanding of integrated systems and the latter as a management tool. However, a clear distinction between these models is not easily made as varying levels of empiricism are introduced to reduce input data requirements. A review of numerical modeling approaches of water dynamics in the unsaturated zone was given by Feddes et al. (1988a).

During this irrigation research, a deterministic, mechanistic model was used which is described in the following sections.

3.2 Simulating Water Dynamics

Feddes et al. (1978) developed a numerical model SWATR (Soil Water Actual Transpiration) to calculate the actual use of water by a field crop. This model was extended by Belmans et al. (1983) named SWATRE(xtended). The process of transient saturated - unsaturated soil water flow, considering water uptake by roots, takes place in a one-dimensional soil profile for which the water balance is calculated. The rate of dry matter growth of a crop having an optimal supply of nutrients can be calculated by the water-limited crop production submodel CROPR (CROp PRoduction) of Feddes et al. (1978). A schematic overview of both submodels is given in Appendix 2.

Over the years, the growing demand for and extensive use of the SWATRE model has led to many adaptations to suit hydrological situations worldwide. As such, the model has been extensively described in the literature for many applications:

- water balance and crop growth : potatoes (Feddes et al., 1988c; Feddes et al., 1988b; grass (De Jong and Kabat, 1990); oat (Ragab et al., 1990a, 1990b)

- integrated approaches : to predict changes in water management by drainage on trafficability and workability in spring, sowing/planting time, emergence date, transpiration, growth and dry matter yield of potatoes and summer wheat. (Van Wijk and Feddes, 1986; Van Wijk et al., 1988).

- comparison with other models : compare different soil-water flow / crop-growth models (Feyen, 1987; Schouwenaars et al., 1988).

- irrigation related studies : in Egypt (Van Aelst et al., 1988), in the Netherlands (Wesseling and Van den Broek, 1988; Gabriels and Kabat, 1990), in India (Mahey et al., 1984), in Mozambique (Schouwenaars, 1988).

The primary advantages of using the SWATRE model in this irrigation study is its ability to calculate the actual amount of water transpired by the plant in heterogeneous soil-root systems under water-limited conditions and the ability of the model to calculate capillary rise in areas with shallow groundwater tables. Other advantages are the possibility to use different top and bottom boundary conditions making the model applicable for many types of hydrological situations. One of the main restrictions in using this version of the SWATRE model is its inability to reproduce phenomena at high temporal resolutions, i.e. rain and irrigation intensities can not be entered but rather 24-hour average values are used. Other restrictions are no hysteresis and no sloped surface calculations.

To obtain a unique solution of the partial differential equation corresponding to the physical process of soil water movement, additional information about the physical state of the process must be known. The use of the Darcy equation requires characterization of the soil profile and definition of initial and boundary conditions. Boundary conditions include the geometry of the soil profile under consideration, i.e. lower and upper boundaries with their respective conditions. The soil profile is divided into different soil layers (having compartments of varying height) each with different soil hydraulic properties making it a heterogeneous soil-root system. Transport taking place between the upper and lower boundaries of the system is calculated by solving the flux density and continuity equations numerically in each compartment. Richard's equation is solved by a finite difference scheme which is implicit and applies an explicit linearization of hydraulic conductivity K and soil water capacity C. Knowing the initial and boundary conditions, the system of equations for all the compartments is solved for each (variable) time step by applying the so-called Thomas tri-diagonal algorithm (Belmans et al., 1983). The treatment of the initial and boundary conditions in the model SWATRE are described in the following sections.

3.3 Boundary conditions

Initial conditions required at the beginning of the simulation period consist of soil water pressure head as a function of depth, soil water content as a function of depth or equilibrium conditions with the presence of a groundwater table.

Lower boundary conditions are described by Mercer and Faust (1981):

- Dirichlet conditions: h is specified (e.g. zero at the phreatic surface)
- Neumann conditions: the flux is specified (e.g. free drainage or no-flow boundary)
- Cauchy conditions: the flux is a function of a dependent variable (e.g. h)

For the unsaturated zone, the lower boundary is usually taken as the water table, i.e. the phreatic surface where h =0. The possibilities of unsaturated/saturated bottom boundary conditions of the soil system domain within the model SWATRE are illustrated in Appendix 3.

The upper boundary of the soil profile is the soil surface. This boundary is under the influence of the atmosphere and the soil surface, i.e. incoming and outgoing fluxes.

While potential evapotranspiration from a cropped soil depends primarily on atmospheric and field conditions, the actual flux across the soil surface is limited by the ability of the soil to transmit water. Also if water supply exceeds the actual infiltration capacity of the soil, then part of the water may accumulate on the soil surface or eventually runoff, as the actual flux across the soil surface is limited by soil water conditions. Thus exact top boundary conditions cannot be estimated directly but a solution is found by maximizing the absolute flux (Feddes et al., 1988a):

$$q(K,h) < q_s \tag{25}$$

$$h_{lim} < h < 0 \tag{26}$$

where: $q(K,h)$ = actual Darcian flux through soil interface (cm d^{-1}),
q_s = potential flux through soil interface (cm d^{-1}),
h_{lim} = minimum allowed h at the soil surface (cm), and
h = soil water pressure head at the soil surface (cm).

These fluxes present either soil evaporation or infiltration depending on their direction. The value h_{lim} can be calculated assuming that the soil water pressure head at the soil surface is in equilibrium with the atmosphere:

$$h_{lim} = \left(\frac{RT_a}{Mg}\right) \ln(f) \tag{27}$$

where: R = universal gas constant (J mol^{-1} K^{-1}),
T_a = absolute temperature (K),
M = molecular weight of water (kg mol^{-1}),
g = acceleration due to gravity (m s^{-2}), and
f = relative humidity of air (fraction).

In the SWATRE-model, the top boundary condition ET_p is partitioned over potential soil evaporation E_p and potential transpiration T_p as described in the following sections.

3.4 Modeling Potential and Actual Soil Evaporation

Methods and models available to estimate soil evaporation (Ritchie and Johnson, 1990) often differ in estimating the fraction of crop covering the soil surface and the location of the evaporation front. When the evaporation front is assumed to be at the soil surface, water will be able to evaporate freely at the evaporative demand of the atmosphere but limited as described by equation (25). When soil cover increases, soil evaporation gets smaller and transpiration larger. Different types of crops give different soil cover patterns, i.e. row crops (potatoes and maize) give a partially covered soil, whereas other crops give a more fully covered soil. As the soil is not fully covered during the entire growing season, soil evaporation may constitute a major portion of the seasonal water balance. Taking this into account, the partitioning of ET_p into T_p and E_p becomes very important when determining crop water requirements.

The SWATRE-model calculates potential soil evaporation E_p as a function of leaf area index and soil cover based on a model developed by Ritchie (1972) and modified by Belmans et al. (1982):

$$E_p = e^{(-0.6\ LAI)}\ ET_p \tag{28}$$

where LAI is leaf-area-index ($m^2\ m^{-2}$), calculated as:

$$LAI = aSc + bSc^2 + cSc^3 \tag{29}$$

where: Sc = soil cover (fraction) to be given as daily input, and
a,b,c = crop dependent regression coefficients.

A crucial difference between equations 28 and 29 is that the latter is crop dependent while the former is not. The effect of different types of crops on E_p is illustrated in Figure 7. Although potatoes amd maize are both row crops, at the same soil cover fraction, soil evaporation is lower at the potatoes than at the maize crop indicating different LAI values.

Belmans et al. (1982) determined the coefficients for potatoes as applied in equation 29 (a =2.6, b =1.5 and c =0.9).

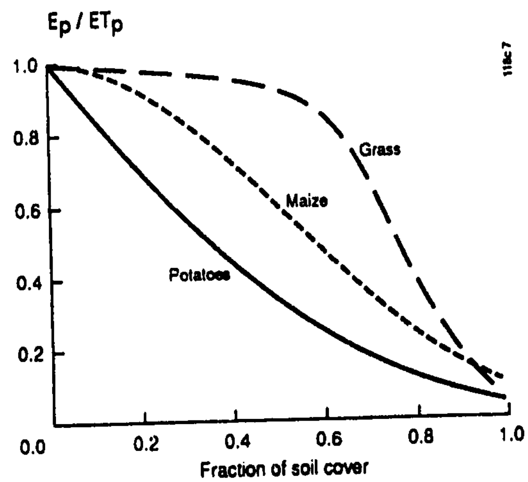

Figure 7. Ratio of potential soil evaporation E_p over potential evapotranspiration ET_p in relation to soil cover for different crops. (adapted from Feddes and Bastiaanssen, 1990).

In a dry period actual soil evaporation E can be evaluated in a rather simple way, according to Black et al. (1969):

$$E = \delta\sqrt{t+1} - \delta\sqrt{t} \tag{30}$$

where: δ = soil dependent parameter, and
t = time after dry period started (d).

In the model SWATRE any dry period ends the day after $Pr \geq 1$ cm d^{-1}. Then the procedure starts again. The value of δ was assumed to be 0.35, an average value cited by Ritchie (1972).

The potential flux through the soil surface q_s (equation 25) consists of two components E_r and E_i stated as:

$$q_s = E_r - \left(Pr + Ir - E_i\right) \tag{31}$$

where: E_r = reduced potential soil evaporation (cm d^{-1}),
Pr, Ir = precipitation, irrigation (cm d^{-1}), and
E_i = evaporation flux of intercepted water (cm d^{-1}).

The value E_r is estimated as the minimum value of E_p and E whereas the value E_i is estimated as:

$$E_i = Sc\, u Pr^{(v - wPr)} \tag{32}$$

where u, v and w are regression coefficients taken respectively as 0.044, 0.53 and 0.18 as given for potatoes by Belmans et al. (1982). Irrigation and precipitation are treated equally in this equation.

In the case of evaporation (q_s positive), the actual evaporation is the Darcian flux q(K,h) from the top nodal point to the soil surface. Actual soil evaporation E is taken as the minimum of q_s and q(K,h).

In the case of infiltration (q_s negative), the actual infiltration , again the Darcian flux q(K,h) through the soil surface to the top nodal point. Actual infiltration is the minimum of q_s and q(K,h).

3.5 Modeling Potential and Actual Transpiration

Potential transpiration T_p can now be determined as the difference between ET_p and E_p. Potential or actual transpiration flux must be equal to the water uptake rate of the plant roots and is influenced by the evaporative demand of the atmosphere. Feddes et al. (1988a) reviewed some of the early research in root water uptake such as describing a widely accepted common expression to estimate transpiration under steady-state conditions with an analogue of Ohm's law by Feddes and Rijtema (1972) as:

$$T = \frac{h - h_r}{R_s} = \frac{h_r - h_l}{R_p} \tag{33}$$

where: T = actual transpiration rate (cm d^{-1}),
h, h_r, h_l = respec. pressure head in soil, at root surface and in the leaves (cm), and
R_s, R_p = respec. flow resistance in soil and plant (d).

This so-called microscopic (single root) approach is often used to evaluate complex soil-root geometries on water/nutrient uptake (De Willigen and Van Noordwijk, 1987). The difficulties involved in testing microscopic scale models under natural field conditions have restricted their applicability. Consequently macroscopic approaches were developed for dynamic modeling (Howell, 1990). Water uptake by plant roots is represented by a sink term S embedded in the continuity equation in conjunction with Darcy's law to yield Richards' equation for a heterogeneous soil root system:

$$\frac{\partial h}{\partial t} = \frac{1}{C(h)} \frac{\partial}{\partial z}\left[K(h)\left(\frac{\partial h}{\partial z} + 1\right)\right] - \frac{S(h)}{C(h)} \tag{34}$$

where: S = volume of water taken up by roots per unit bulk volume of soil per unit time.

The magnitude of this sink can be calculated for each depth within the root zone and each time period. It is assumed that the vapor flux leaving the stomata is equal to the moisture flux taken up by the plant roots. This implies that no water is held within the plant, and that there is no delay between the atmospheric demand and the root extraction rate if atmospheric demand changes. This means that potential transpiration is equal to the integral of the maximum sink term value over the rooting depth:

$$T_p = \int_{Z_r}^{0} S_{max}\, dz \tag{35}$$

where: S_{max} = maximum water extraction by plant roots (d^{-1})

Many of these macroscopic water-extraction models with numerous S functions, differing in aim, structure and detail, have been formulated and used. An overview of these models was given by Feddes (1981) and Malik et al. (1989). Hoogland et al. (1981) provided a list of S_{max} values for various arable crops. Alaerts et al. (1985) compared four different S functions with the SWATRE model and concluded that even though a similar total amount of water extraction can be simulated, the distribution of the extraction rate through time and depth depends strongly on the selected sink term.

The SWATRE model used in this reseach, based on the root extraction function, divides the soil into several layers, while the crop above the soil is taken as a single unit. In this irrigation study, the sink term function was used according to Feddes et al. (1978) where in the interest of practicality, a homogeneous distribution of S_{max} with rooting depth, i.e. water extraction takes place equally over the entire rooting depth Z_r (Figure 8) expressed as:

$$S_{max} = \frac{T_p}{Z_r} \tag{36}$$

If for example under optimal conditions T_p =0.5 cm d^{-1} and Z_r =25 cm, then from each 10-cm layer of root zone, the maximum possible water extracted is 0.2 cm d^{-1}. But conditions are not always optimal, i.e. the root zone may be either too wet or too dry leading to reduced water extraction patterns.

Feddes et al. (1978) proposed to use a sink term solely depending on soil water pressure head, h, and described S semi-empirically:

$$S(h) = \alpha(h)\, S_{max} \tag{37}$$

where: $\alpha(h)$ = dimensionless function of h ($0 \le \alpha \le 1$)

This function where S_{max} and $\alpha(h)$ vary in space and time describes optimal and non-optimal conditions dependant on the soil water pressure head distribution within the soil root zone as indicated by Figure 9.

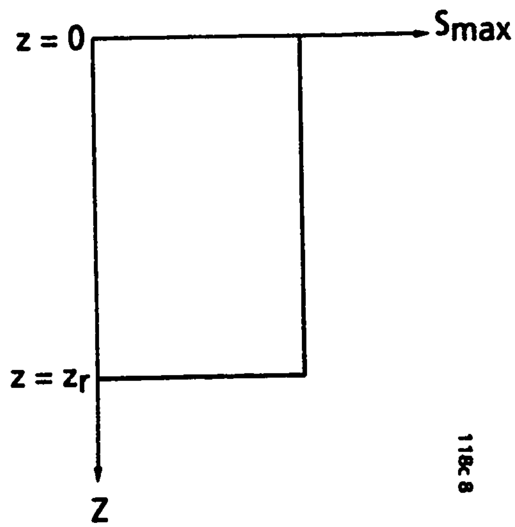

Figure 8. The water uptake function as proposed by Feddes et al. (1978) where the maximum water extraction by plant roots S_{max} takes place over the entire root zone depth Z_r.

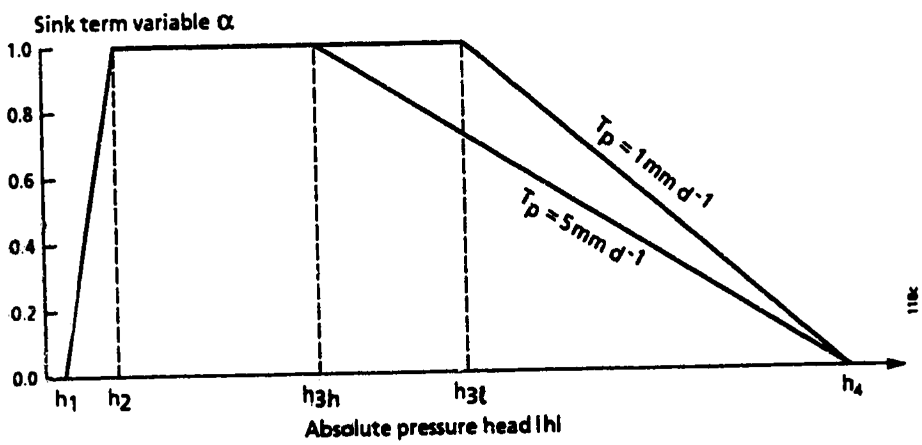

Figure 9. Dimensionless sink term α as a function of the absolute value of soil water pressure head h (after Feddes et al., 1978). Water uptake below h_1 (oxygen deficiency) and above h_4 (wilting point) is set to zero. Between h_2 and h_3 (reduction point) water uptake is maximal. The value of h_3 varies with potential transpiration T_p.

Water uptake below h_1 is zero as no gas diffusion can take place (oxygen deficiency). Uptake is also zero above h_4 (wilting point) when no more available water is left. Between h_1 and h_2 and between h_3 and h_4, a linear increase and decrease in root extraction respectively take place. Optimal water extraction takes place between the h_2 and h_3 values. The h_3 values are considered the critical or threshold values below which transpiration reduction occurs and subsequently yield reduction will take place. They are crop dependent and vary with changing evaporative demand of the atmosphere (high, h_{3h} and low, h_{3l}). Taylor and Ashcroft (1972) provided a table with critical or threshold h_3 values for many types of arable and horticultural crops under varying atmospheric demand.

Thus actual transpiration T is calculated as:

$$T = \int_{z_r}^{0} S(h,z)\, dz \qquad (38)$$

This sink term function indicates that the water storage in the root zone can become influential only when a certain critical value of the pressure head (h_3) is reached. This value at a specified depth in the root zone is the primary time criterion during in study, based on research by Hellings et al. (1982) and Van der Schans et al. (1984) on the potato crop.

4.0 MATERIALS AND METHODS

4.1 Site Description

Field experiments were conducted during the 1986 and 1987 growing seasons at two research stations: Rusthoeve (near the town of Colijnsplaat) situated in the south-western area and Vredepeel (near the town of Vredepeel) in the south-eastern area of Holland (Figure 10). Rusthoeve is situated near the coast with predominantly marine clay and peat bog soils. Vredepeel is situated in the 'higher' region of the country consisting mainly of sandy soils, which often suffer from water shortages. Due to crop rotation, the experiments were moved to another location at the research station for the 1987 season.

At each research site, three irrigation treatments were used:

- no irrigation, i.e. rainfed,
- irrigation based on farmer's decision (manager of research station), and
- irrigation based on model prediction.

The irrigation treatments are abbreviated in the text and the figures as N (non-irrigated); M (model-irrigated) and F (farmer-irrigated).

At Rusthoeve, the experiment was performed as a single plot experiment with each treatment adjacent to the next (Figure 11). Each treatment block was 27 m wide and approx. 56 m long. A buffer of approx. 11 m was on both sides of each block prevented irrigation overlap and wind drift, making the gross working width per treatment consistent with the irrigation equipment used. To create replicates, each treatment was further subdivided into 112 small blocks: 100 were for periodic harvesting and 12 were for field measurements (Figure 12). During periodic harvesting plant characteristics, fertilizer uptake by plants and tuber yields were determined.

At Vredepeel the experiment was performed as a split plot experiment where each treatment was repeated six times. The total irrigated field was 18 m wide and 162 m long with each treatment being 9 m wide and 18 m long (Figure 13) to accommodate the irrigation equipment used.

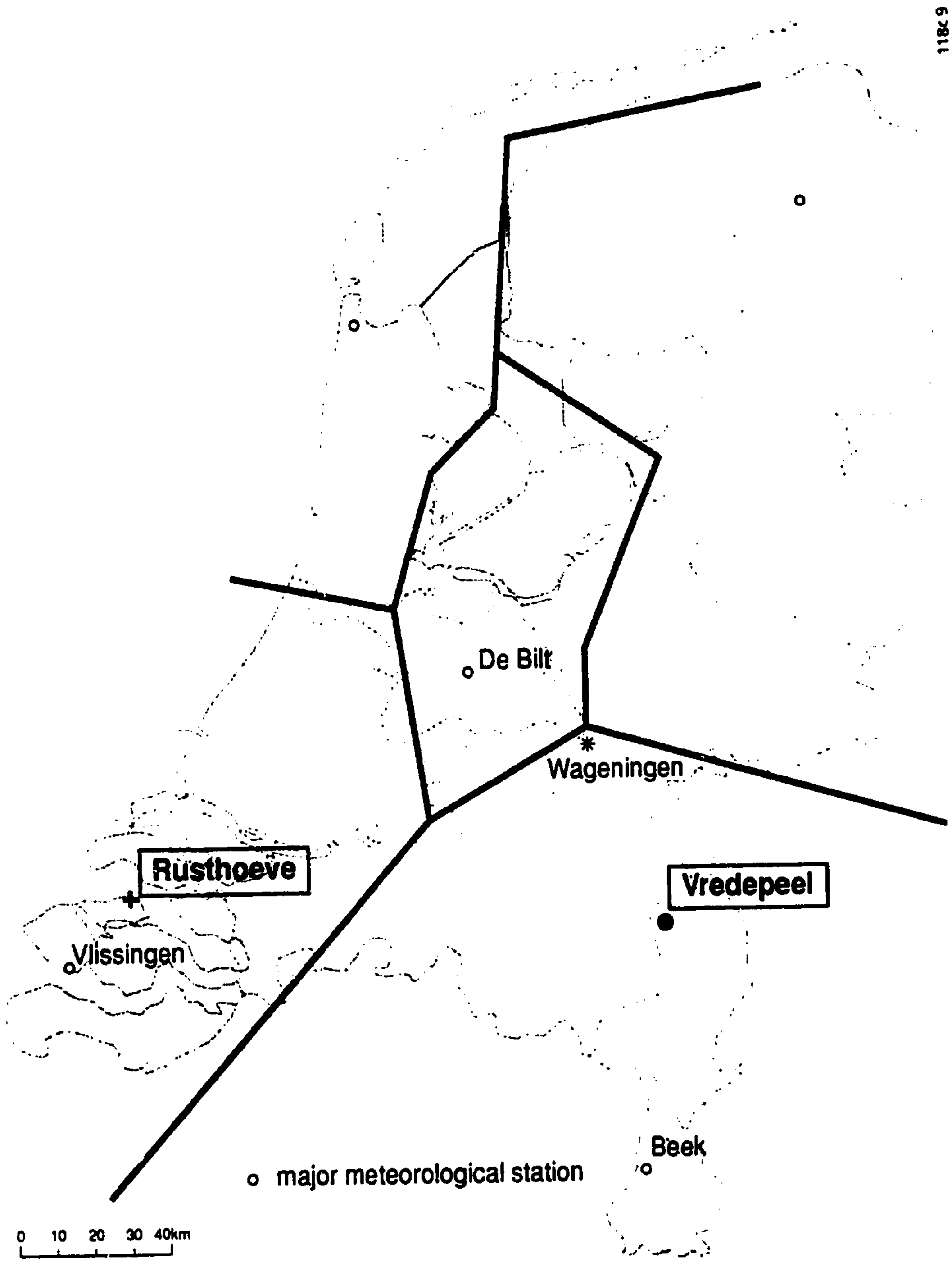

Figure 10. Location of two research sites (boxes) and the five major meteorological stations (o) in the respective regions.

