n of the water of arable land and pastures

G.F. Makkink and H.D.J. van Heemst

Simulation of the water balance of arable land and pastures

Simulation Monographs

Simulation monographs is a series on computer simulation in agriculture and its supporting sciences

Simulation of the water balance of arable land and pastures

G.F. Makkink and H.D.J. van Heemst

Wageningen
Centre for Agricultural Publishing and Documentation
1975

Books already published in this series:

C. T. de Wit and H. van Keulen
Simulation of transport processes in soils
1972, 108 pages, ISBN 90 220 0417 1, price Dfl. 15.00

J. Beek and M. J. Frissel
Simulation of nitrogen behaviour in soils
1973, 76 pages, ISBN 90 220 0440 6, price Dfl. 12.50

C. T. de Wit and J. Goudriaan
Simulation of ecological processes
1974, 167 pages, ISBN 90 220 0496 1, price Dfl. 22.50

H. G. Fransz
The functional response to prey density in an acarine system
1974, 149 pages, ISBN 90 220 0509 7, price Dfl. 20.00

M. J. Frissel and P. Reiniger
Simulation of accumulation and leaching in soils
1974, 124 pages, ISBN 90 220 05300, price Dfl. 17.50

H. van Keulen
Simulation of water use and herbage growth in arid regions
1975, 184 pages, ISBN 90 220 0557 7, price Dfl. 27.50

ISBN 90 220 0566 6

Cover design: Pudoc, Wageningen

Printed in Belgium

Contents

1 Introduction

1.1 Purpose

The continuing interest in water relations between soil and plant has stimulated many studies on the factors that control the water balance of the soil. Especially the processes that govern water storage and movement in the soil below and above the watertable, the evapotranspiration of green surfaces, the status of the water in the plant and the opening condition of the stomata have been studied extensively and with considerable success.

Still badly understood are the factors that control the exploration for water of the soil by roots, both with respect to the growth and development of the root system and the movement of water towards the roots and its uptake.

Nevertheless, there is sufficient information to make it worthwhile simulating the water balance of the soil. Then the depth of the watertable and the amount of water in the soil above this table can be continuously computed based on macrometeorological data, the physical proporties of the soil, the hydrological situation of the field and some pertinent data on the crop cover throughout the year.

This monograph present such a simulation, which includes the physical and plant physiological aspects as far as possible, but in which also some bold assumptions are made where this is necessary.

Simulation is a very unsatisfactory tool, if validation is impossible. However, this is possible here because the water balance of a small polder in the Netherlands has been recorded and analysed for many years.

1.2 The Rottegats Polder

Already 30 years ago, a committee was set up in the Netherlands to study the water relations of cropped areas and so increase knowledge about evapotranspiration from vegetation and bare soil surfaces. As a first experimental tool, the water balance method was chosen. The

Rottegats Polder in the North East of the country was a suitable isolated unit because it contained no underground water sources or sinks, the in and outflow of water could be determined at a pumping station and the watertable was very uniform. Thus the whole polder of 86 ha could be used as a lysimeter. In addition 4 plots of 25 × 25 metre were laid out on an experimental field of 1.5 ha as smaller lysimeters. Drainage pipes were laid 5 metres apart and each plot was surrounded by a closed main drain. Since it was found that in this way the plots were not sufficiently isolated, each plot was surrounded in 1950 by a wooden wall to a depth of 3.5 metre in an impermeable clay layer. The whole field, including the plots, was covered with the same crop, which varied from year to year. It turned out, however, that in the plots the watertable fluctuated considerably.
The inflow and outflow of water, the soil moisture content, the depth of the watertable and the relevant meteorological data were recorded. The meteorological observations were done several times a day and the inflow and outflow through the pumps were also recorded continuously. At first soil moisture content was determined every month by sampling in the proximity of the plots, but from 1960 it was determined every 14 days by a neutron moisture meter in access tubes on the plots themselves.
The watertable has been recorded twice a week since 1958. The lysimeters and methods have been described and a vast mass of data have been analysed in a series of publications by Bloemen (1966), Deij (1955, 1956), Hooghoudt (1952), Makkink et al. (1966), Peerlkamp (1955), Rijtema et al. (1968), Stam (1946, 1952), Wind (1958). Evapotranspiration as the final unknown, was calculated from the water balance equation:

Evapotranspiration = rain + infiltration − run-off − difference in soil moisture content at begin and end of the period.