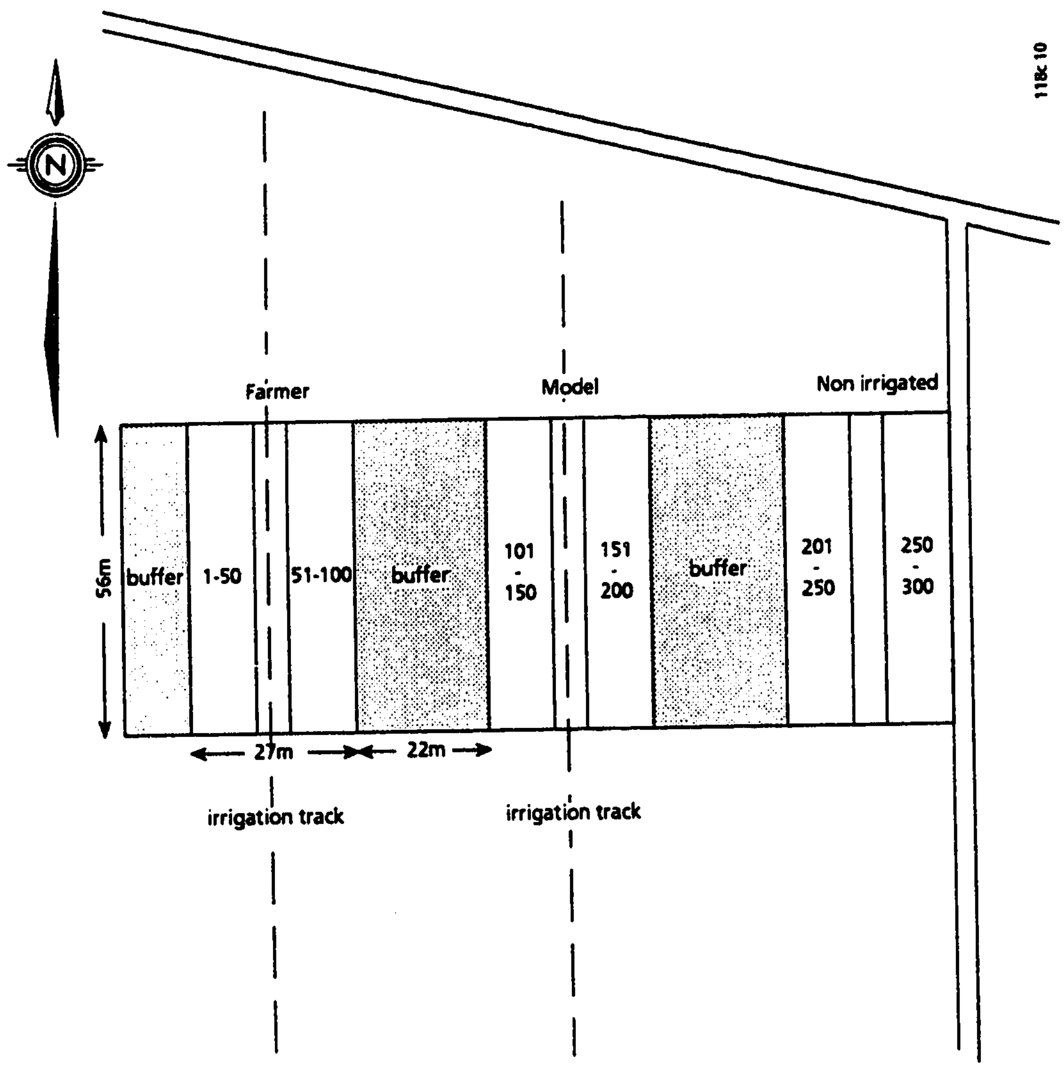

Figure 11. Layout of the irrigation treatments at the Rusthoeve station. Numbers refer to subdivided blocks where periodoc harvests took place.

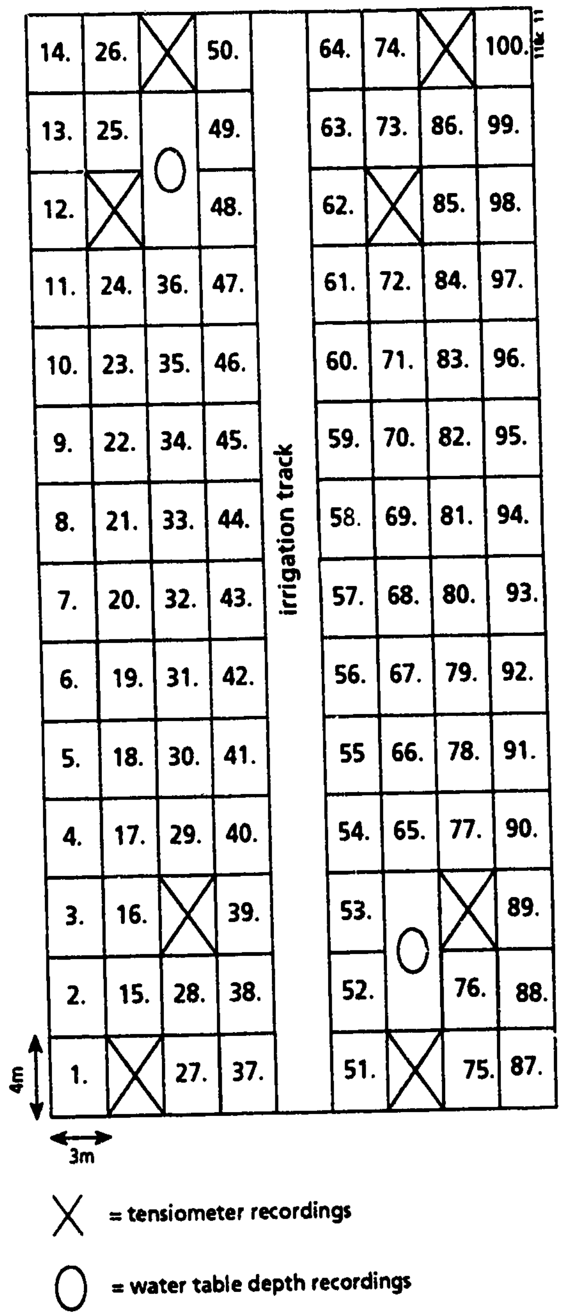

Figure 12. Detailed layout of the model irrigation treatment at the Rusthoeve station. Numbers refer to subdivided blocks where periodic harvests took place.

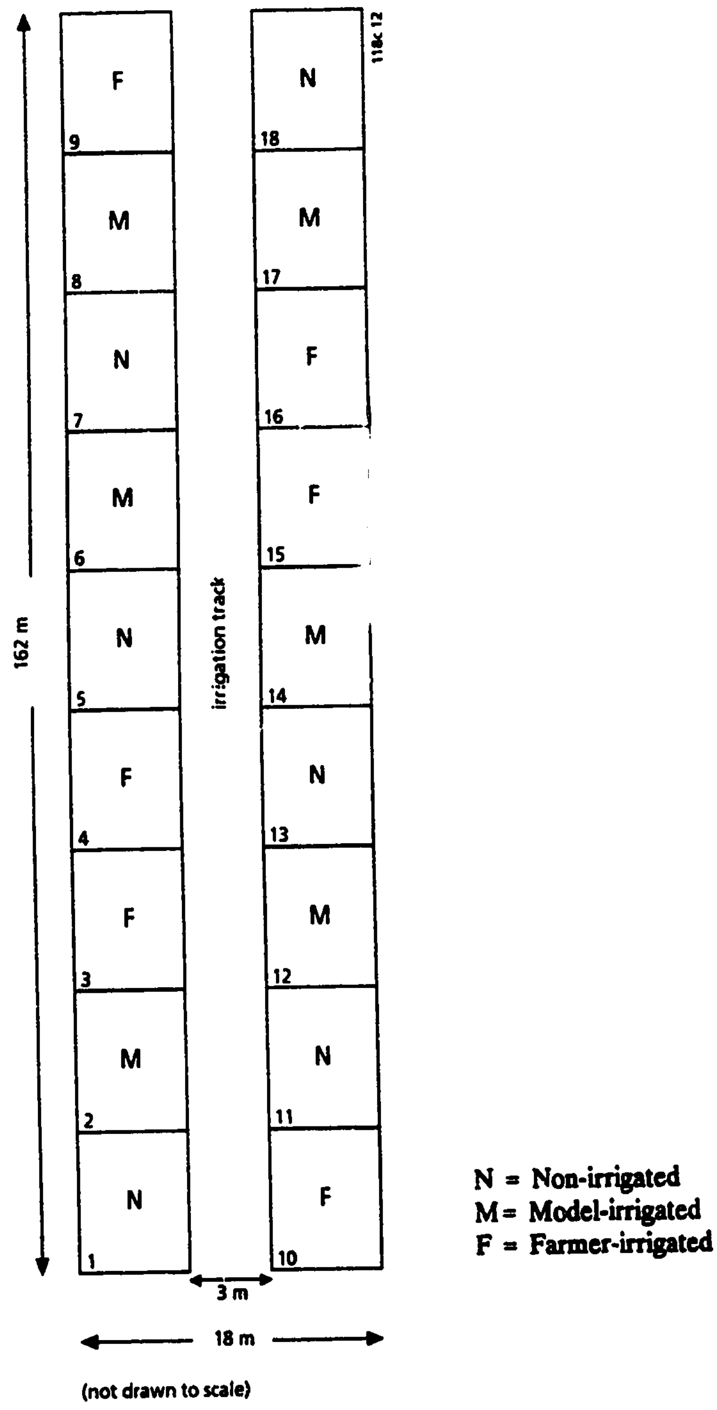

Figure 13. Layout of the irrigation treatments at the Vredepeel station. Numbers refer to subdivided blocks where periodic harvests took place.

4.2 Field Operations

In both years, potatoes (Solanum tuberosum, cultivar Bintje) were grown. The potatoes were planted as a row crop in ridges of approx. 20 cm high. Row spacing was 75 cm and plant spacing was 33 cm. After planting, more ridging or hilling operations were performed to shape the beds and enhance development. These cultivations also control weeds in the first period after emergence. Important dates in the growing season are given in Table 1.

Table 1. Dates of planting, full emergence and harvest at both research sites for 1986 and 1987.

	Rusthoeve		Vredepeel	
	1986	1987	1986	1987
Planting	30 April	15 April	23 April	23 April
Full emergence	23 May	20 May	20 May	14 May
Harvest	19 Sept.	19 Sept.	25 Sept.	21 Sept.

Beside these field operations, irrigation, fertilizer applications and disease management are also included. At the beginning of each growing season, soil chemical properties ($CaCO_3$, P, Mg, K_2O and mineral Nitrogen) were determined at each site. Additional fertilizers (chemical and manure) of Nitrogen, Phosphorous and Potassium were applied to ensure optimal growth as potatoes require an adequate nutrient supply. For complete details, see Ouwerkerk (1987).

Irrigated potatoes are considered high risk for potato blight (phytophthora infestans) and thus disease control needs to be planned accordingly (Bailey, 1990). On both research sites, necessary steps for disease management were taken. If, however, during the irrigation scheduling period a time of spraying coincided with an irrigation decision either by the farmer or predicted by the model, the time of spraying was delayed and if necessary extra chemicals were applied.

4.3 Potato Crop

Wright and Stark (1990) reviewed the literature on the potato crop in general and its relation to water use and irrigation. The potato is an annual herbaceous plant with fleshy tubers arising from underground stems. It has a relatively shallow, fibrous root system with the majority of the roots in the top 30 - 40 cm of the soil. Below this depth, less water is extracted compared to deeply rooted crops such as sugarbeets. The lack of deeper root development is attributed to the inability of the relatively weak root system to penetrate restrictive layers. However, rooting depths deeper than 1 m have also been reported under favorable soil conditions (Wolfe et al., 1983). Potatoes grow well on a wide variety of soils, although coarse-textured and loamy soils are preferable, giving high yields of marketable tubers. Properly fertilized and irrigated sandy soils will also produce high yields. Potatoes require ample nutrients to ensure rapid, steady growth and normal tuber development.

Potato has a limited drought tolerance likely due to the effects of a relatively shallow, inefficient root system and to the tendency for the stomata to close and expansive crop growth to decrease in response to mild water deficits. As the potatoes are sensitive to water stress compared to many other common crops, adequate soil water is necessary to ensure production of well shaped tubers and avoid tuber disorders that are directly related to water stress. Irrigation is thus an essential component of commercial potato production. In humid and subhumid regions, supplemental irrigation is often beneficial since even short periods of drought can jeopardize economic returns. Sprinkler irrigation is presently the most widely used method of irrigating potato. It permits more frequent light irrigations and provides more uniform water distribution in the potato root zone than surface irrigation methods. This is especially important during the early season when uniform wetting of the hill is required as the root system is not fully developed. On many soils, the instantaneous application rate by sprinkling irrigation exceeds the infiltration rate, and runoff occurs from the application area. Shedding of water by the potato plants prior to full canopy cover accentuates this problem.

4.4 Irrigation Systems

The irrigation systems at both research sites were over-head sprinklers consisting of hose-reel irrigators. At Rusthoeve, a single spray raingun was pulled in by its supply hose and slowly wound onto a large hose-reel. Its application width was 48 m, covering each treatment block. These machines are subject to poor distribution patterns, particularly in windy conditions, and it is difficult to regulate the application rate. However, they are very popular due to their low labour requirement. Single plot experiments are most practical with this type of irrigation system. For each irrigated treatment and application, the system had to be dismantled and set up again. The water supply for the Rusthoeve system was groundwater pumped up via vertical tubes connected to deepdrains. Deepdrains are horizontal plastic drains with a diameter of 10 cm and an organic filter placed around them, installed at a depth of approx. 5 m below the soil surface in the sandy aquifers. The aquifers are recharged by rain water and the quantity of water available depends on the amount of rainfall and the hydraulic conductivity of the aquifer. The length of a deepdrain is dependent on farm size and usually ranges between 70 to 100 m.

As the Rusthoeve research station is located in the low part of the Netherlands, next to the estuaries, salt water intrusion occurs. The quality of the water is dependent on the amount of chloride present. In periods of prolonged dryness, water quality checks are often performed as the fresh water supply diminishes and salt water may intrude. The installation of deepdrains in this region started in 1984 and continues.

At the Vredepeel, site a hose-reel system was also used. Here, however, a 24-m wide spraying boom consisting of two booms each 12 m in width with nozzles spraying upwards, was drawn over the field. These booms are subject to uneven distribution in wind, but considerably less so than rainguns. Water application rates can be regulated over a short distance, but high instantaneous application rates are liable to cause runoff. The Vredepeel site is located in the high region of the Netherlands where irrigation water is usually pumped from deep aquifers. At this site water was pumped from a depth of 20 m.

As potatoes are one of the most sensitive crops to salinity, they are usually not grown on saline soils or with irrigation water of high salinity. Groundwater salinity at the Rusthoeve site is higher than at Vredepeel (Table 2).

Table 2. Irrigation water quality at both research sites in spring 1986.

parameter	units	Rusthoeve	Vredepeel
pH		7.5	5.8
Electrical Conductivity (20°C)	($mS\ m^{-1}$)	84	32
Calcium (Ca^{2+})	($mg\ L^{-1}$)	162	7.2
Hydrocarbonate (HCO_3^-)	($mg\ L^{-1}$)	342	13
Chloride (Cl^{-1})	($mg\ L^{-1}$)	54	17
Sulphate (SO_4^{2-})	($mg\ L^{-1}$)	135	85
Total hardness	($mmol\ L^{-1}$)	4.65	0.4

James (1988) rated the threshold salinity value for potatoes at 300 mS m^{-1} (electrical conductance, EC). The EC of the groundwater at Rusthoeve (84 mS m^{-1}) was well below this threshold value and thus salinity caused no restriction on water availability to the plant. The high calcium content at the Rusthoeve site often indicates seepage areas, while low calcium contents, at the Vredepeel site, are often present in sandy areas where infiltration may occur.

4.5 Data Acquisition and Monitoring

General

Data collected at the research sites were used in the SWATRE model to simulate the soil water balance and to predict the times of irrigation. As stated in the objectives of this research, most data required as model input should be easily accessible to the farmer if this model is to be used in a management scheme to advise farmers in their irrigation practise. Besides soil physical data and soil moisture content, all other data required as model input may be obtained relatively easily by the farmer. Other data measured at the sites, include parameters related to growth, production, quality, fertilizers applied and fertilizer plant uptake

(Ouwerkerk, 1987; Dekkers, 1988; Mol, 1988; and Van der Schelde, 1988).

Soil Physical Properties

For modeling soil water movement in the unsaturated zone, soil-physical properties must be known. In the spring of 1986 soil samples were taken at both research sites to determine soil type and profile characteristics. Soil hydraulic properties corresponding to those of the soil type at the research sites were taken from a Dutch soil database which contains the most commonly occurring soils in the country. In the 1980s soil water retention and hydraulic conductivity curves were measured for a great number of soils in the Netherlands during large soil survey projects. Soils were classified according to texture (according to the Netherlands Soil Survey Institute system), and type of horizon, (topsoil - A horizon; subsoil - B and C horizons) on scales of 1:50000. This classification resulted in twenty different soil groups comprising a total of 197 individual hydraulic curves forming a unique database covering a broad spectrum of soils. Data for each soil group were calculated and presented in tabulated form as the "Staring-Series" by Wösten et al. (1986,1987). Analytical functions were fitted to the 197 curves by a non-linear least-squares optimization program (Van Genuchten, 1980) to estimate the parameters of these hydraulic functions (Wösten, 1987). Wösten and Van Genuchten (1988) described how these parameters were determined for this Dutch database.

The first version of the Staring Series appeared in 1986, but due to mathematical averaging anomalies a corrected version appeared in 1987. This 1987 version provided mainly lower hydraulic conductivities, and to a lesser extent, lower water retention values. This change of Series had a significant effect on this study as will be explained in Chapter 5.

Profile descriptions of the research sites, including the textural characteristics and the corresponding 1987 Staring Series selected for model input is given in Table 3, while the soil physical curves of these five soil types are given in Appendix 4. Profile depths were entered in the model as 2 m depths to allow water table fluctuations to take place.

Table 3. Soil profile characteristics at both research sites in 1986 and 1987.

Site	Year	Depth (cm)	Soil Texture			Org. matter	Dry bulk density (g cm^{-3})	Soil type	1987 Staring series
			Sand (2-0.05 mm)	Silt (50-2μm)	Clay (< 2μm)				
			%						
Rusthoeve	1986	0- 30	55	21	24	1.9	1.52	Sandy clay loam	B 08
		30-200	60	20	20	-	1.54	Sandy loam	O 02
Rusthoeve	1987	0- 40	-	-	-	1.9	-	Sandy clay loam	B 08
		40- 75	-	-	-	-	-	Clay loam	B 10
		75-200	-	-	-	-	-	Sandy loam	O 02
Vredepeel	1986	0- 30	85	10	5	2.9	1.58	Loamy sand	B 01
		30-200	85	10	5	-	1.62	Loamy sand	O 01
Vredepeel	1987	0- 30	-	-	-	3.7	-	Loamy sand	B 01
		30-200	-	-	-	-	-	Loamy sand	O 01

- not measured

Meteorological Conditions

Meteorological data were gathered on a daily basis and used to estimate the upper boundary conditions in the model. Reference evapotranspiration values ET_r were obtained via fax, radio or special telephone lines set up by the Royal Netherlands Meteorological Institute, (KNMI). Until 1986 these values were based on the equation of Penman (1948) while from 1987 onward these values are based on the equation of Makkink (1957). The KNMI determines daily reference evapotranspiration for five large regions of the Netherlands. Each region has its own major meteorological station (Figure 10) at which ET_r is calculated and used as an average value for the specific region. For the Rusthoeve site, the nearest meteorological station is Vlissingen (approx. 30 km away) and for Vredepeel is Beek (approx. 60 km away). In 1986, ET_r values for both research sites were mistakenly obtained from De Bilt station, however, the difference in cumulative evapotranspiration between De Bilt station and the nearest meteorological stations for the research sites was less than four percent over the 100-day scheduling period. In 1987, the ET_r values were obtained from the appropriate stations. For each method different crop coefficients k_c were applied to potatoes as determined by Feddes (1987) for Dutch conditions (Table 4).

Table 4. Crop coefficients k_c for potatoes according Penman (1948) and Makkink (1957) (after Feddes, 1987).

	May			June			July			August			September		
10-day period	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
Penman	0.4	0.5	0.7	0.8	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.6	-	-
Makkink	0.5	0.7	0.9	1.0	1.2	1.2	1.2	1.1	1.1	1.1	1.1	1.1	0.7	-	-

Raingauges at the research stations were read at 0900 h (local time) every day: no rain intensities were measured. The precipitation patterns at both research stations including the cumulative values of potential evapotranspiration and precipitation, during both years are presented in Figure 14 (a-d).

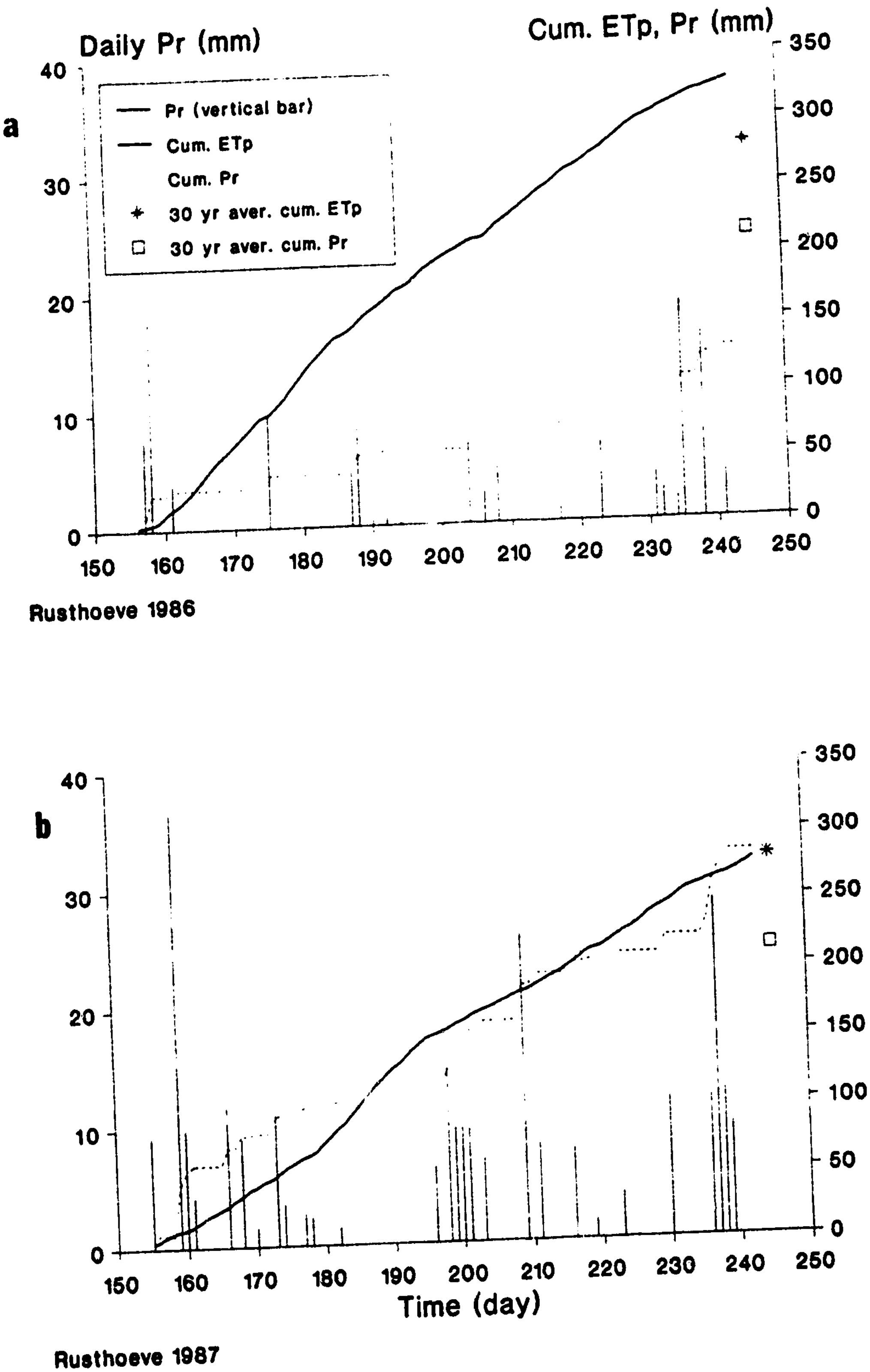

Figure 14. Weather data (ET_p and Pr) at Rusthoeve during the 1986 (a) and 1987 (b) seasons.

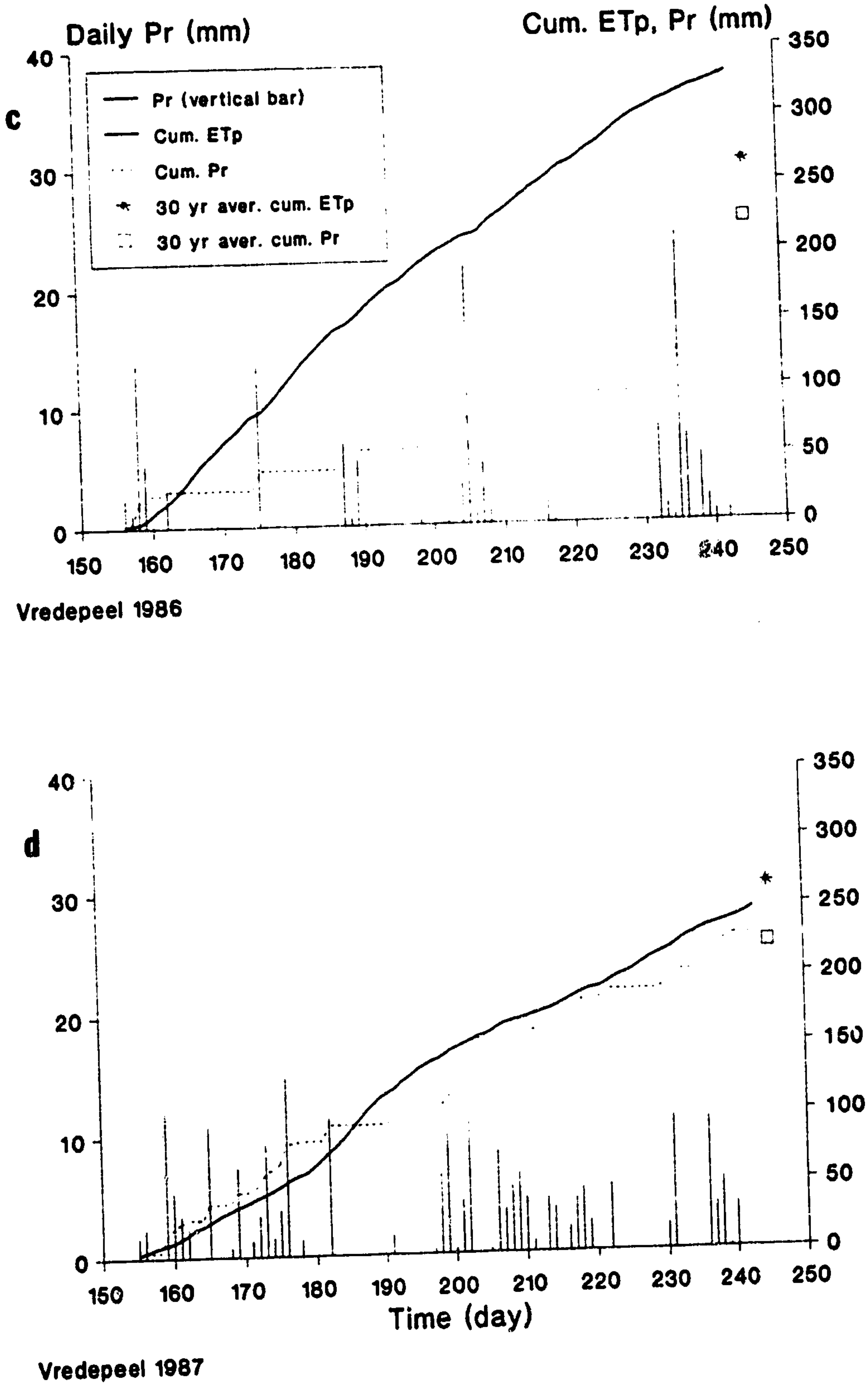

Figure 14. Weather data (ET_p and Pr) at Vredepeel during the 1986 (c) and 1987 (d) seasons.

The 1986 and 1987 growing seasons differed remarkably in weather, with the 1986 year deviating significantly from the 30-year means of ET_p and Pr. The long-term average cumulative potential evapotranspiration and precipitation for the same period as given in the figures show that 1986 was significantly drier with an ever increasing precipitation shortage for the whole scheduling period. Cumulative values for 1987 were close to the mean with the main precipitation deficit occurring in the very dry month of July.

Water Table

At the Rusthoeve site, piezometers of 5-cm diameter were installed at each treatment (Figure 12) to a depth of 2 m and regularly monitored (twice a week). Differences among the treatments were only observed in 1986 as this was a dry year, while in 1987 no differences were observed. At the Vredepeel site, the split plot experimental design did not allow for different recordings of water table depths. Therefore, one piezometer was installed approx. 20 m from the irrigation treatment providing one water-table depth for all three treatments. The water-table levels were taken as the lower boundary condition in the simulation model. Water tabel levels for Rusthoeve for the irrigation treatments is given in Chapter 5. Water table depths at Vredepeel in 1986 for all treatments was 100 cm at the start of the scheduling period and linearly increased to 170 cm at the end. During the 1987 season, water table depths were the same for all treatments; at Rusthoeve from 140 cm slowly increasing to 155 and at Vredepeel starting at 120 cm increasing to 155 cm.

Soil Cover and Rooting Depth

The necessary crop data as model input were soil cover and rooting depth, which were determined for each treatment. Soil cover was measured twice a week by the same person for the entire growing season to maintain consistency. Soil cover was estimate visually as no other tools were present at the research stations. Crop development in 1986 differed remarkably between the irrigated and non-irrigated treatments because of the dry season. On the irrigated treatments, soil cover reached a maximum of 95 % while reading just 55 - 60 % on the non-irrigated treatment. Soil cover development in 1987 at both research sites showed no difference among the irrigated treatments and non-irrigated treatment due to the wet season.

Rooting depths were obtained by carefully digging up plants and measuring the length of the roots. Another method involved pushing a hollow soil sampler into the profile to check on root parts in the soil sample. At the end of the season, pits were dug to look at the rooting patterns in each irrigation treatment. Rooting depths differed negligibly between the three irrigation treatments at each site and reached a maximum depth of 40 cm during both years at approx. 25 - 30 days after planting.

Model Comparison Data: Soil Water Content and Soil Water Pressure Head

One of the objectives of this research was to validate the model for each irrigation treatment. This was done by comparing simulated values with measured values of soil water content and soil water pressure head. These measured values were not used during the scheduling period to update the actual soil water status of the model but used after the study to validate the model simulations.

Soil Water Content

Soil water content was determined gravimetrically from a 100-cm^3 soil retrieval core which was taken to the laboratory, weighed and dried, and from which volumetric measurements were obtained. Measurements were taken at each treatment, at depths of 10, 20, 30, 40 and 60 cm below the top of the ridge. At the beginning of each growing season these measurements served as the initial conditions for the model input. During the scheduling period, these measurements, taken intermittently (3 - 5 times), served to determine the total water stored in the root zone and the actual soil water distribution in the profile to compare with simulation results. At the Rusthoeve site, these measurements were always taken in duplicate randomly in each treatment, while at Vredepeel, measurements were taken in two of the six replicates.

Soil Water Pressure Head

Because of the critical threshold levels of available water and the limited root zone of the potato crop, the available method of gravimetric sampling and the use of tensiometers is a good balance of methods to determine the actual soil water status. Soil water pressure head data were collected by using Jet-fill tensiometers which were installed at approx. a 20 - 25 cm depth, which is approx. the centre of the root zone when the potato crop is fully grown. The top of the ridge was taken as reference level. At the Rusthoeve site, eight tensiometers were installed in each irrigation treatment (Figure 12) and at Vredepeel one tensiometer was placed in each replicate, i.e. six per treatment. Tensiometer measurements were made frequently, twice or three times a week, as pressure head was the time criteria in determining when to irrigate and served to compare with the simulation results as presented in Chapter 5. At the 1986 Rusthoeve site, a few tensiometers were installed at a deeper depth of approx. 50 cm but these data were not analyzed (see Mol, 1988).

4.6 Irrigation Decision

General

As potatoes need a water supply and irrigation system capable of providing the needed irrigation on schedule, the three system components: flow rate, frequency and duration were never limited during both growing seasons, i.e. a 'demand system' was available at both research sites. The time and depth criteria on which the decisions of irrigation were based are described below.

Farmer

The time criterion used by the research station manager to start an irrigation was based primarily on his experience (using visual observation of the crop and checking the soil water status by digging into the soil) and by keeping track of ET_r and rainfall data. The depth criterion was taken as a fixed maximum amount of approx. 20 mm per application. As the manager was responsible for the whole irrigation scheme, his awareness of the aims of this study and the possible desire to 'compete' with a simulation model, may have played an important role in his decision criteria.

Model

In the model, the time criterion selected, was a critical soil water pressure head value, at a specified depth in the root zone, below which transpiration reduction takes place. Irrigation is applied when the actual soil water pressure head at this depth dropped below the critical value. Wright and Stark (1990) cited several authors who established the critical soil water pressure head value at a certain depth while still permitting maximum potato yield. Fulton (1970) found a minimum soil water pressure head value of -50 kPa (approx. -500 cm) at a depth of 15 cm and Van Loon (1981) concluded from a literature review that the minimum soil water pressure head value before transpiration reduction takes place ranged between -20 kPa (approx. -200 cm) and -60 kPa (approx. -600 cm) depending on the atmospheric demand. De Graaf (1982) found similar values as cited by Van Loon, at approx. 20 cm depth, during irrigation experiments done in the Netherlands. The critical value for this research was taken as the average of the latter two values, i.e. -400 cm as critical value in the root zone at 20 cm depth being the centre of the root zone when the potato crop is fully grown. This critical h_3 value was given previously in the sink-term function (Figure 9). Overlaying Figure 9 on top of the soil moisture retention curves belonging to the top soil for Rusthoeve (Staring Series: B8) and Vredepeel (Staring Series: B1), gives the ranges of soil water availability at each site.

Obvious differences exist between the selected sandy clay loam (Rusthoeve) and the loamy sand (Vredepeel) with regards to the total available water (TAW, cross hatched area) to the plants (Figure 15a-b).

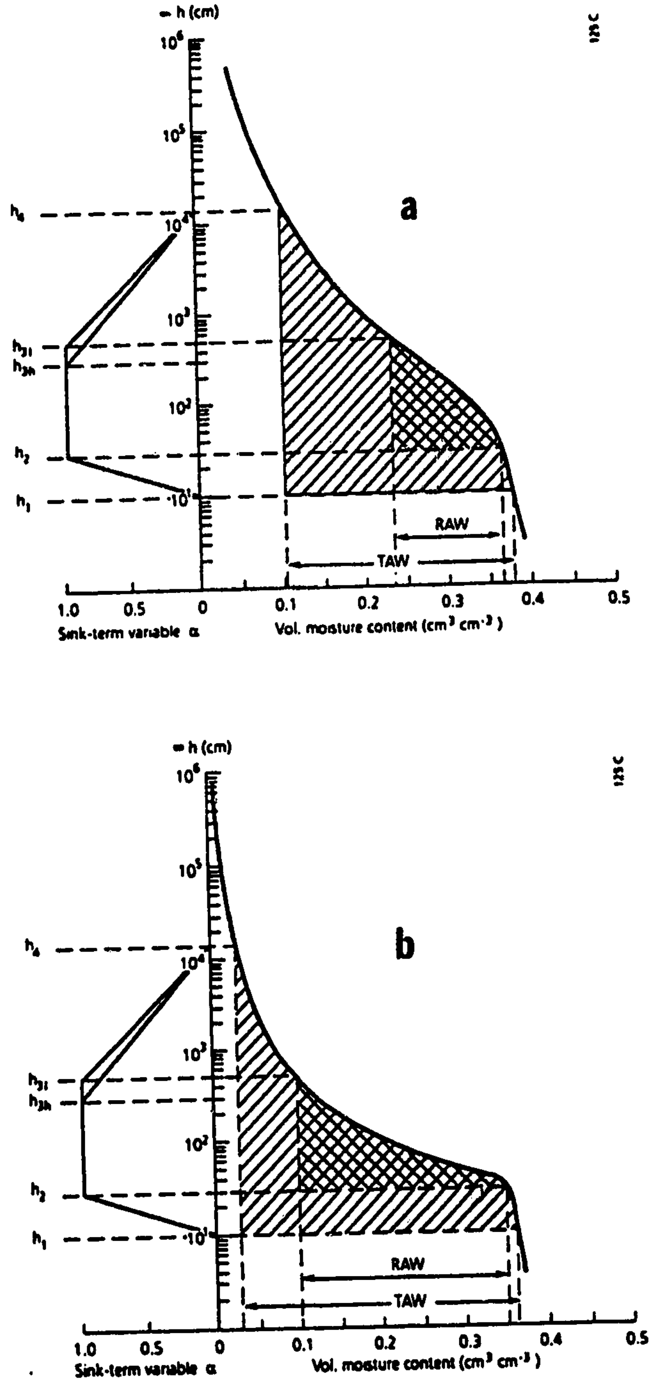

Figure 15. Soil water content θ and the sink term variable α as a function of the soil water pressure head h for the top soils at (a) Rusthoeve and (b) Vredepeel. TAW is total available water and RAW is readily available water.

Of importance is the optimal root water extraction, readily available water (RAW, meshed area), which takes place between h_2 and h_3 (critical value). The two h_3 values indicate critical values at a high evaporative demand h_{3h} (T_p =5 mm d^{-1}) and a low evaporative demand h_{3l} (T_p =1 mm d^{-1}) with the avarage critical pressure head selected as -400 cm. For T_p values ranging between the two h_3 limits, interpolated h_3 values are used. The pressure head values used during this study in the root extraction function and as indicated on the Figure above were: h_1 =-10 cm; h_2 =-30 cm; h_{3h} =-300 cm; h_{3l} =-500 cm; and h_4 =-16000 cm.

The depth criterion used in the model is similar to that of the farmer described above. Once the simulated pressure head drops below the critical threshold value, the model 'applies' a preset fixed irrigation of 20 mm (treated as precipitation for interception calculations).

4.7 Scheduling using the model SWATRE

For both years, simulations with the model SWATRE were initiated in the second or third week of May using the measured volumetric water content as the initial conditions. To check the model for possible start-up errors, a five- to ten-day period was simulated with actual data of rainfall, ET_r, water-table measurements and crop characteristics as described above. After this start-up period, the actual scheduling period lasted approx. 100 days, from the end of May (day 150) till the first week in September (day 250). The scheduling period consisted of repetitive cycles, with each cycle divided into a forecast period and an update period. The forecast period was that time for which the predictions of irrigation times were made with forecasted data and the update period was that time during which real time-data were acquired and the soil water status updated.

Forecast Period

For the five-day forecast period, soil water status was predicted using forecasted climatic data while assumptions were made on changes in water-table depths and crop characteristics. Model input data requirements for the five-day forecast were:

- Precipitation and reference evapotranspiration

  Predicted values for future rainfall and ET_r were obtained from the major meteorological stations. Both values were predicted for the day of inquiry and the day after. Rainfall was given in amounts for the two days and in probabilities for the next three days thereafter. Although, the predicted amounts may be highly variable depending on location, these values were still used. For the remainder of the forecast period, predicted probabilities were not used, but rather the 'worst case' (no rainfall) scenario was entered. The two day forecasted ET_r values were averaged and used for the remaining days of the forecast period.

- Water table

  Water-table depths changes made for the forecast period consisted of a drop of approx. 1 cm per day and depended on the climatic forecast.

- Soil cover and rooting depth

  Soil cover values were slowly increased till the maximum soil cover was measured. Rooting depths was increased by approx. 15 mm per day, starting the day after planting, till the maximum depth of 40 cm was reached.

If during the forecast period rainfall occurred, the research station manager informed the Research Institute and the forecast period was ended and the update period started.

Update Period

During the one-day update period, starting the day after the forecast period, real-time climatic data (including any amount of irrigation water applied), meas water-table depth and crop characteristics of the previous five days were ob from the research station manager and entered in the model replacing the fore data. A simulation run was made to update the actual soil water status and a data set was obtained for the next forecast period. On this one day update per the new data set was entered and a simulation run for the forecast period was made. If during this simulation run the simulated pressure head at a depth of 20 cm

dropped below the critical soil water pressure head value of -400 cm, the respective research station manager was informed of the day on which an irrigation application was required on the model field. The predetermined amount of water to be applied per irrigation was fixed at 20 mm taking into account the amount of water each irrigation system could possibly regulate and to minimize runoff. If an irrigation was predicted, a 20-mm application would be 'applied' to the simulated soil profile and the simulation run continued till the end of the forecast period.
These cycles were repeated till the end of the growing season when the potatoes were defoliated.

During the 100-day scheduling period, the tensiometers were also used as safety check for the model. If more than 50 percent of the Jet-fill-tensiometer on the model treatment dropped below -600 cm, an irrigation application of 20 mm would be applied regardless of the model prediction/simulation. However, this measure was not required during the research period.

In 1986, all model calculations took place at the Research Institute in Wageningen, while during the second year, calculations were made on a PC at the research sites for the research station managers to get hands on experience.

5.0 RESULTS AND DISCUSSION

5.1 General

This chapter describes the results obtained from the field experiments, the amount and times of irrigations applied at each treatment, the verification of simulated results, the simulated water balance and scheduling and crop yield. Two years of research at two research sites with three treatments each, provides a vast amount of data to be processed. For the sake of clarity and to prevent repetition of data presentation, some results as model verification and simulated water balance are presented for one research site only, i.e. Rusthoeve 1986. This combination of site and year is chosen because 1986 was a dry year where much irrigation was required, where a difference in irrigation scheduling between the farmer and the model existed and for which site most research data are available. Model verification for the other sites and years: Vredepeel 1986; Rusthoeve 1987; and Vredepeel 1987 are given in the respective Appendices. In the following sections, the non-irrigated, model-irrigated and farmer-irrigated treatments are respectively denoted as: N, M, F - treatments.

5.2 Irrigation Schedules

During the 100-day scheduling period in 1986, the precipitation deficit grew to approx. 200 mm at the Rusthoeve site and 175 mm at the Vredepeel site. The limited rainfall during the scheduling period required irrigation to provide the crop with the much needed water for optimal growth. The irrigation schedules as predicted by the model and as performed by the farmer at the 1986 Rusthoeve site are given as mean values in Figure 16. Both irrigation treatments were not to have more than 20 mm of water applied at once, but the single spray rain gun used (subject to poor distribution patterns and wind drift) applied irregular amounts. During each irrigation application at the M and F treatment, raingauges were placed to determine the average amount applied while the standard deviations measured per application ranged from 2.3 - 5.4 mm depending on windspeed.

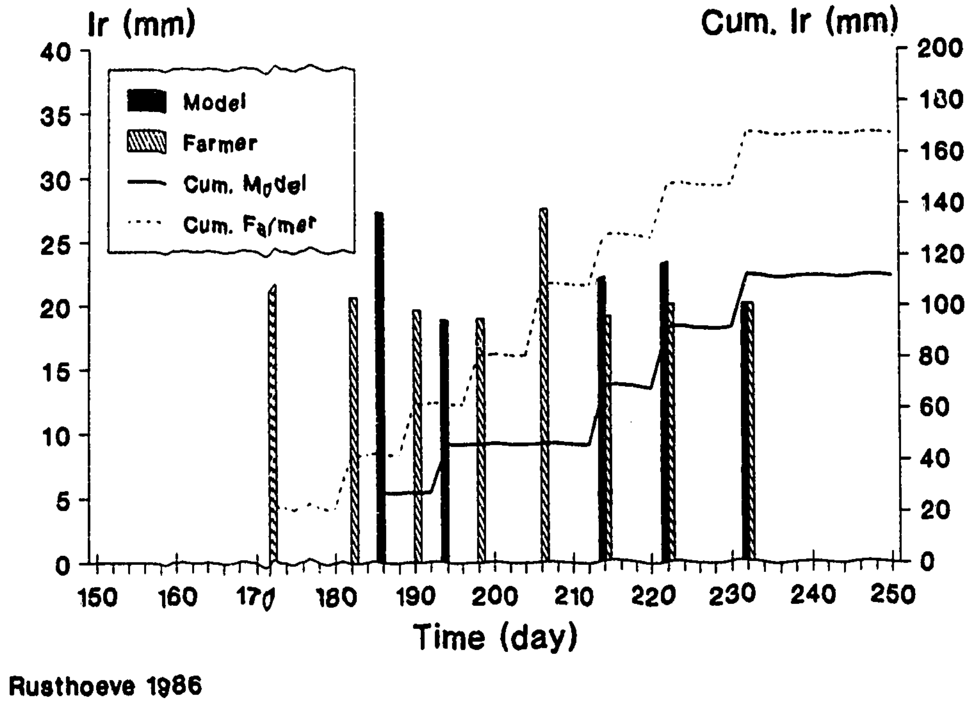

Figure 16. The irrigation schedule applied by the model and the farmer at the Rusthoeve site in 1986.

The farmer's irrigation schedule was regular pattern while the model's was not. The farmer started irrigating approx. 2 weeks sooner, than that the model simulated the first prediction, and applied 42 mm before the M treatment had its first application predicted. However, during 1986 the first version of the Staring Series, which provided relatively high hydraulic conductivity values was used. This meant that the simulated capillary rise provided enough moisture to keep the soil water pressure head well above the critical -400 cm at the specified depth of 20 cm, i.e. no irrigation scheduled. However, model re-runs made, using the corrected 1987 Staring Series with $h_3 \approx -400$ cm and a fixed depth of 20 mm per application, provided a revised schedule (Figure 17).

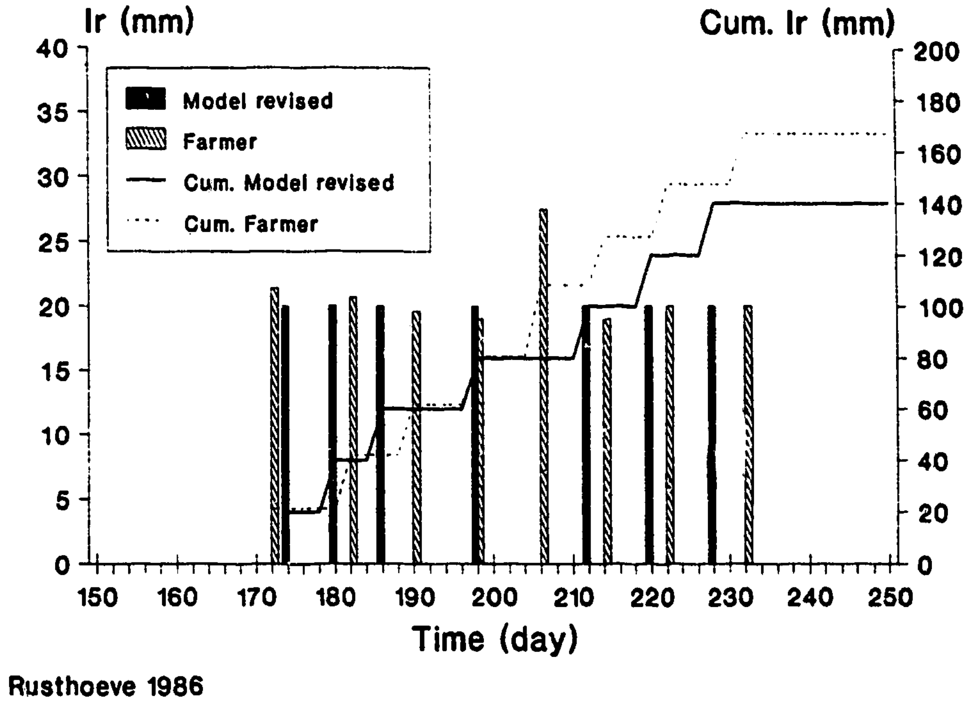

Figure 17. The revised model irrigation schedule at the Rusthoeve site by using the 1987 Staring Series.

The revised schedule starts much sooner and applies more water (140 mm) at regular intervals than the actual schedule (111 mm) did is more similar to that of the farmer.

The irrigation schedules for the Vredepeel M and F treatment in 1986 are rather unexpected as they differ only at the first irrigation while each successive irrigation takes place on the same days (Figure 18). The research station manager may have been influenced by the model predictions. Regulating irrigation water supply with the booms is relatively easy as indicated by the nearly always 20 mm gifts applied. Model re-runs with the corrected 1987 Staring Series, to obtain a revised schedule, provided minor changes to the actual model schedule as soil hydraulic properties for the sandy soils differed little between the first and the corrected Series. The revised model schedule showed an occasional shift of irrigation by 1 or 2 days during the scheduling period, but without a change in the total amount applied. Unexpectedly, the schedules, apart from the first irrigation, are identical during the remainder of the scheduling period.

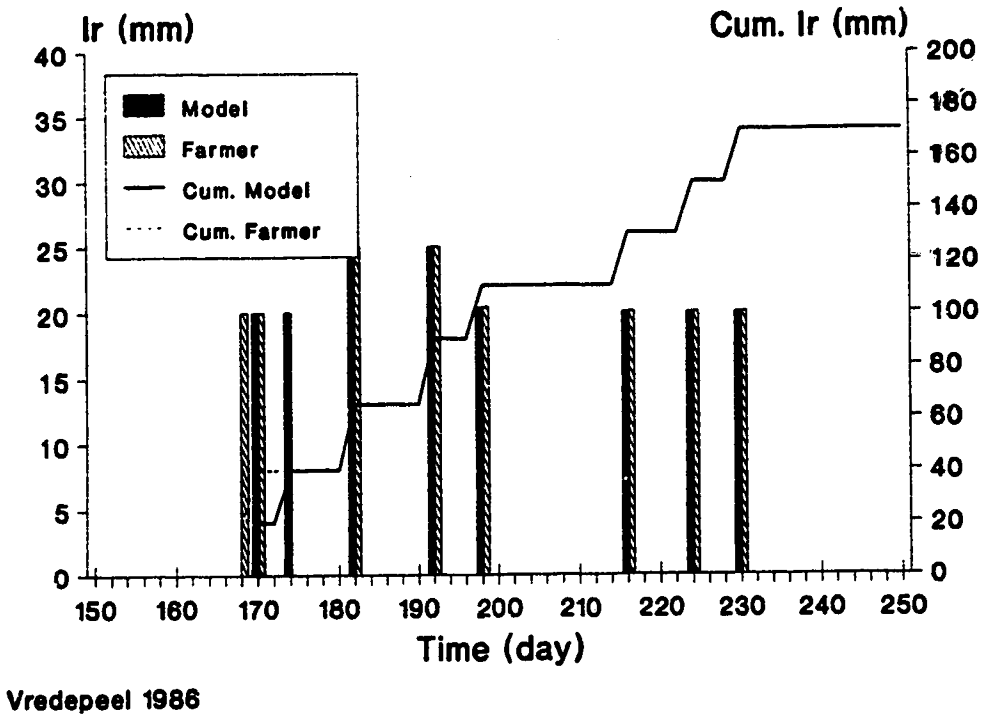

Figure 18. The irrigation schedule applied by the model and the farmer at the Vredepeel site in 1986.

During the 1987 scheduling period when much rain fell, irrigation was only applied during the dry period of July. At Rusthoeve, the model treatment received only one irrigation of 15 mm while the farmer applied 37 mm in two applications. At Vredepeel, the model treatment received two applications totalling 38 mm whereas the farmer applied 65 mm in three applications. The irrigation schedules for both research sites are given in Appendix 5.

5.3 Model Verification

Model verification is the process of comparing the measured values of soil water pressure head and soil water content value with the respective simulated values. This comparison of the soil water status in the root zone as a result of the scheduling performed at each irrigation treatment was made at the end of the season. Although the 1986 Staring Series was used in 1986 to predict the model irrigations, the model was verified with the corrected 1987 Staring Series for the best possible comparison.

Model verification discussed here refers largely to the three irrigation treatments at the Rusthoeve site for 1986. The simulated and measured (a) pressure head values (at 20 cm depth) and the (b) total water stored in the 40 cm root zone including precipitation and irrigation data are given in Figures 19, 20 and 21 for the N, M and F treatments respectively. All other figures concerning model verification at the other sites and years are found in the Appendices 6, 7 and 8 for Vredepeel 1986, Rusthoeve 1987, and Vredepeel 1987 respectively.

N treatment

For the Rusthoeve N treatment, the simulated pressure head and total water stored in the 40 cm root zone corresponded very well with the measured data (Figure 19a - b). This implies that the soil hydraulic properties selected from the database with scale of 1:50000 represent the Rusthoeve soil type. Similar good model comparisons with measured data were observed at the N treatment for the Vredepeel site in 1986 where drying of the soil profile took place due to little rainfall (Appendix 6a). Good comparisons between the simulated results and the observed data were again observed at the N treatments in 1987 but then with alternate drying and wetting of the soil profile due to regular rainfall (Appendices 7a and 8a). Tensiometer readings beyond the working range of -800 cm are left out in all figures.

Beside comparing total water stored in the root zone, the soil water root zone distribution (root extraction at several depths) was also examined. For the Rusthoeve N treatment in 1986, the daily simulated and measured soil water profile distribution patterns are given in Appendix 9a. Each soil water profile (1 - 5) corresponds to the same day in Figure 19b on which the total water stored in the root zone was measured. The profiles presented in Appendix 9a indicate that simulated root extraction at the top half of the root zone stays a bit behind the measured values. The simulated overestimation for the lower half of the root zone cancels out the difference. These differences are mainly due to root zone schematization and the use of a simplified root extraction pattern. The simulated water distribution changes abruptly at the soil layer interface which is mainly due to the schematization of the soil system. A pressure head distribution would show a smoother curve as Richard's equation is solved for h. But different soil water characteristics curves for each layer provide different soil water values at equal pressure head.

M and F treatments

The simulated values of soil water pressure head and total water stored in the root zone values at the Rusthoeve M and F treatments in 1986 compare favorably with the measured data only up to the point where the first irrigations were applied (Figures 20 and 21). After the scheduled irrigations (vertical bars topped with an x), the simulated values of both pressure head and total water stored started to deviate from the measured, i.e. the simulated values were higher. A similar pattern was also found at the other sites and years (Appendices 6, 7 and 8). The main cause for these deviations may be due to irrigation water not infiltrating into the ridged soil evenly. This may have been caused by high application rates exceeding infiltration rates of the ridges causing runoff and collection of water in the troughs between the ridges. This unequal water distribution where the soil underneath the ridges remains drier, is often a problem when growing potatoes under irrigated conditions as reported by Hogenboom and Stienen (1987). This situation also occurred at the research sites, as confirmed by the research station managers. The tensiometers, placed within the centre of the ridge, registered drier conditions than the area in between the ridges after each irrigation. Consequently simulated values of pressure head and total water stored in the root zone were always higher after irrigation applications (Figures 20 and 21, Appendix 6b, 6c, 7b, 7c, 8b and 8c). This was again confirmed by the soil water profile distribution calculations for the Rusthoeve M and F treatments where simulated values are higher than measured values after irrigation had started (Appendices 9b and 9c).

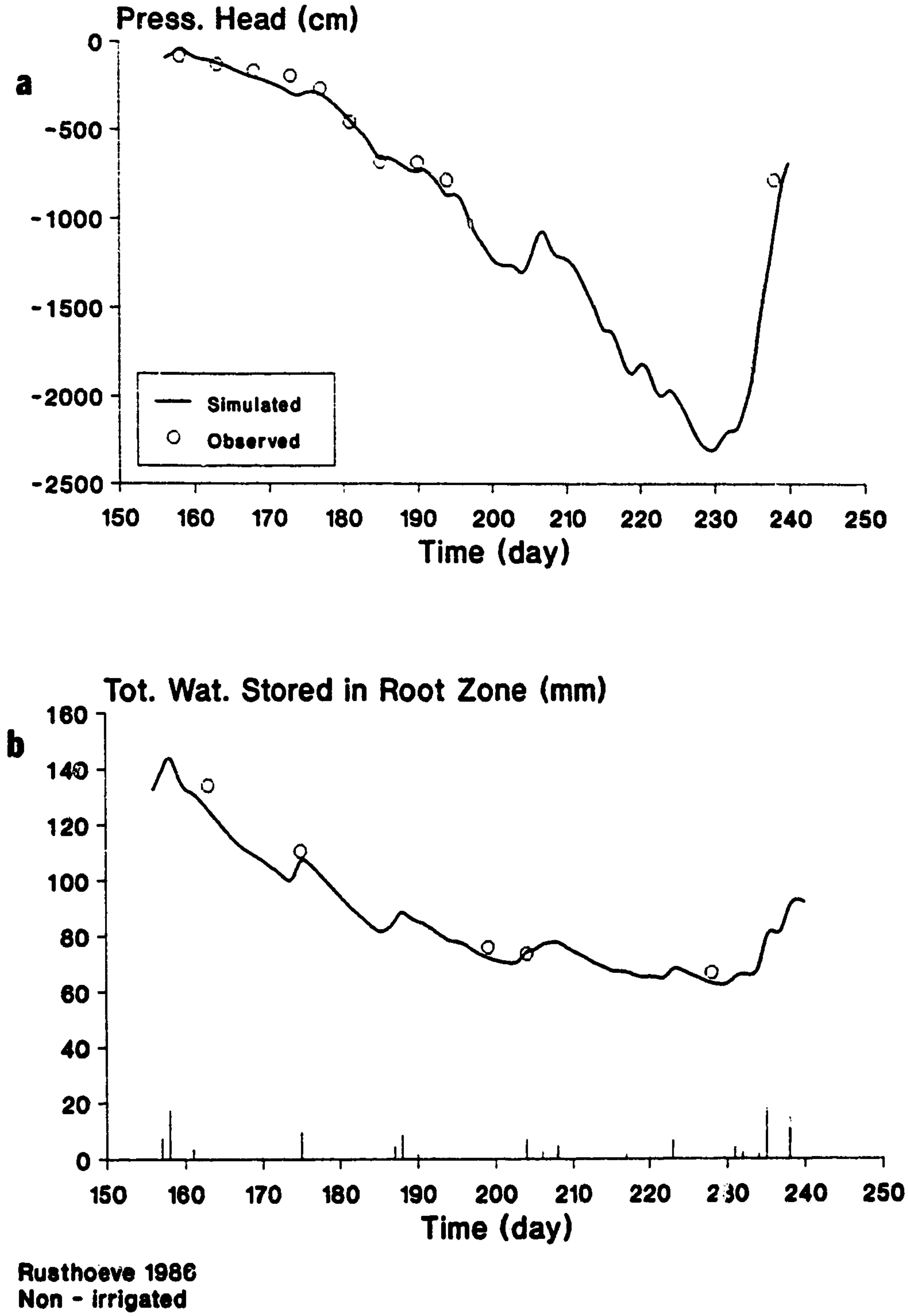

Figure 19. Simulated and measured values of (a) pressure head at 20 cm depth and (b) total water stored in the 40 cm root zone at the Rusthoeve N treatment in 1986. Precipitation is denoted as vertical bars.

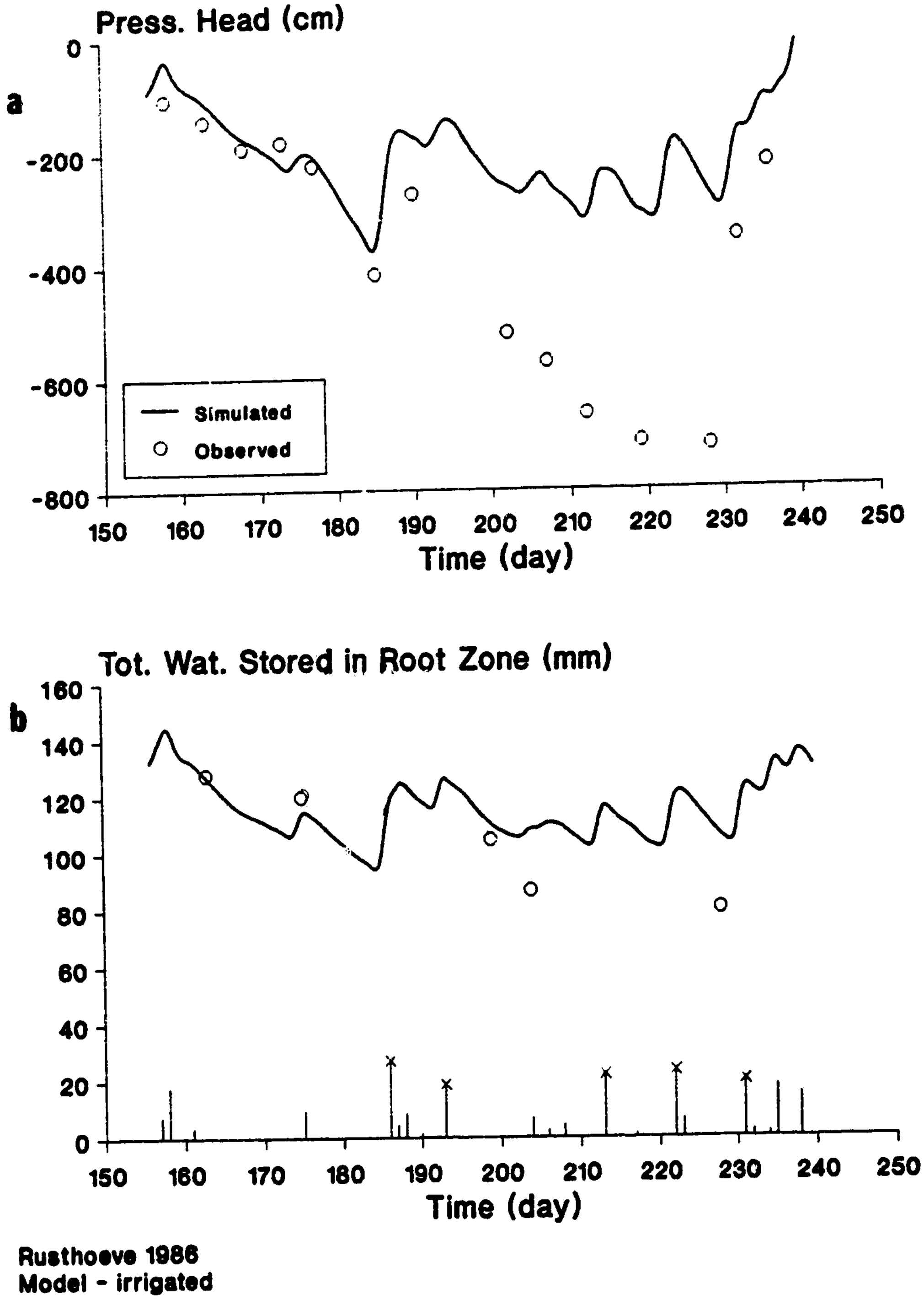

Figure 20. Simulated and measured values of (a) pressure head at 20 cm depth and (b) water storage in the 40 cm root zone at the Rusthoeve M treatment in 1986. Precipitation is denoted as vertical bars while irrigation as vertical bars with an x.

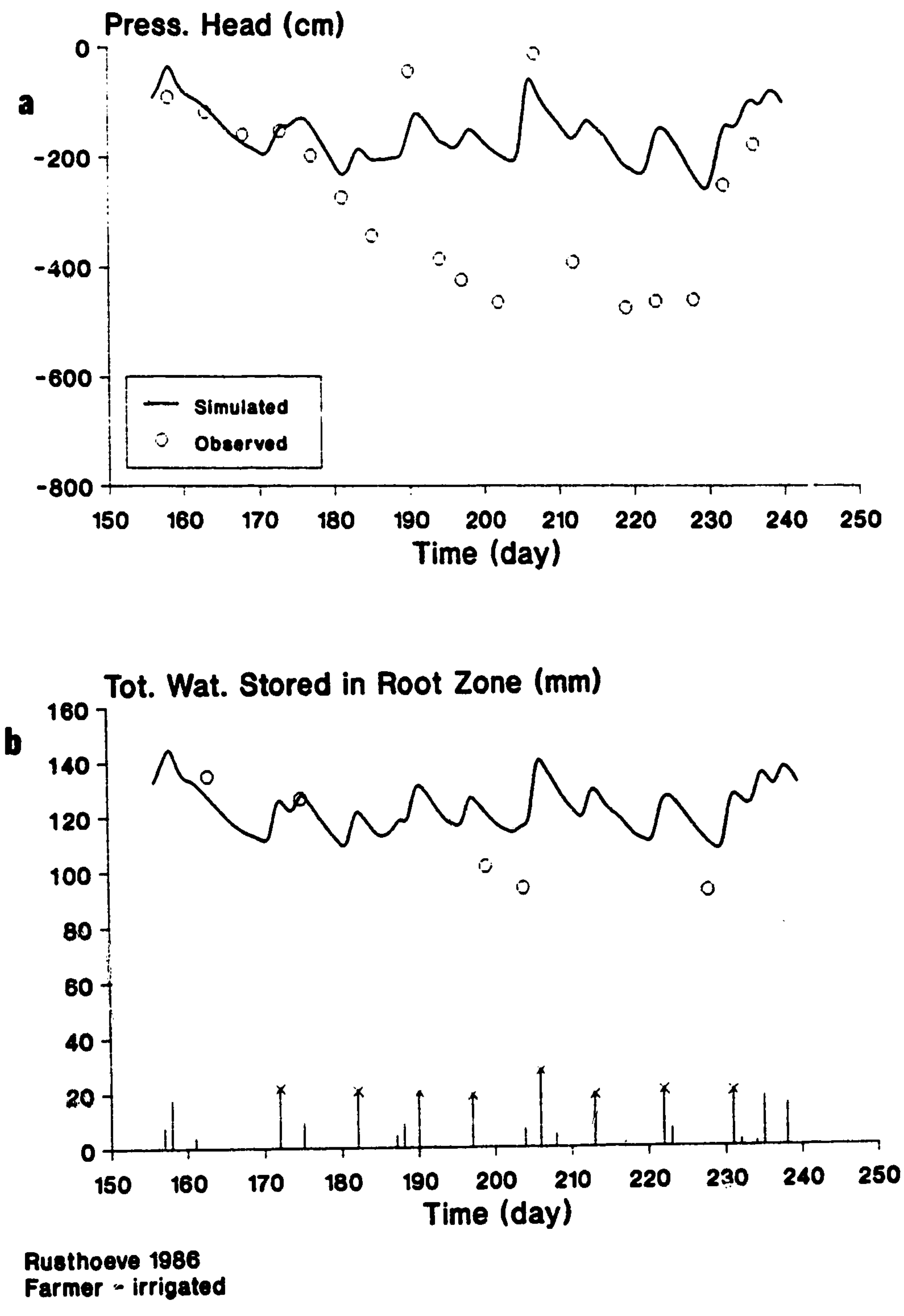

Figure 21. Simulated and measured values of (a) pressure head at 20 cm depth and (b) water storage in the 40 cm root zone at the Rusthoeve F treatment in 1986. Precipitation is denoted as vertical bars while irrigation as vertical bars with an x.

5.4 Simulated Water Balance

The water balance calculations for the Rusthoeve site in 1986 as presented here, is a seasonal integration of what is shown in the section above on root water storage. The simulated water balance terms quantify the process of water flow in the profile and show for example how much deep percolation took place, in particular at the M and F treatments, and the contribution of capillary rise to water storage in the root zone. The simulated water balance terms for the whole soil profile (2-m depth) are presented from day 160 onward till day 240 in Figures 22, 23 and 24 for Rusthoeve N, M and F treatments in 1986 respectively. These figures were obtained with an animation program (Wesseling, 1991).

Explanation of Figures 22-24 is as follows:

All square blocks have time (days) on the X-axis and amount (mm) on Y-axis. Blocks a, b and c represent the upper boundary conditions of the soil profile, while blocks e and f represent the lower boundary conditions of the soil profile.

Block a:	cumulative precipitation(incl. irrigation) and infiltration (Pr and I).
Block b:	cumulative potential and actual transpiration (T_p and T).
Block c:	cumulative potential and actual soil evaporation (E_p and E).
Block e:	cumulative pos. qdrain (subsurface irrigation) and neg. qdrain (surface or subsurface drainage).
Block f:	cumulative pos. qbot (seepage) and neg. qbot (deep percolation) (q_{b+} $+q_{b-}$).
Block d:	change in total water stored in the 2-m profile (dW).
Block g:	time clock from day 0 - 365 (shaded area is simulated period from day 160 -240). Small rectangular block below clock shows last day of calculations: day 239.
Block h:	water table level at day 239.
Block i:	change of water table level over time in 2-m profile.

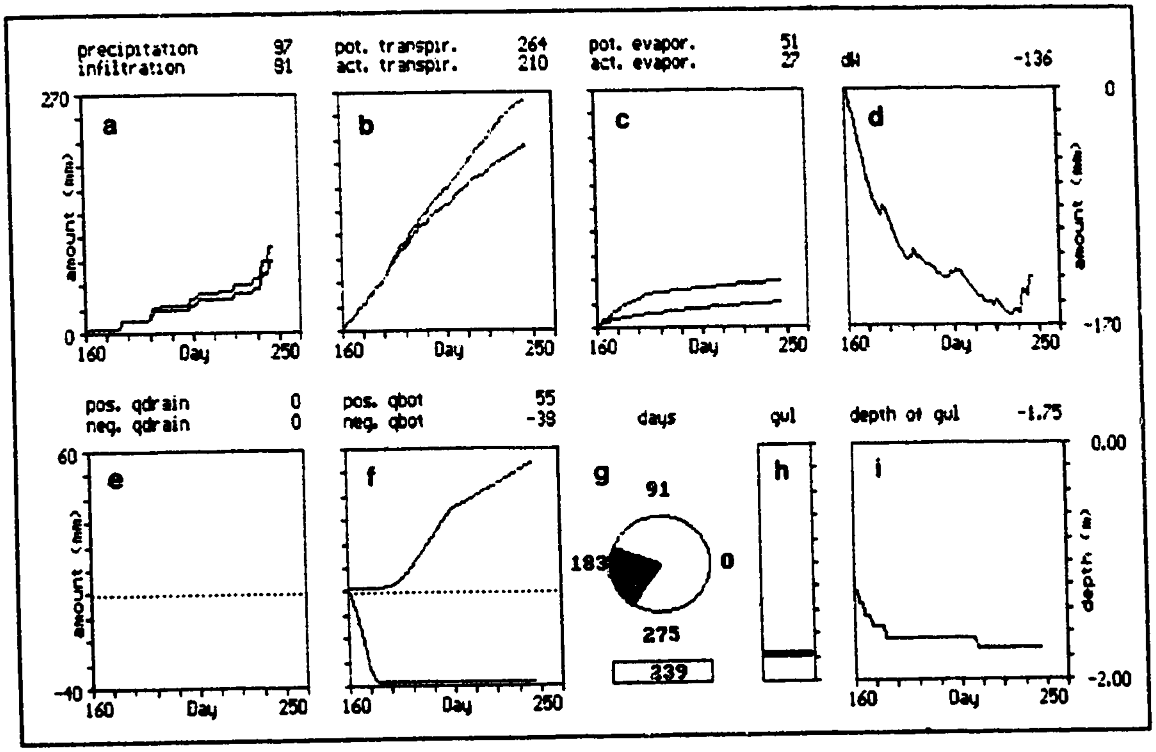

Figure 22. Simulated water balance terms for the Rusthoeve N treatment in 1986.

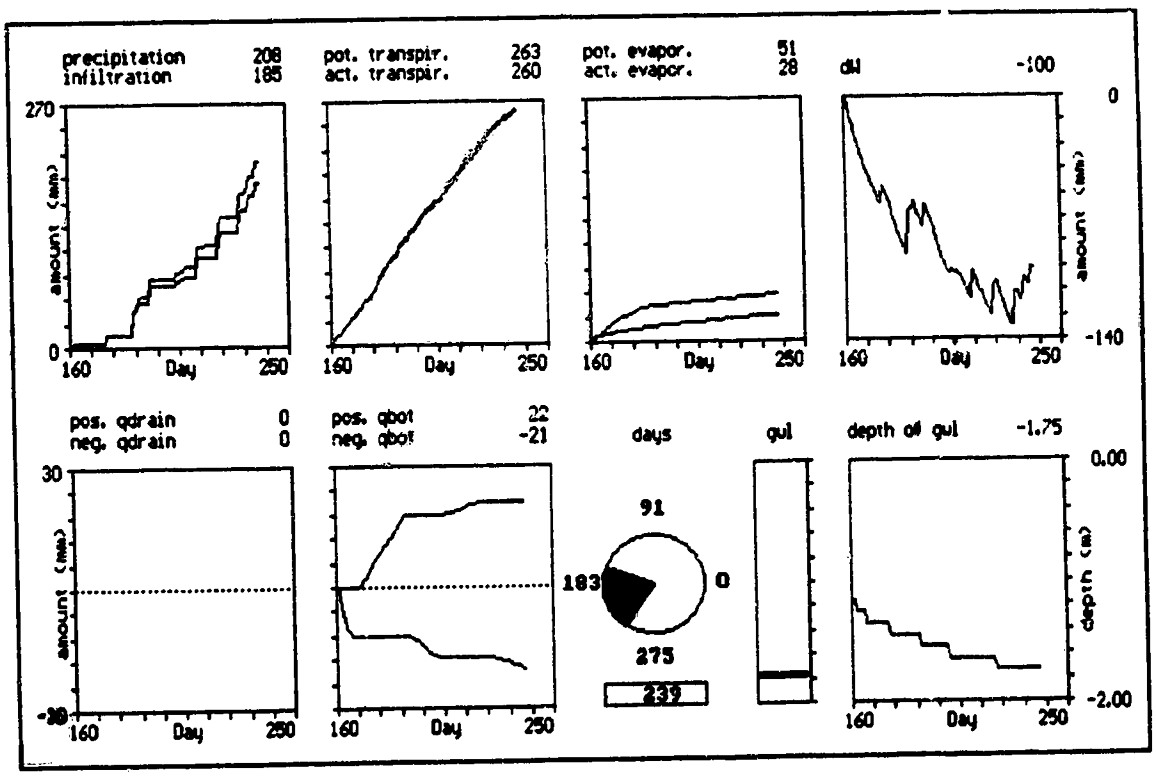

Figure 23. Simulated water balance terms for the Rusthoeve M treatment in 1986.

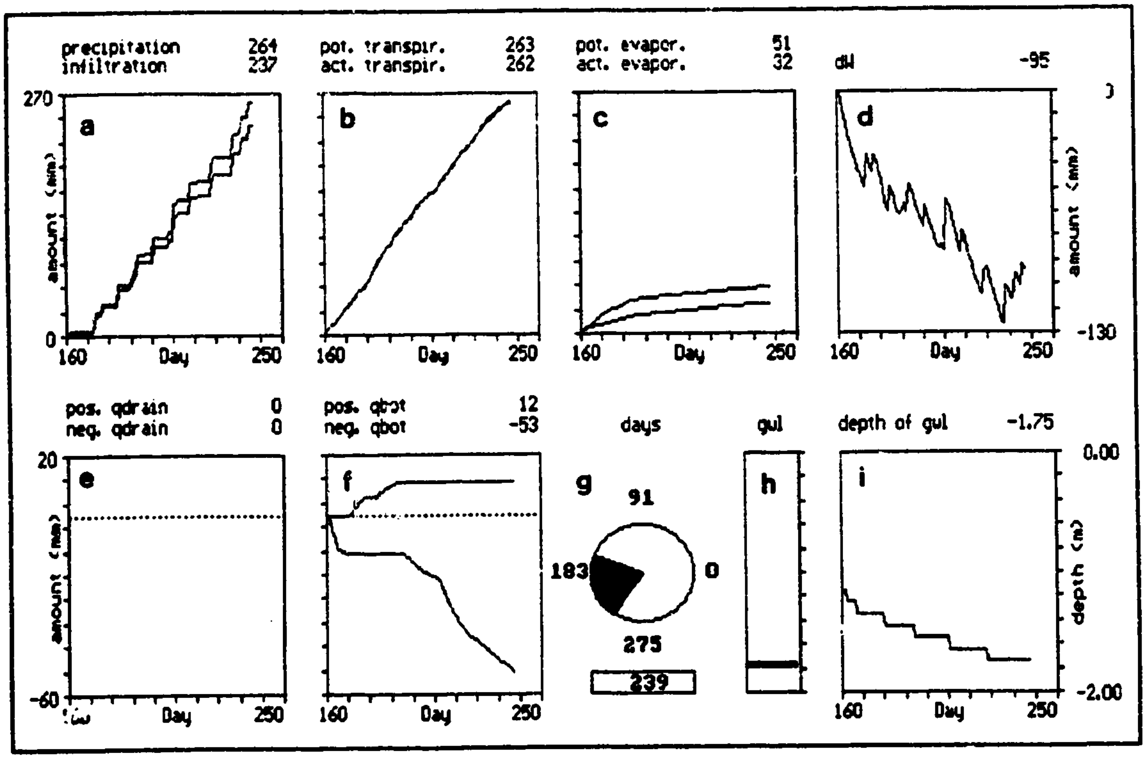

Figure 24. Simulated water balance terms for the Rusthoeve F treatment in 1986.

The cumulative water balance values given in these Figures may be substituted into the equation for the soil water balance (Equation 20, Section 2.2). The term Q_s is comprised of two terms:

$$Q_s = q_{b+} - q_{b-}$$

where: q_{b+} = upward flow through bottom of subsoil (seepage), and

q_{b-} = downward flow out of subsoil (deep percolation)

Substituting the calculated cumulative water balance values as presented in these Figures into the equation yields:

	ΔV	= I	- (T	+ E)	+ (q_{b+}	- q_{b-})
N:	-136	= 81	- (210	+ 27)	+ (55	- 38)
M:	-100	= 185	- (260	+ 28)	+ (22	- 21)
F:	-95	= 237	- (262	+ 32)	+ (12	- 53)

The change in volume in the soil profile, ΔV, is equal to the dW value given in the upper right hand block 'd' (Figures 22-24) with the negative value indicating water was lost during the scheduling season. The differences between the three treatments is expressed in the dW value, obviously due to different amounts of water received.

Other significant changes between the three water balance calculations is the amount of water flowing in and out of the bottom of the soil profile and the amount infiltrating. For the N treatment (Figure 22), deep percolation only took place at the very beginning of the scheduling period due to wet conditions. For the M and F treatments deep percolation also took place during the scheduling period, a total of 21 mm for the M and 53 mm for the F treatment (Figures 23 and 24). This quantification of the soil water balance shows that deep percolation possibly occurred for the Rusthoeve F treatment, which would at first sight indicate over-irrigation, especially during the second half of the scheduling period.

The actual transpiration values for the M and F treatments are equal to the potential values, indicating no water shortage to the plants during the scheduling period. For the N treatment however, the actual transpiration falls below the potential values as the season progresses, indicating water stress in the root zone with negative effects on yield to be expected.

A similar equation can also be set up for the 40-cm root zone to quantify what is shown in Figures 19b, 20b and 21b and to determine how much water Q_r (simulated by the model) was contributed by the subsoil to the root zone:

$$\Delta V_r = I - T + E + Q_r$$

$$N: -40 = 81 - (210 + 27) + 116$$

$$M: +3.9 = 185 - (260 + 28) + 106.9$$

$$F: +4.5 = 237 - (262 + 32) + 61.5$$

This soil water balance shows the significant contribution of the water table to the root zone, for the N treatment 116 mm and for the F treatment 61.5 mm.

5.5 Scheduling and Crop Yield

Yield response to plant water stress is more complex for potatoes than for most other crops and water stress during the different growth stages of the potato crop plays a significant role on both total yield and quality. To determine whether enough irrigation water had been applied, and to know which schedule was 'best', tuber yield data and amount of water applied and used must be analyzed.

Table 5. Irrigation scheduling results on potato tuber yield at Rusthoeve and Vredepeel in 1986.

Site	Irrigation: Treat-ment	Irrigation: No. of Applic.	Irrigation: Sched. Amount	Total Water (incl. rain) (mm)	Gross Tuber Yield ($t\ ha^{-1}$)	Mark. Tuber Yield ($t\ ha^{-1}$)	Marketable Tuber Yield/Gross Tuber Yield
Rusthoeve	N	-	-	190	40.8	33.9	0.83
	M	5	111	301	54.8	34.4	0.63
	F	8	168	358	56.1	40.2	0.72
Vredepeel	N	-	-	195	48.9	33.3	0.69
	M	8	170	365	65.2	54.9	0.84
	F	8	170	365	61.3	50.2	0.82

all recordings from day 155 (June 4) till harvest
- not applicable
N = Non-irrigated
M = Model-irrigated
F = Farmer-irrigated

The irrigation schedules performed at each treatment including precipitation and the final fresh tuber yields obtained at the Rusthoeve and Vredepeel sites during 1986 are given in Table 5. Gross tuber yield includes all tubers harvested regardless size or quality, while marketable tubers are defined in this research as those without any malformations, i.e. these tubers are desirable for consumption.

Gross yields obtained for the Rusthoeve M and F treatments differ very little but the F treatment received 57 mm more water. However, the marketable yield obtained for the F treatment is approx. 17% higher than that for the M treatment, indicating higher quality with more irrigation water applied.

Gross and marketable yields obtained for the Vredepeel M and F treatment are expected to be equal as the same amounts of water were applied. The gross tuber yields at Vredepeel are higher than at Rusthoeve. This higher yield at the Vredepeel site may be attributed to the sandy soils at the Vredepeel site on which potatoes grow very well under adequate water supply and fertilizers applied.

To determine the tuber quality obtained from the different irrigation schedules, a ratio of marketable yield to gross yield was used. Analysis of these yield ratios shows contradictory results. The ratio for the Rusthoeve N treatment was higher than those for the M and F treatments; at Vredepeel the opposite was true. These seemingly contradictory ratios may possibly be explained on the basis of water supply during critical crop growth stages as given by (Wright and Stark, 1990). A fluctuating water supply during the different growth stages of potato growth largely affect tuber growth and quality aspects. A sufficient and constant supply of water during the growing period gives high yield and good quality tubers. Water stress during tuber initiation and early development generally has the greatest effect on tuber quality. Water deficit during this growth stage interrupts the normal pattern of tuber enlargement, increasing the incidence of malformations. During the next growth stage, tuber bulking, water stress usually affects total yield more than tuber quality. Drought stress early in the season is sufficient to reduce plant size causing tuber yield reduction. Based on the above theory by Wright and Stark (1990), the yield ratios may be explained.

The high ratios for the Vredepeel M and F treatment and surprisingly in the Rusthoeve N treatment indicate a constant supply of water. The Rusthoeve N treatment had a slowly decreasing supply of water with additional capillary rise (116 mm) providing for a non-fluctuating supply of water in the root zone. This is also shown on Figure 19a where during the larger part of tuber initiation and tuber bulking, pressure head values were still within the total available water (TAW) range. The Vredepeel N treatment in 1986 had a low ratio due to a shortage of water and where capillary rise was not sufficient to provide the necessary water.

The Rusthoeve M treatment had a very low ratio which was mainly due to a water shortage during the tuber initiation stage, but after rewatering by the first irrigation, the sudden rise in water content could have disrupted the normal expansion pattern and resulted in tuber malformations and secondary growth. The revised irrigation schedule, with the corrected Staring Series, for this Rusthoeve M treatment in 1986 predicting earlier irrigations, would have provided sufficient water at the beginning of the season and a more constant water supply during the scheduling period, possibly enough to attain a higher yield ratio.

Gross tuber yields in 1987 obtained at both research sites did not differ significantly among each treatment. Marketable tuber yield data were not available and as such could not be analyzed. More detail on yields in 1987 are give by Van der Schelde (1988) and Dekkers (1988).

6.0 CONCLUSIONS AND RECOMMENDATIONS

Two years of irrigation study with each year having very different climatic conditions has provided limited opportunity to state definite conclusions on the use of the dynamic model as an irrigation scheduling tool on potatoes. This opportunity is further limited by the use of faulty soil physical data in predicting irrigation schedules during the very dry year of 1986 such that comparison with the scheduling by the farmer was difficult to make. The difference in irrigation schedules between using the faulty and corrected soil physical data shows the importance for selecting representative soil physical data in simulation studies.

Although the input data required for the SWATRE model was obtained at different scales, the simulated results have shown favorable comparison with measured data. The meteorological data (reference evapotranspiration) and soil physical data were obtained on a regional scale while other data (soil cover, rooting depth and groundwater level) were measured at each research site. The objective in irrigating potatoes, as a medium drought sensitive crop, is to maintain an optimal water supply for producing high yielding good quality tubers. Therefore, over-irrigation on potatoes often occurs, which may cause the leaching of Nitrogen fertilizers. The water balance calculations in this study have shown that under varying irrigation scheduling deep percolation did take place. Another main problem with irrigated potatoes is often the uneven infiltration of water in the ridges, which may partly be due to high application rates. These same calculations have also shown how capillary rise contributes to the water availability of the plant and consequently the overall quality of potatoes.

In this research, the decision criteria for the model to predict an irrigation is solely based on the energy status of the water in the root zone. However, tuber yield and respective quality obtained under varying irrigation schedules during two years with varying climatic conditions have shown the importance of water stress relations during different potato growth stages. Therefore, the criterion of tuber quality, not included in these model predictions, should be considered if this model is to be implemented in an irrigation farm management system.

Other important factors to consider in a farm management system are the various management aspects such as different irrigation supply systems and rotating irrigation equipment to be used on other crops.

Including this model in a farm irrigation management scheme requires the addition of a broader set of variables.

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Appendix 1. Two tables with 10-day crop-coefficient values respectively related to the open water evaporation (Penman, 1948) (Table 1) and the reference crop evapotranspiration (Makkink, 1957) (Table 2) for several arable and horticultural crops. (after Feddes, 1987).

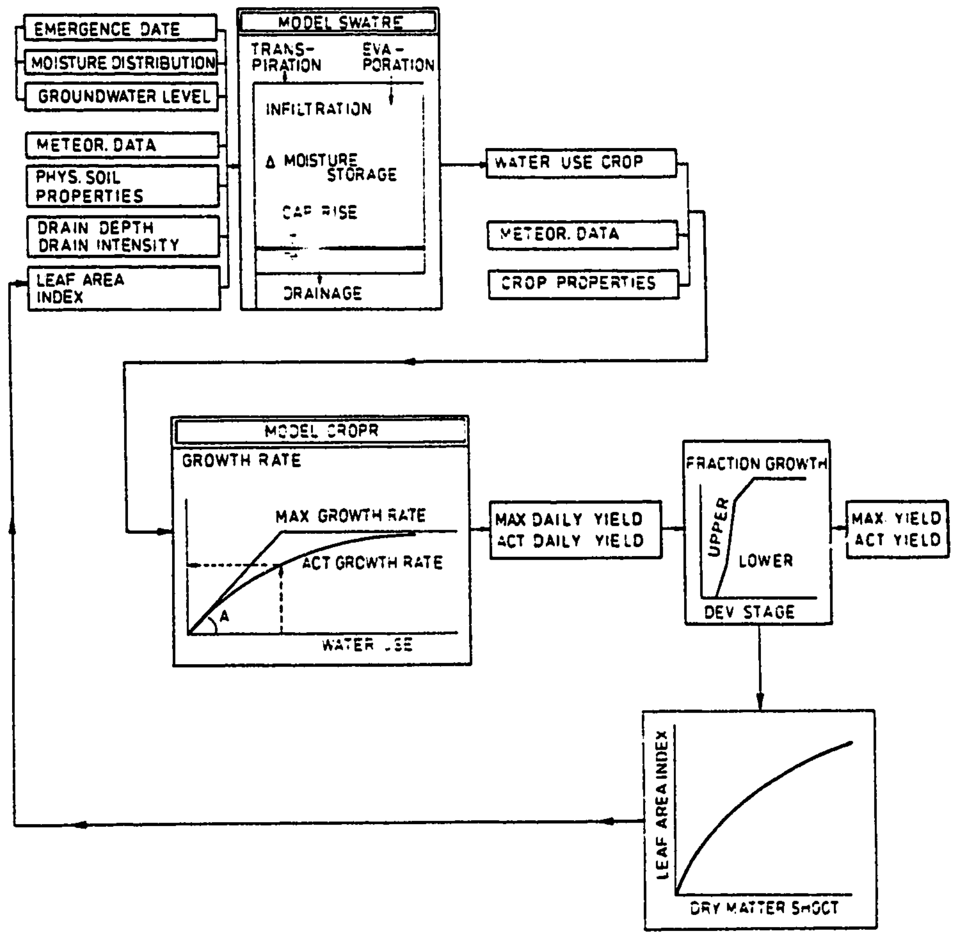
Table 1. 10-day crop coeficients k_c values related to open water evaporation Penman (after Feddes, 1987).

	April			May			June			July			August			September		
	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
Grass	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
Cereals	0.5	0.6	0.7	0.8	0.8	0.8	0.9	0.9	0.9	0.8	0.7	0.6	0.5	-	-	-	-	-
Maize	-	-	-	0.4	0.5	0.6	0.7	0.8	0.9	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Potatoes	-	-	-	0.4	0.5	0.7	0.8	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.6	-	-
Sugar Beets	-	-	-	0.4	0.4	0.4	0.6	0.8	0.8	0.9	0.9	0.9	0.9	1.0	1.0	1.0	0.9	0.9
Leguminous plants	-	0.4	0.5	0.6	0.7	0.8	0.9	0.9	0.9	0.8	0.6	-	-	-	-	-	-	-
Plant-onions	0.4	0.5	0.5	0.6	0.6	0.7	0.8	0.8	0.8	0.8	0.8	0.8	0.8	-	-	-	-	-
Sow-onions	-	0.3	0.4	0.4	0.5	0.5	0.6	0.6	0.7	0.8	0.8	0.8	0.8	0.8	0.8	0.6	-	-
Chicory	-	-	-	-	-	-	0.4	0.4	0.4	0.6	0.8	0.9	0.9	0.9	0.9	0.9	0.9	0.9
Winter carrots	-	-	-	-	-	-	0.4	0.4	0.4	0.6	0.8	0.9	0.9	0.9	0.9	0.9	0.9	0.9
Celery	-	-	-	-	-	0.4	0.5	0.5	0.5	0.6	0.6	0.7	0.8	0.9	0.9	0.9	0.9	-
Leek	-	-	-	-	0.4	0.4	0.4	0.4	0.5	0.5	0.6	0.6	0.7	0.8	0.8	0.8	0.8	0.8
Bulb/tube crops	-	-	-	-	0.4	0.5	0.5	0.7	0.9	0.9	0.9	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Pome/stone-fruit	0.8	0.8	0.8	1.1	1.1	1.1	1.2	1.2	1.2	1.3	1.3	1.3	1.1	1.1	1.0	1.0	1.0	1.0

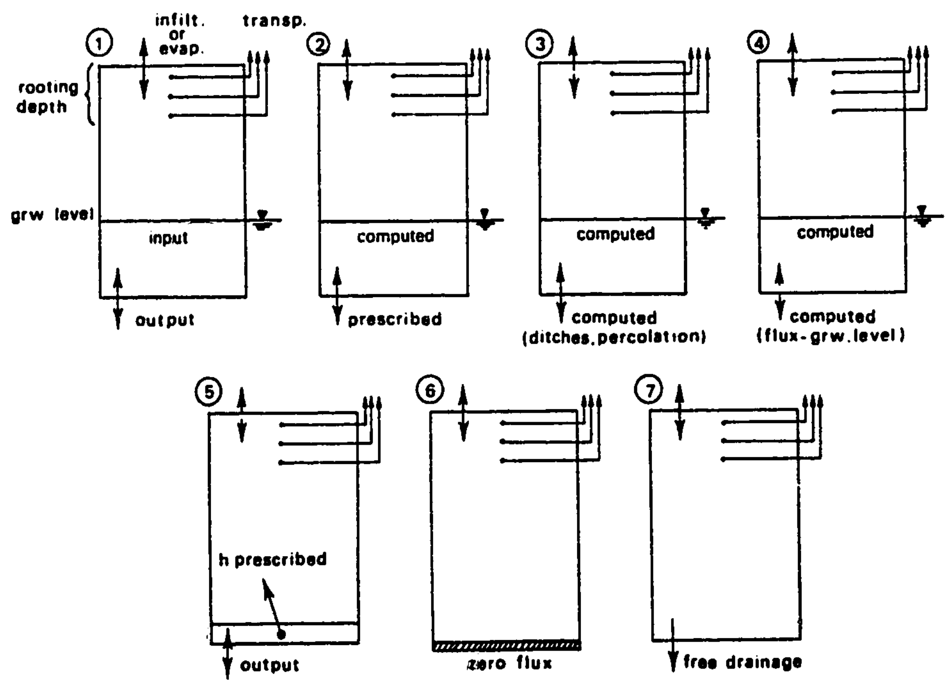
Table 2. 10-day crop coeficients k_c values related to reference crop evapotranspiration Makkink (after Feddes, 1987).

	April			May			June			July			August			September		
	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
Grass	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.9	0.9	0.9	0.9
Cereals	0.7	0.8	0.9	1.0	1.0	1.0	1.2	1.2	1.2	1.0	0.9	0.8	0.6	-	-	-	-	-
Maize	-	-	-	0.5	0.7	0.8	0.9	1.0	1.2	1.3	1.3	1.2	1.2	1.2	1.2	1.2	1.2	1.2
Potatoes	-	-	-	0.5	0.7	0.9	1.0	1.2	1.2	1.2	1.1	1.1	1.1	1.1	1.1	0.7	-	-
Sugar Beets	-	-	-	0.5	0.5	0.5	0.8	1.0	1.0	1.2	1.1	1.1	1.1	1.2	1.2	1.2	1.1	1.1
Leguminous plants	-	0.5	0.7	0.8	0.9	1.0	1.2	1.2	1.2	1.0	0.8	-	-	-	-	-	-	-
Plant-onions	0.5	0.7	0.7	0.8	0.8	0.9	1.0	1.0	1.0	1.0	1.0	1.0	1.0	-	-	-	-	-
Sow-onions	-	0.4	0.5	0.5	0.7	0.7	0.8	0.8	0.9	1.0	1.0	1.0	1.0	1.0	0.9	0.7	-	-
Chicory	-	-	-	-	-	-	0.5	0.5	0.5	0.8	1.0	1.1	1.1	1.1	1.1	1.1	1.1	1.1
Winter carrots	-	-	-	-	-	-	0.5	0.5	0.5	0.8	1.0	1.1	1.1	1.1	1.1	1.1	1.1	1.1
Celery	-	-	-	-	-	0.5	0.7	0.7	0.7	0.8	0.9	1.0	1.1	1.1	1.1	1.1	1.1	-
Leek	-	-	-	-	0.5	0.5	0.5	0.5	0.7	0.7	0.8	0.8	0.8	1.0	0.9	0.9	0.9	0.9
Bulb/tube crops	-	-	-	-	0.5	0.7	0.7	0.9	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2
Pome/stone-fruit	1.0	1.0	1.0	1.4	1.4	1.4	1.6	1.6	1.6	1.7	1.7	1.7	1.3	1.3	1.2	1.2	1.2	1.2

Appendix 2. Flowchart of the SWATRE model consisting of the water balance model and the crop growth model CROPR.

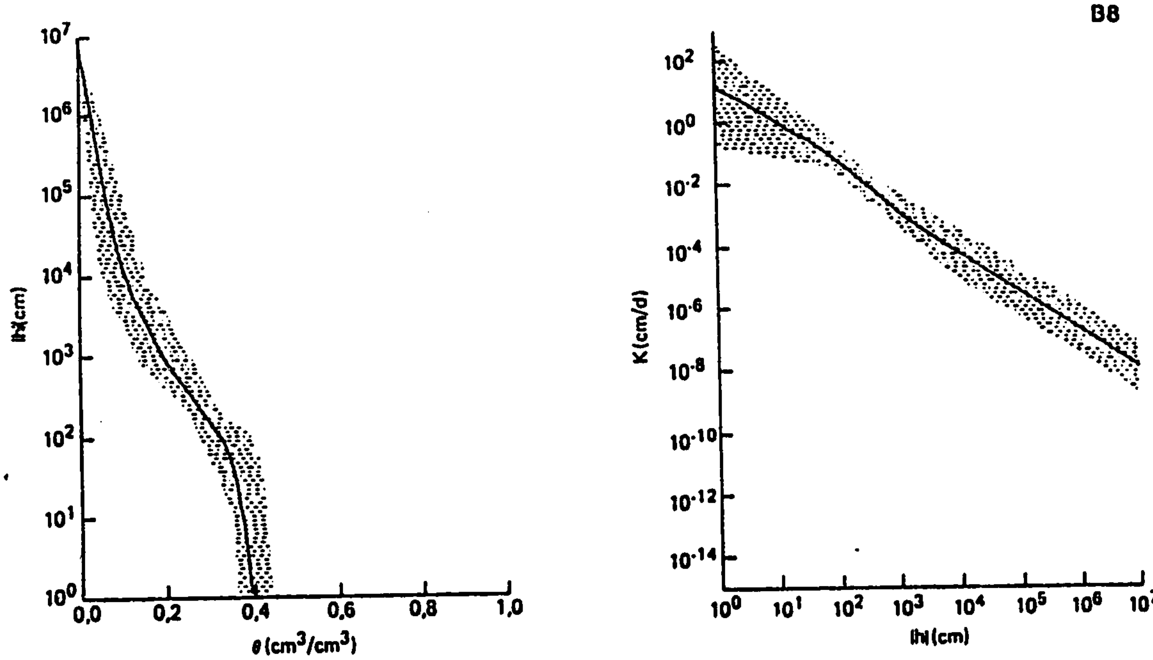


Appendix 3. Schematic representation of the bottom boundary conditions in the model SWATRE when the soil system is partly saturated (1 - 4) or remains unsaturated (5 - 7).

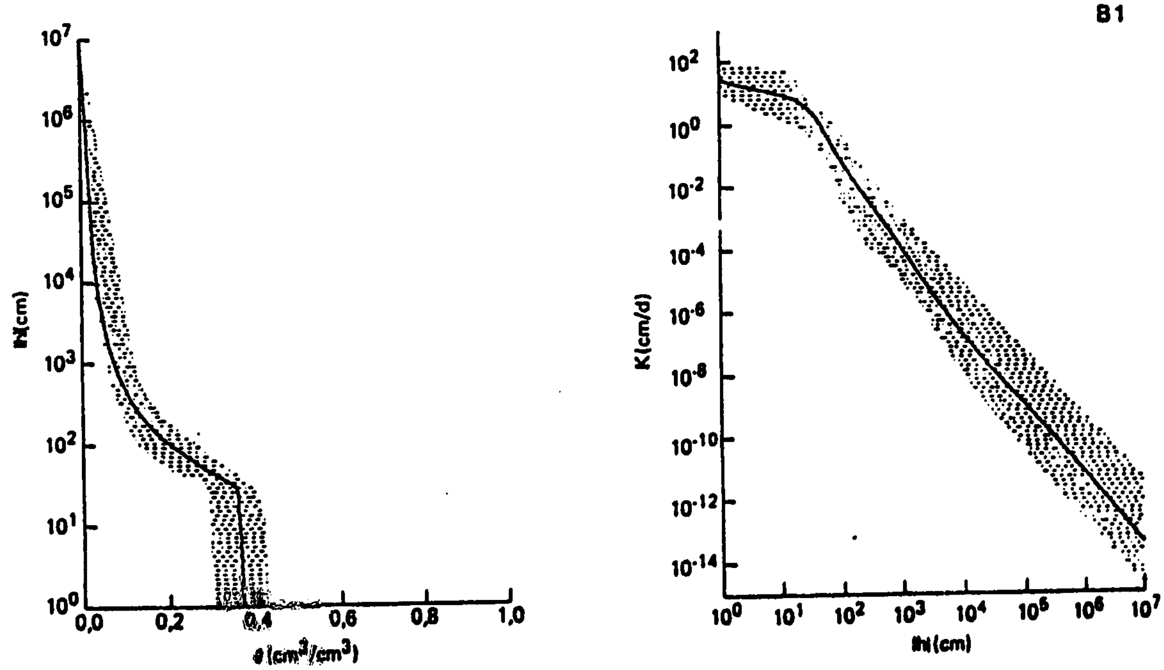


Appendix 4. Soil moisture retention and hydraulic conductivity curves for the five representative 1987 Staring Series selected. The solid line in the h(θ) and K(h) curves represents the average values and the shaded area the range between the minimum and maximum value. (after Wosten, 1987).

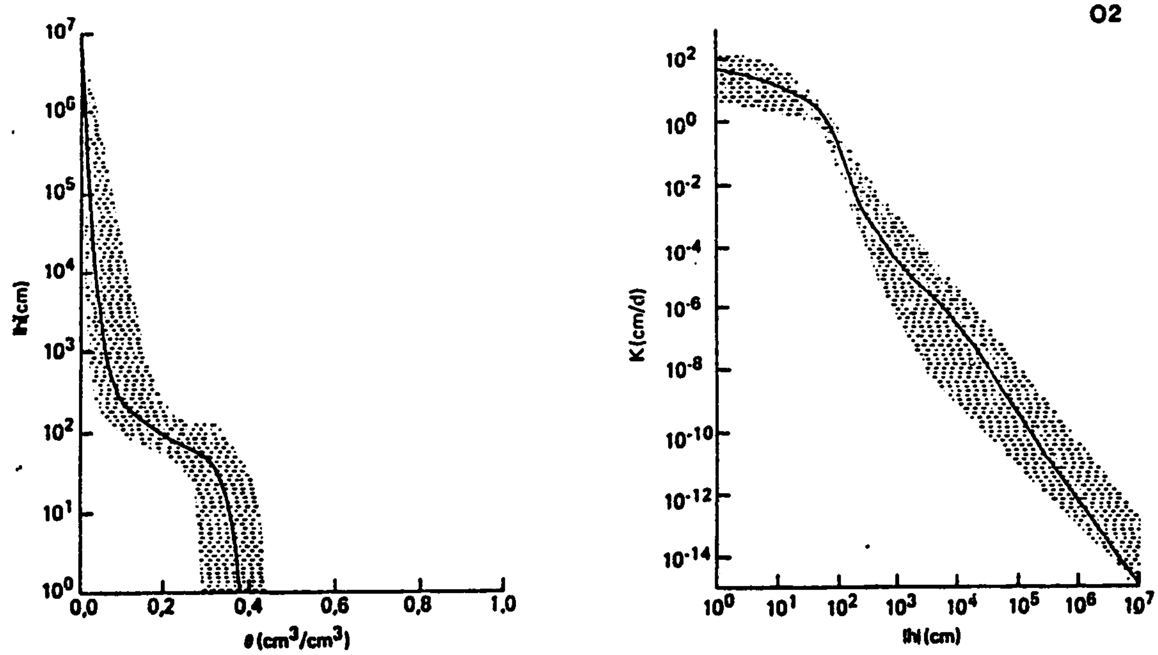
B8



B1

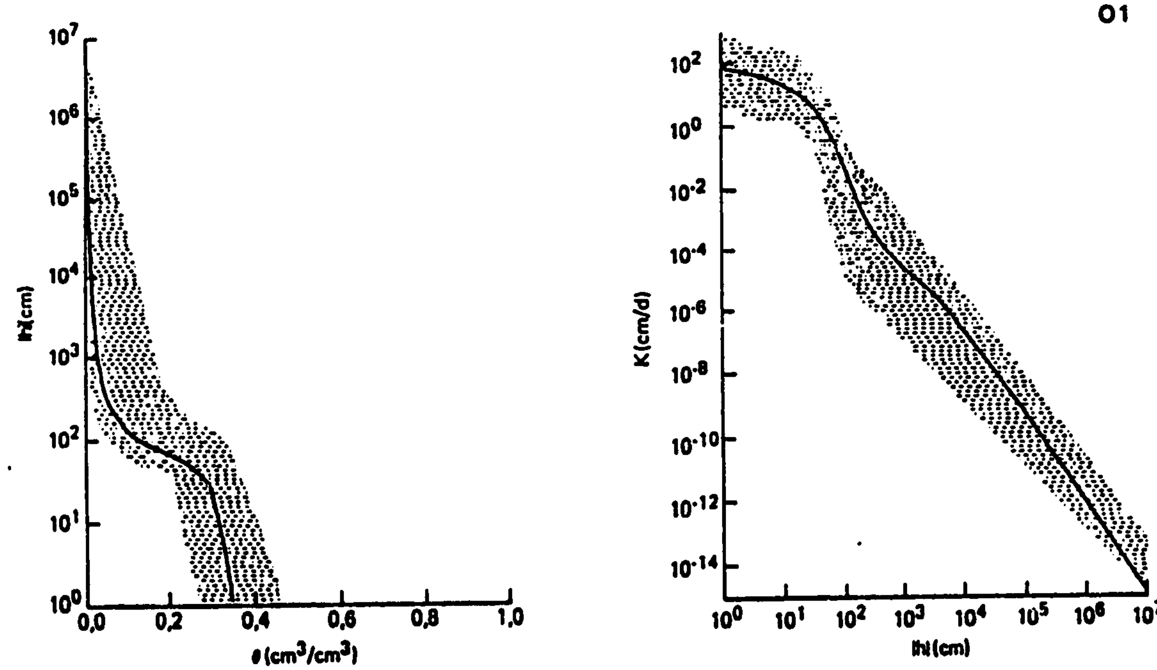


O2



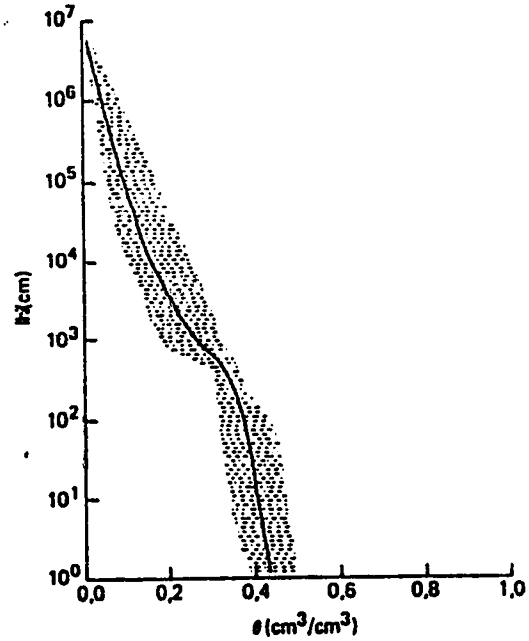
|h|(cm)
θ (cm³/cm³)
0,0 0,2 0,4 0,6 0,8 1,0
K (cm/d)
|h| (cm)

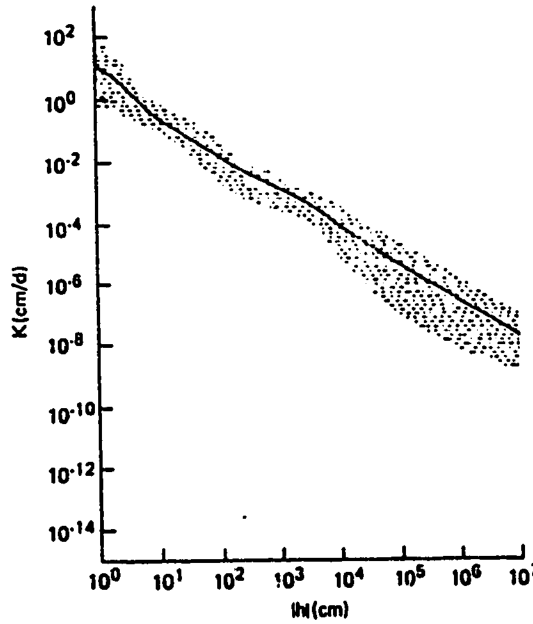
O1



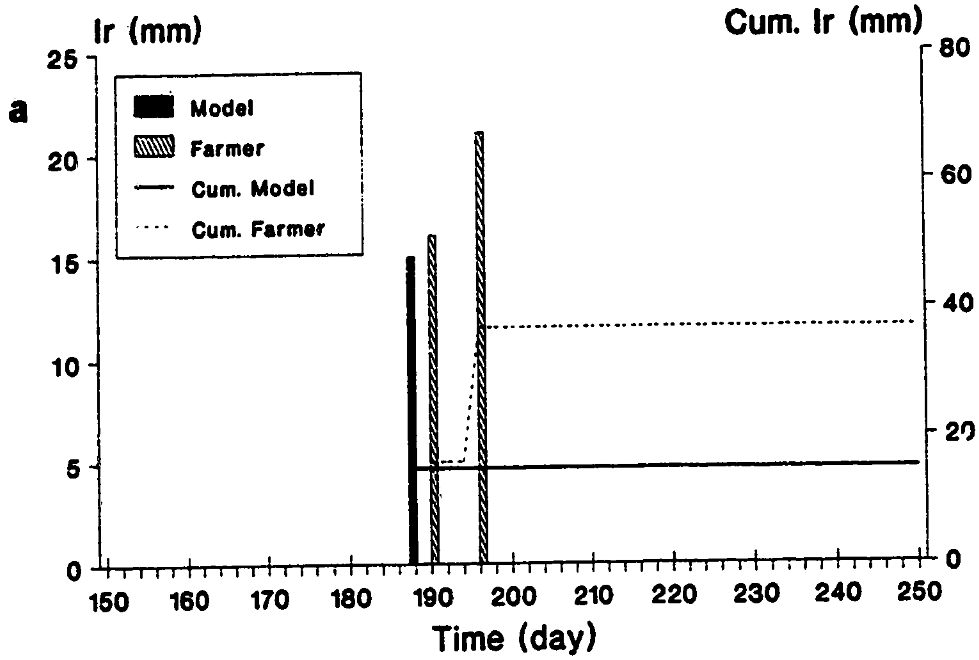
|h|(cm)
θ (cm³/cm³)
0,0 0,2 0,4 0,6 0,8 1,0
K (cm/d)
|h| (cm)

B10

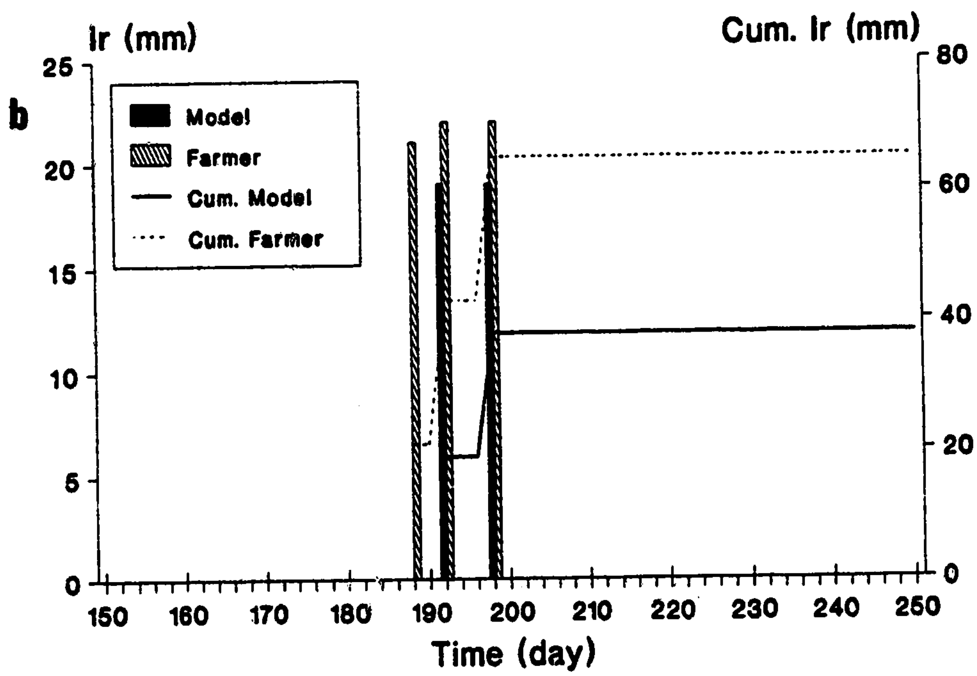




Appendix 5. The irrigation schedules by the model and the farmer at the Rusthoeve (a) and the Vredepeel (b) site in 1987.

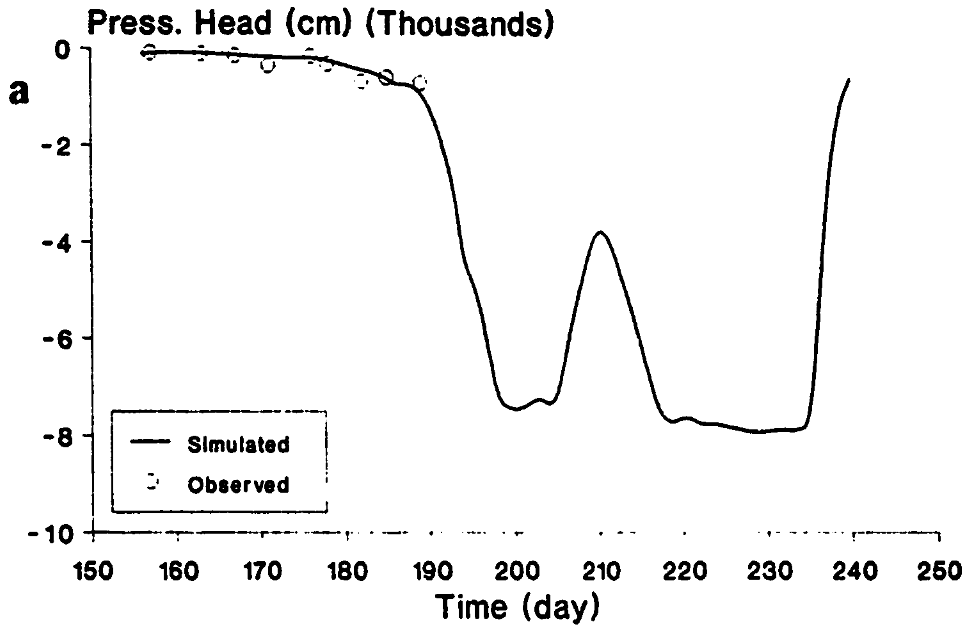


Rusthoeve 1987

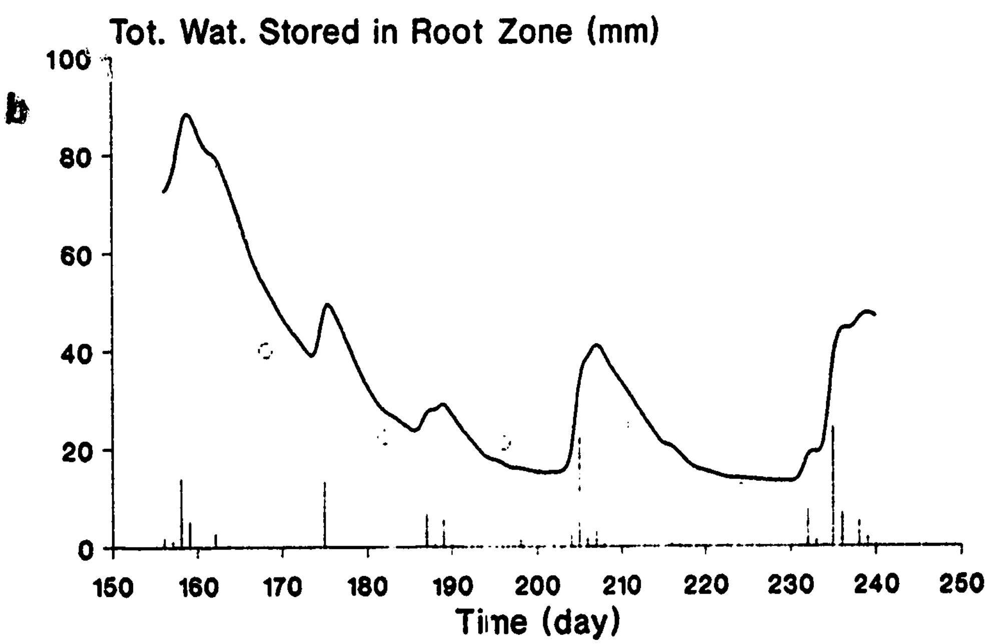


Vredepeel 1987

Appendix 6a. Simulated and measured values of (a) pressure head at 20 cm depth and (b) water storage in the 40 cm root zone at the Vredepeel N treatment in 1986. Precipitation is denoted as vertical bars.

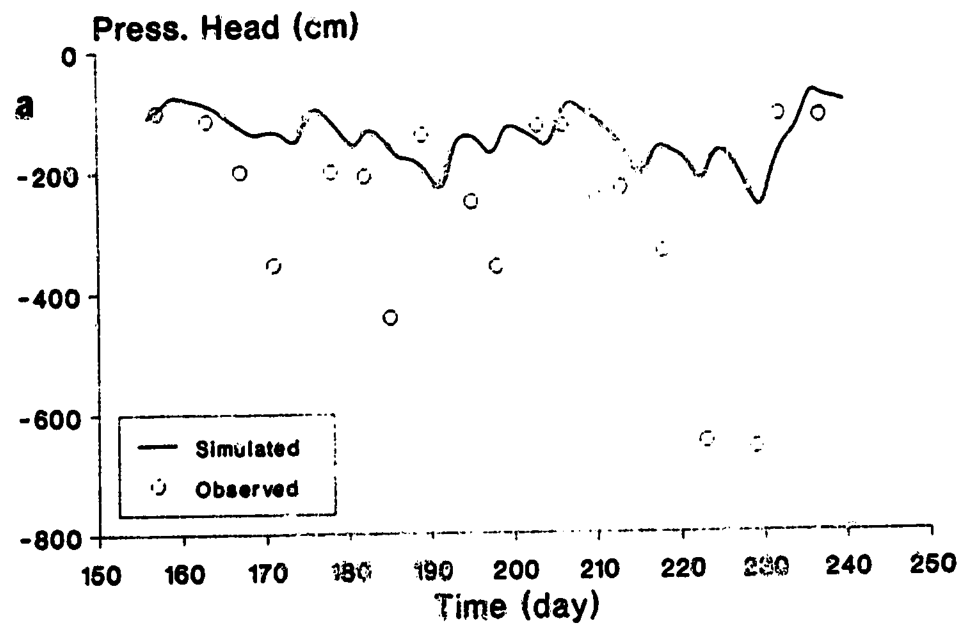


Vredepeel 1986
Non - irrigated

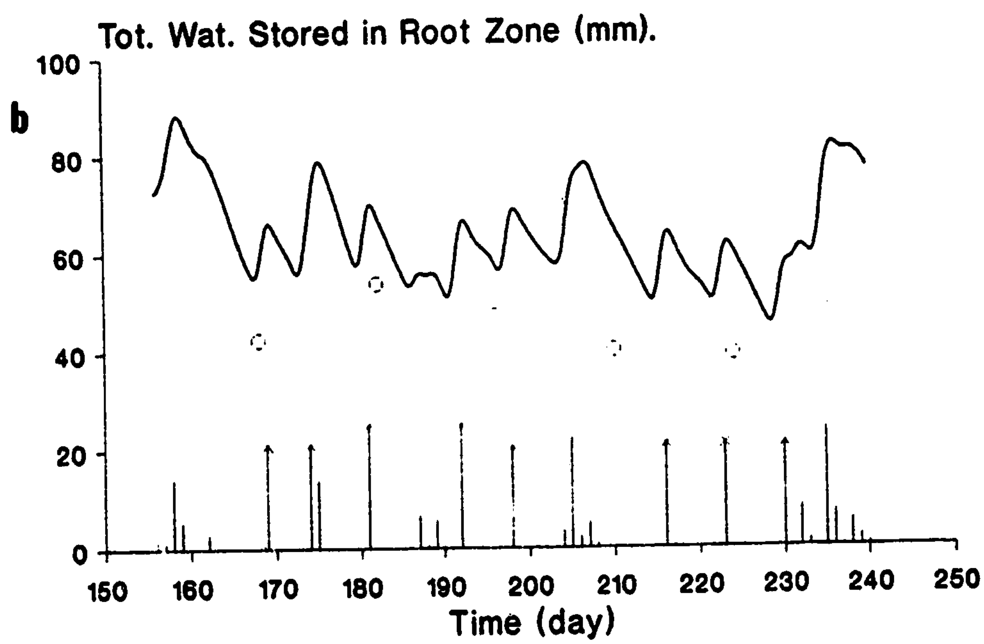


Vredepeel 1986
Non - irrigated

Appendix 6b. Simulated and measured values of (a) pressure head at 20 cm depth and (b) water storage in the 40 cm root zone at the Vredepeel M treatment in 1986. Precipitation is denoted as vertical bars while irrigation as vertical bars with an x.

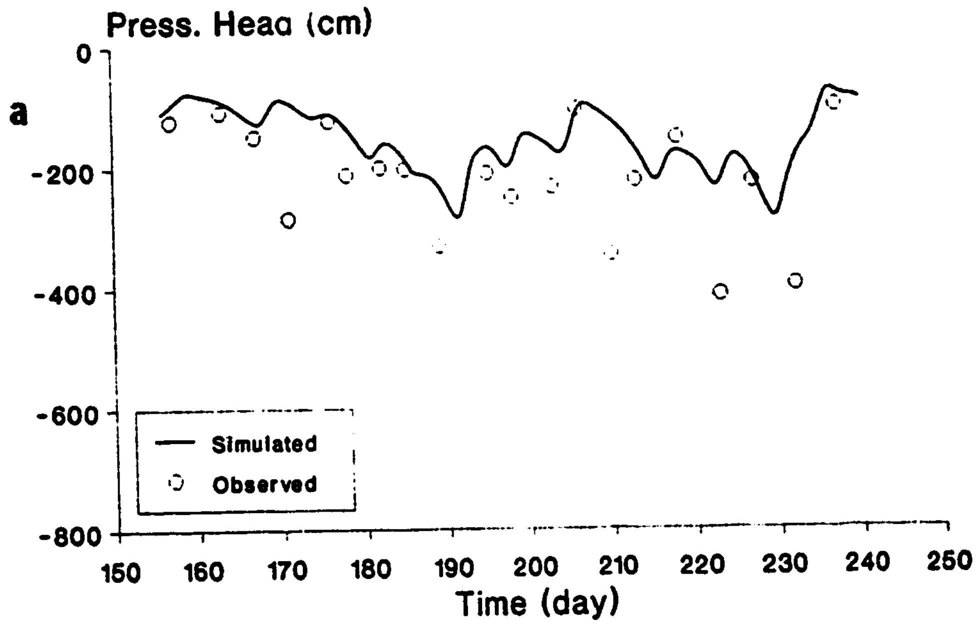


Vredepeel 1986
Model - irrigated

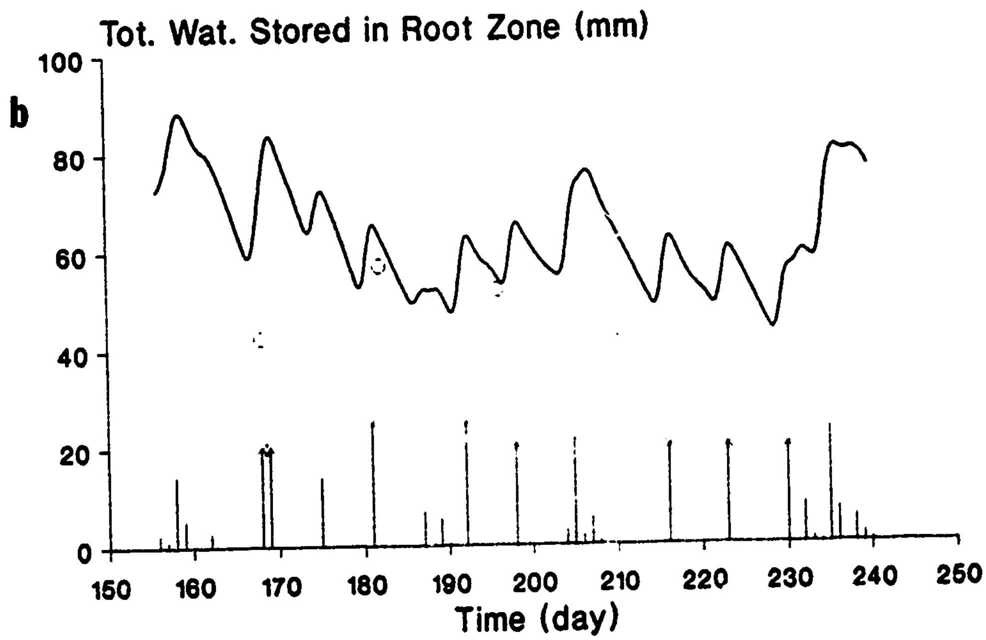


Vredepeel 1986
Model - irrigated

Appendix 6c. Simulated and measured values of (a) pressure head at 20 cm depth and (b) water storage in the 40 cm root zone at the Vredepeel F treatment in 1986. Precipitation is denoted as vertical bars while irrigation as vertical bars with an x.

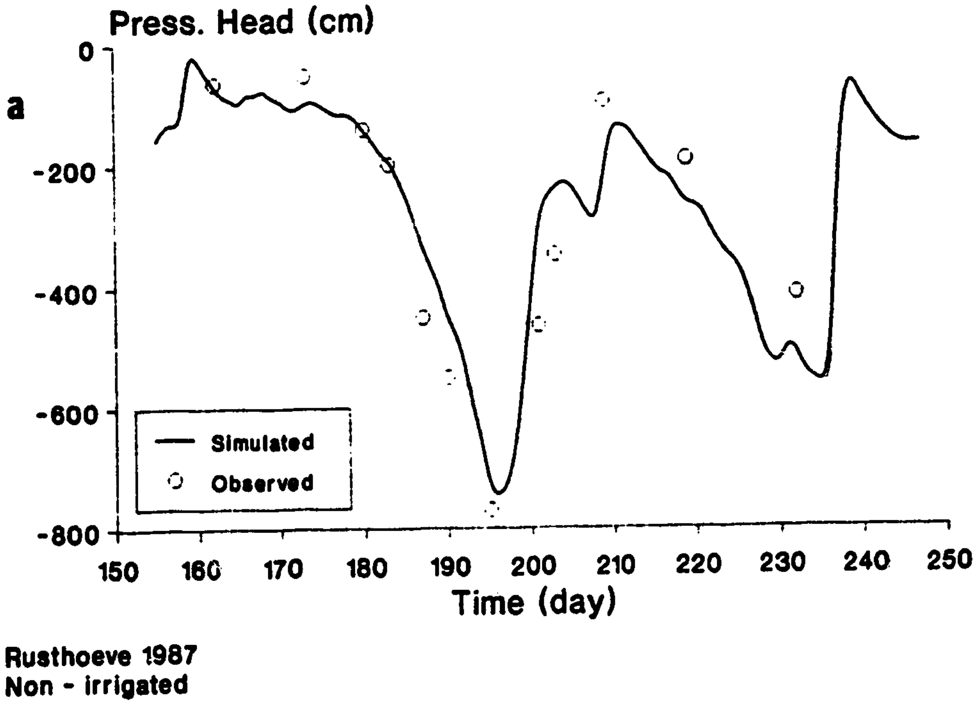


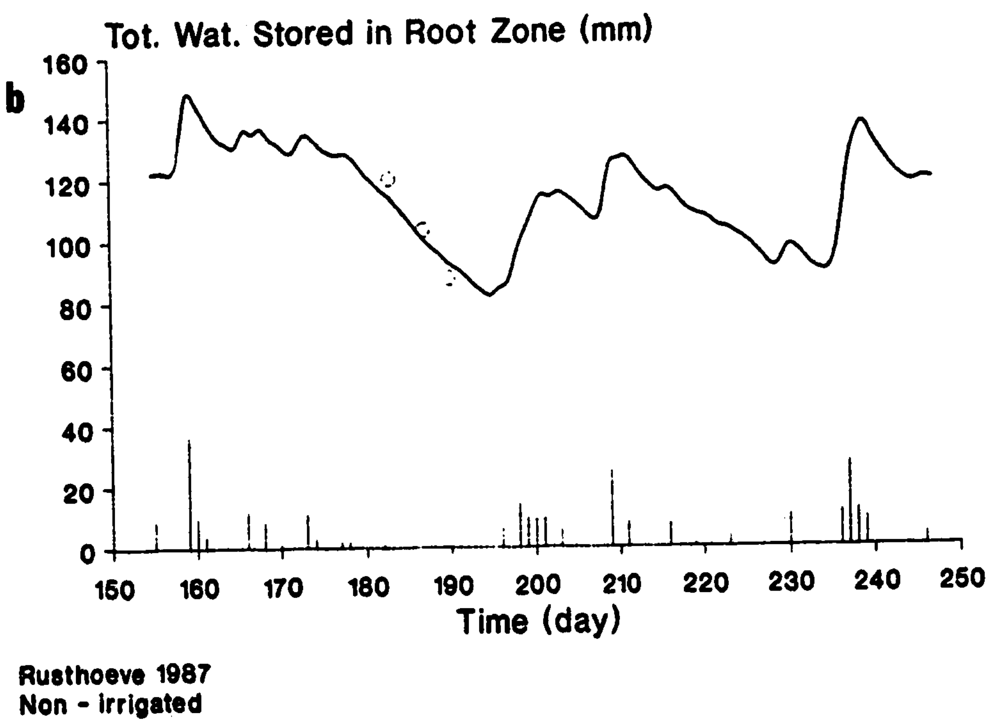
Vredepeel 1986
Farmer - irrigated



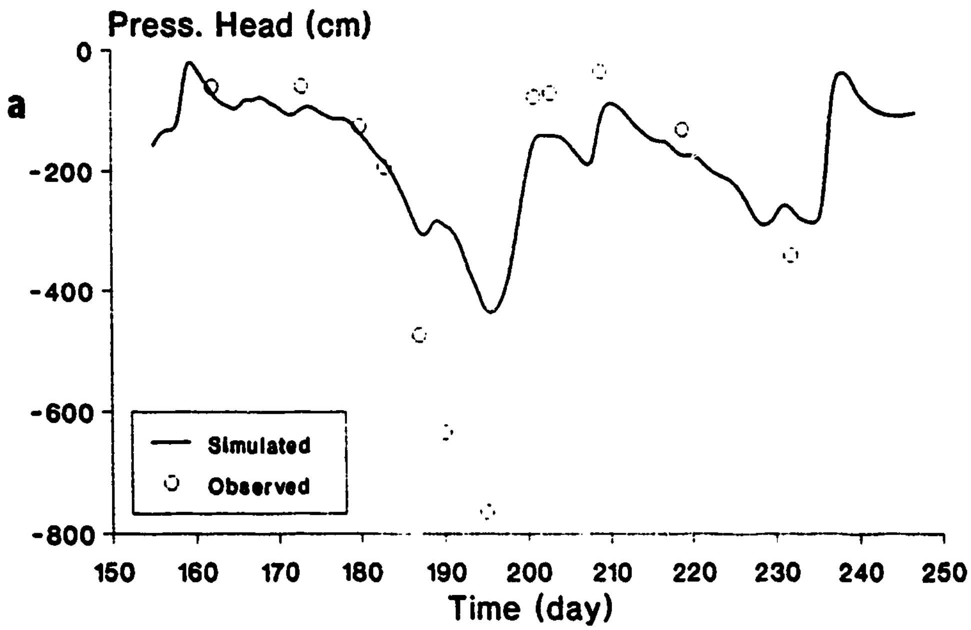
Vredepeel 1986
Farmer - irrigated

Appendix 7a. Simulated and measured values of (a) pressure head at 20 cm depth and (b) water storage in the 40 cm root zone at the Rusthoeve N treatment in 1987. Precipitation is denoted as vertical bars.

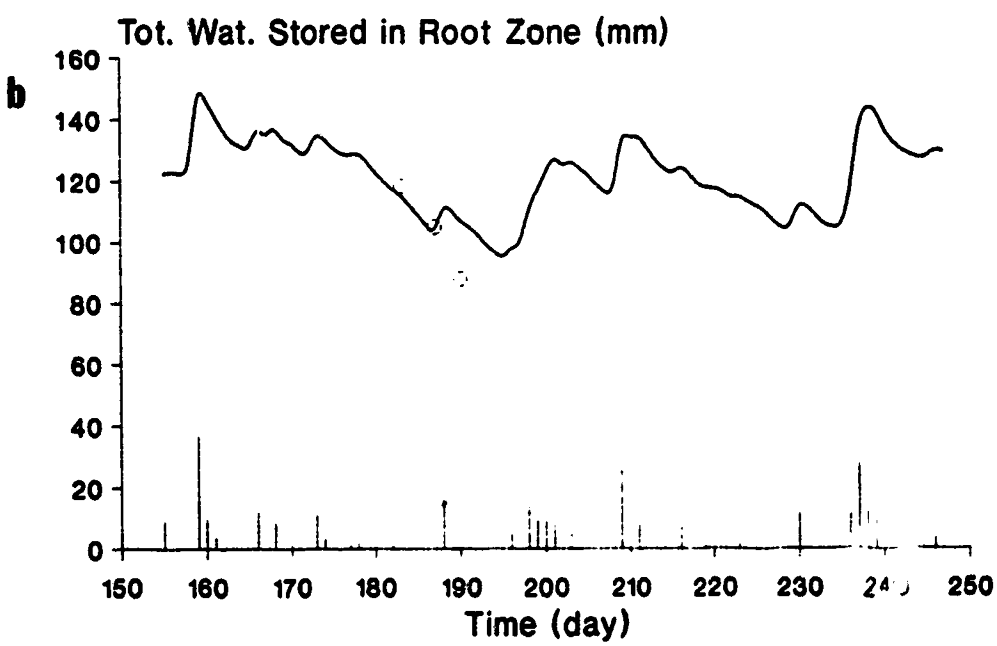




Appendix 7b. Simulated and measured values of (a) pressure head at 20 cm depth and (b) water storage in the 40 cm root zone at the Rusthoeve M treatment in 1987. Precipitation is denoted as vertical bars while irrigation as vertical bars with an x.

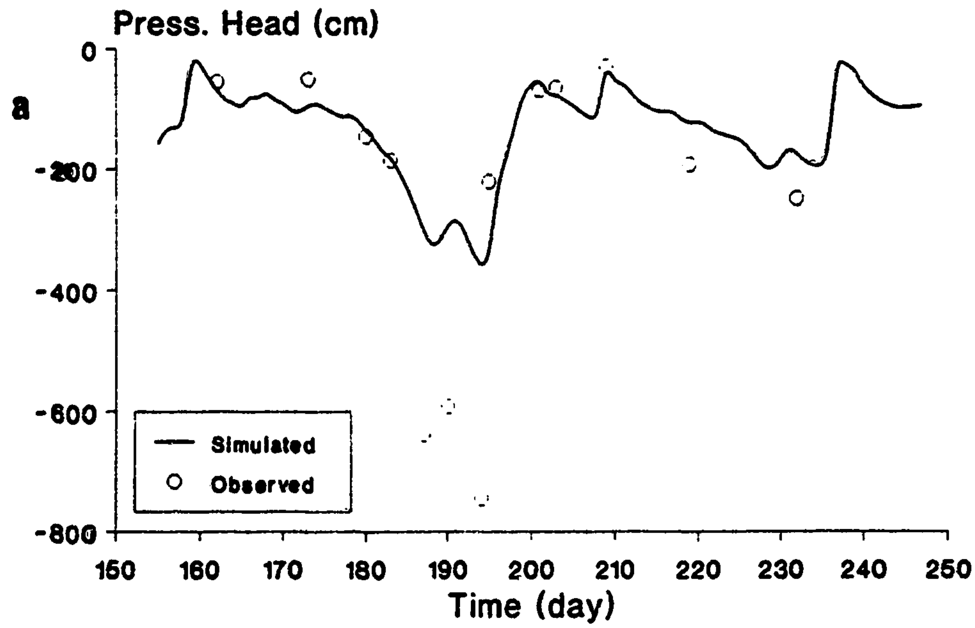


Rusthoeve 1987
Model - irrigated

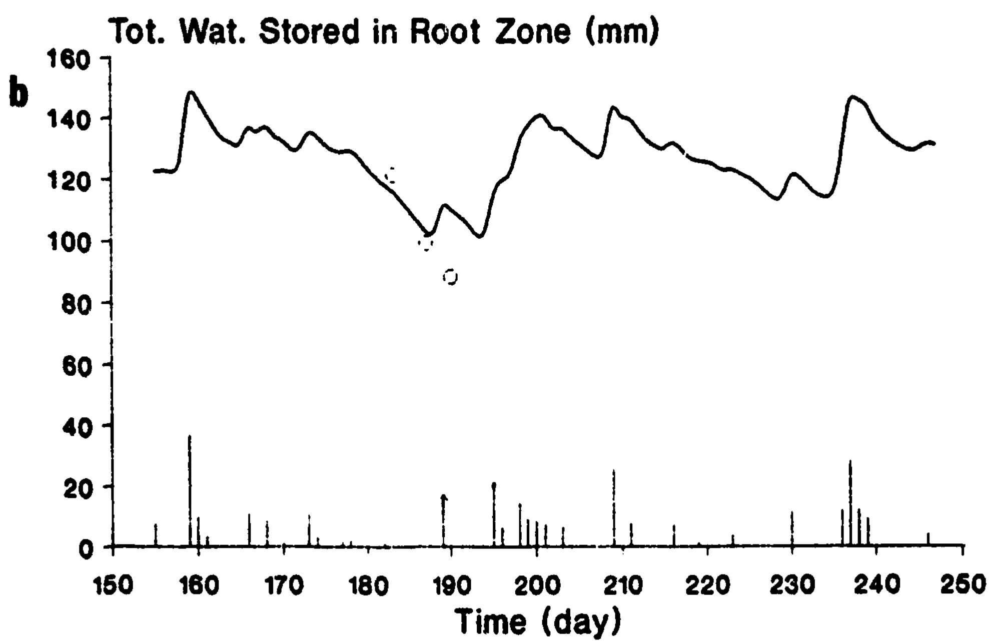


Rusthoeve 1987
Model - irrigated

Appendix 7c. Simulated and measured values of (a) pressure head at 20 cm depth and (b) water storage in the 40 cm root zone at the Rusthoeve F treatment in 1987. Precipitation is denoted as vertical bars while irrigation as vertical bars with an x.

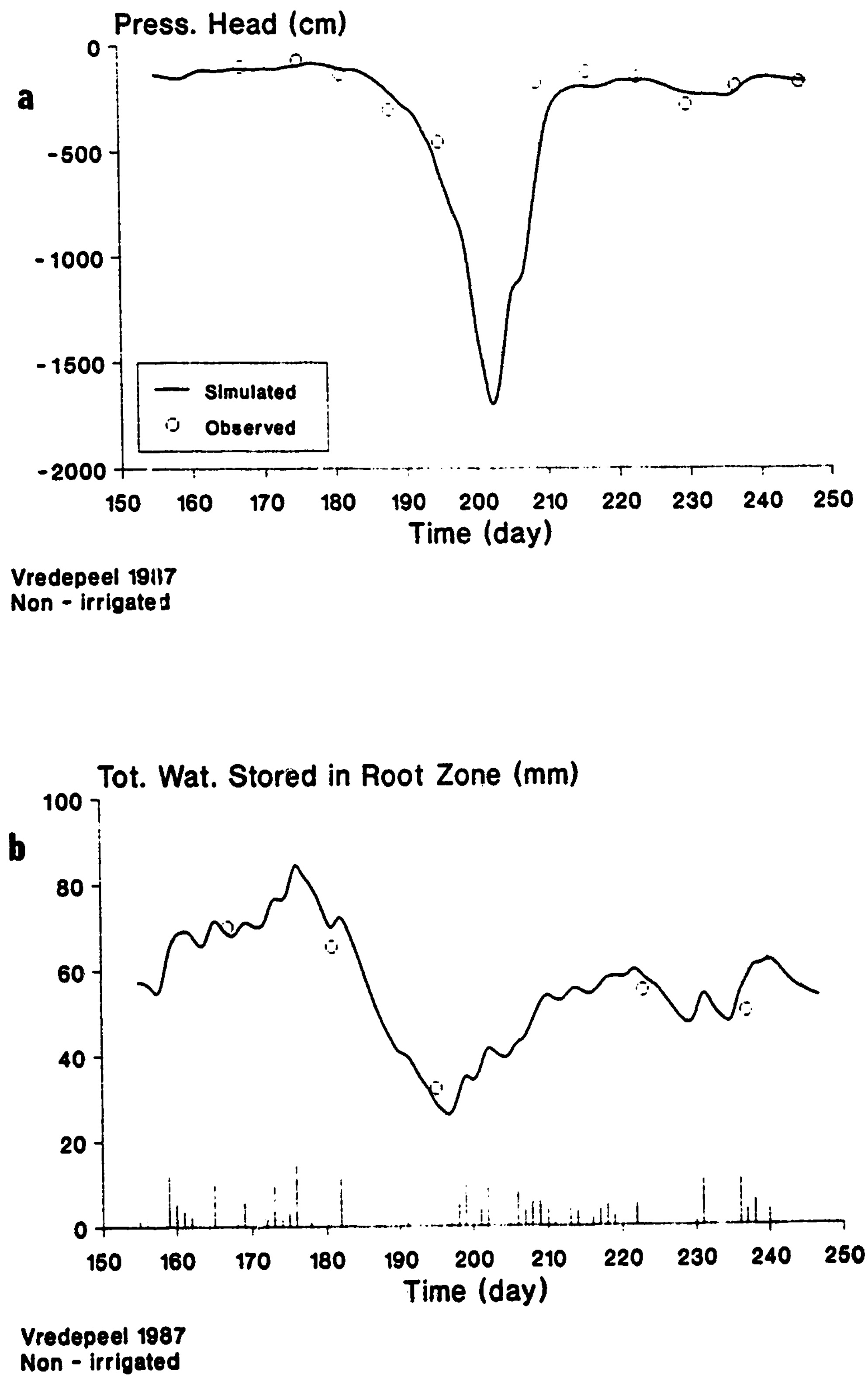


Rusthoeve 1987
Farmer - irrigated

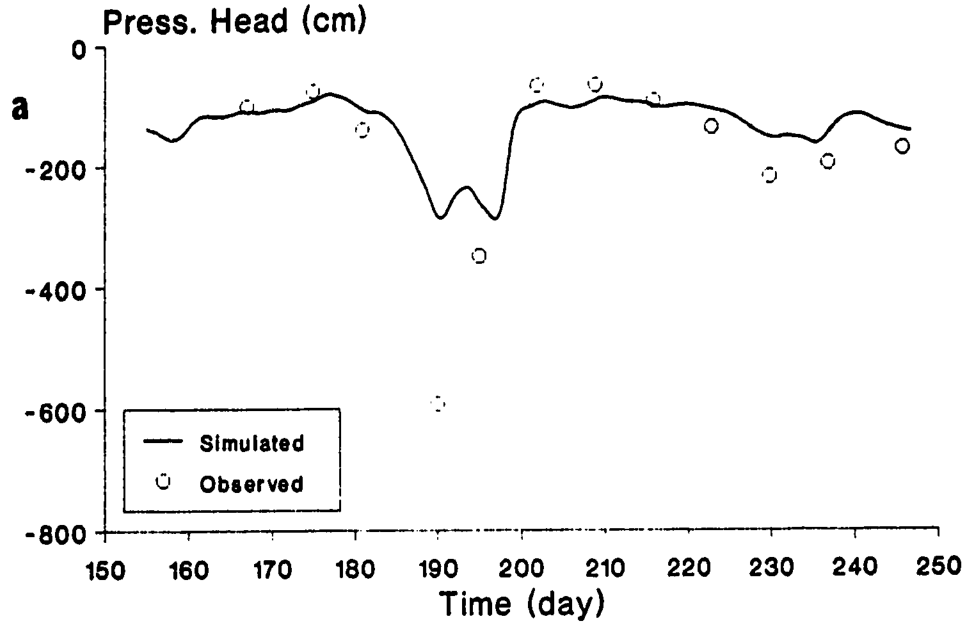


Rusthoeve 1987
Farmer - irrigated

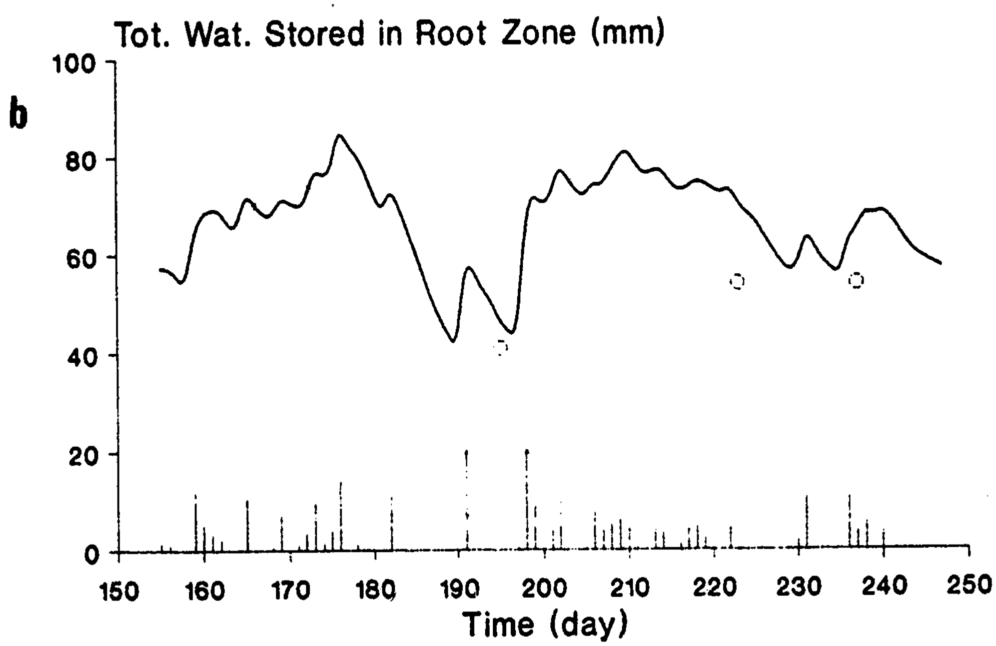
Appendix 8a. Simulated and measured values of (a) pressure head at 20 cm depth and (b) water storage in the 40 cm root zone at the Vredepeel N treatment in 1987. Precipitation is denoted as vertical bars.



Appendix 8b. Simulated and measured values of (a) pressure head at 20 cm depth and (b) water storage in the 40 cm root zone at the Vredepeel M treatment in 1987. Precipitation is denoted as vertical bars while irrigation as vertical bars with an x.

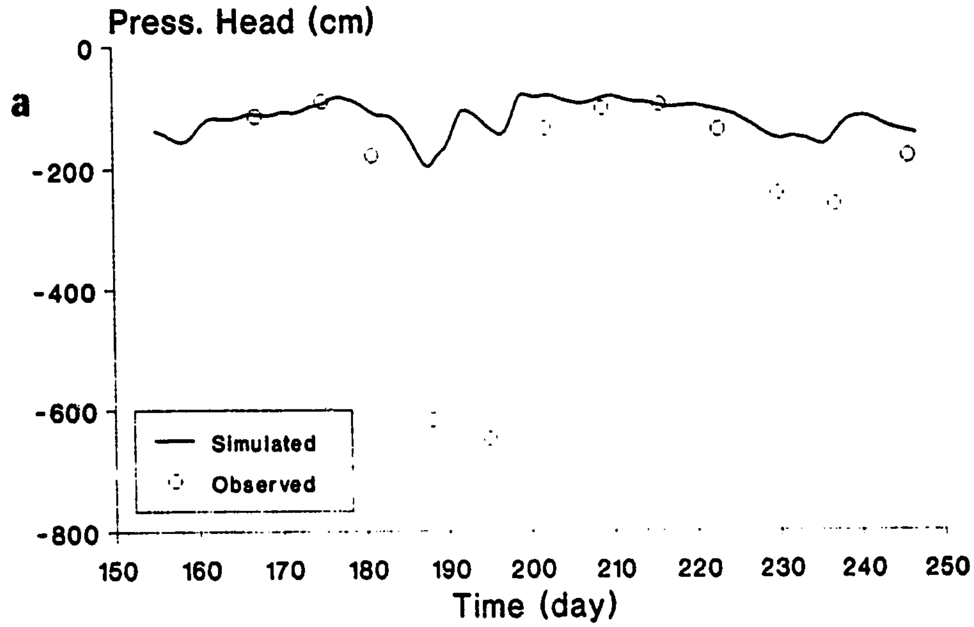


Vredepeel 1987
Model - irrigated

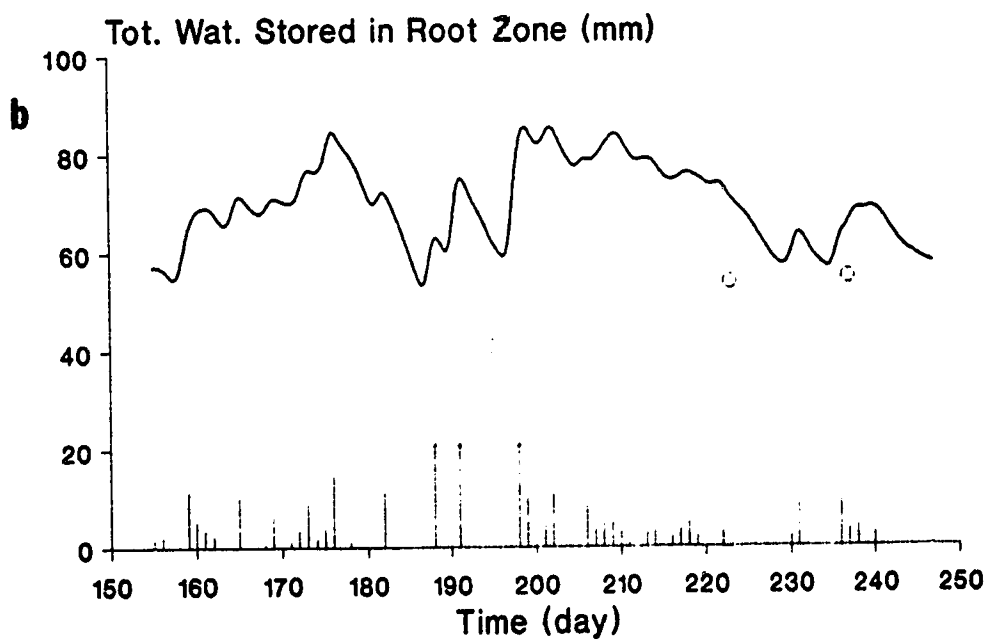


Vredepeel 1987
Model - irrigated

Appendix 8c. Simulated and measured values of (a) pressure head at 20 cm depth and (b) water storage in the 40 cm root zone at the Vredepeel F treatment in 1987. Precipitation is denoted as vertical bars while irrigation as vertical bars with an x.

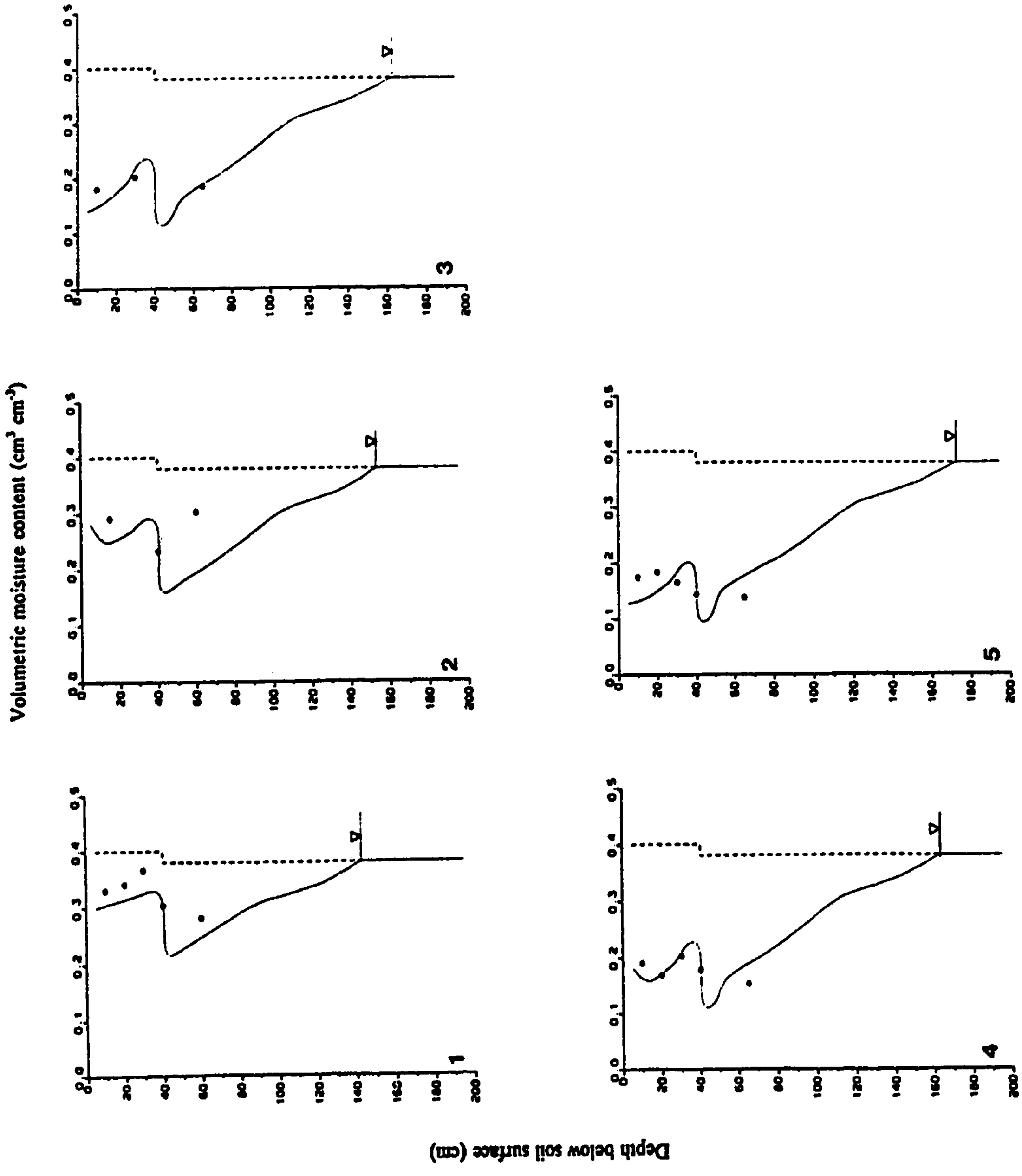


Vredepeel 1987
Farmer - irrigated

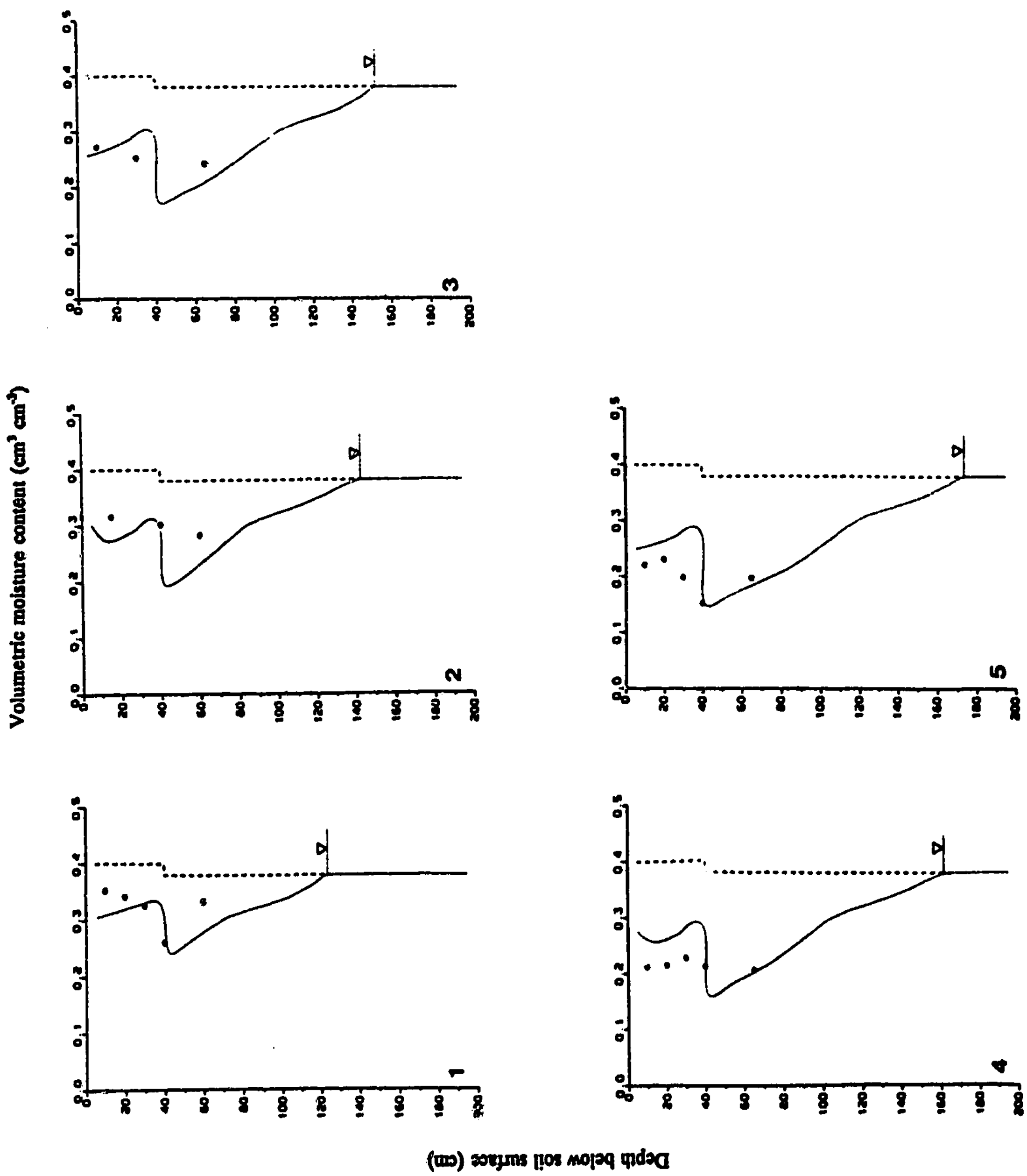


Vredepeel 1987
Farmer - irrigated

Appendix 9a. The simulated (line) and measured (dots) soil moisture profiles for the Rusthoeve N N treatment in 1986. The vertical dotted line indicates the saturation content of the profile layers. Water table depth is indicated as arrow.



Appendix 9b. The simulated (line) and measured (dots) soil moisture profiles for the Rusthoeve M treatment in 1986. The vertical dotted line indicates the saturation content of the profile layers. Water table depth is indicated as arrow.



Appendix 9c. The simulated (line) and measured (dots) soil moisture profiles for the Rusthoeve F treatment in 1986. The vertical dotted line indicates the saturation content of the profile layers. Water table depth is indicated as arrow.