In addition, the Royal Netherlands Meteorological Institute (KNMI) equipped the observation field in the Rottegats Polder for the determination of evapotranspiration by means of the vapour transfer method through the air. This was done by measuring wind speed and humidity at 25, 50, 100 and 200 cm above the soil or the top of the crop.
In this monograph, the data from the lysimeters are used for evaluating a simulation model of the water balance, which is constructed from

information about the processes that take part. As input it only needs the macrometeorological weather data, soil physical parameters, the crop rotation and a few measurements of crop height.

1.3 The simulation approach

The plant soil system is subdivided in compartments, which may contain water. The rates of transfer between the compartments is dependent on a quantitative formulation of the relevant processes. At any moment these rates depend on variables such as: the meteorological data, the crop cover and height, and the water content of the compartments. When at an instant of time, the rates of transfer are computed, they hold for a small time interval, after which the new state of the system can be calculated. The principles of the simulation of such state determined systems are described in another monograph of this series (de Wit & Goudriaan, 1974).

However, the present approach differs in various respects. The first difference concerns the choice of time interval. The processes with small time constants, like the change in adhering water on the crop or in standing water on the soil surface are rapid. Their time constant, defined as the ratio of amount of water and the rate of change may be of the order of minutes. In systems that are really state determined the time interval of integration would also be of the order of minutes. Hence far too many steps would be needed to simulate the water balance throughout a year. A good compromise would be a time interval of integration of 0.2 days, but this necessitates the introduction of some artificial procedures to treat processes requiring a smaller time constant. In order to avoid that within such a time step more water is removed from a compartment than it contains or that more water is stored than is possible, limiting functions of the following kind are introduced:

$$ES = MIN(S_{t-1}/DT, EOS)$$

where

- ES is evaporation of snow (mm/day)
- S_{t-1} is the content of the compartment for snow at time t−1 (mm)
- DT is the time interval of integration (day)
- EOS is evaporation from snow according to the Penman formula (mm/day)

MIN determines the minimum of the values between brackets.
Hence, if EOS is greater than S_{t-1}/DT, the integration is performed according to

$$S_t = S_{t-1} + (S_{t-1}/DT) * DT = S_{t-1} - S_{t-1} = 0.$$

In this way the compartment is emptied. This occurs within a part of the time interval, which equals (ES/EOS) * DT. In the remaining part, i.e. (1 − ES/EOS) * DT, the soil is then free from snow, and water may evaporate at its computed rate from bare soil. Hence, it is essential to compute first the evaporation rate from the snow and then that from the bare soil. This consecutive computation rather than parallel computation, which is done in simulation programs with small time intervals, is the disadvantage of using too large a DT.
The second difference concerns the division of the soil in compartments. If there are many small compartments the time interval of integration is of the order of seconds. In each small compartment it may be assumed that the water is equally distributed. This is not so in a large compartment and therefore some assumptions are necessary about the water status in the soil.
To describe the condition of water in the soil only the mechanical forces moving water through the soil are considered. At a specific point, water in unsaturated soil is under a negative pressure compared with free water. By using the term suction for negative pressure, the minus sign is avoided.
The average moisture retention curve (pF curve) of the soil gives the relationship between moisture content and suction. The water in the soil is at hydrostatic equilibrium when there is no flow of water in the soil, i.e. when at every point in the soil the moisture potential in cm water suction equals the distance to the watertable (Fig. 2a). From the pF curve are derived the equilibrium curves of Fig. 27 (the saturation capacity), Fig. 8 (the water missing from the soil, that is the difference in water content between saturation and hydrostatic equilibrium), Fig. 13 (the available moisture capacity) and Fig. 25 (the capacity of available water).
When there is more water in the soil than at hydrostatic equilibrium, this water can be anywhere in the unsaturated soil (Fig. 2b). Because it is not possible to ascertain the position of this amount, it is assumed to be equally distributed over the unsaturated soil. When there is less water than at hydrostatic equilibrium, it is assumed that this missing water

has left the soil by evapotranspiration and comes from the layer of the unsaturated soil in which the plant is assumed to root (Fig. 2c).
The plant can not extract all the water from the soil. When the suction of the soil moisture is at a value of 16 atm. (pF = 4.2, the permanent wilting point), the plant is unable to extract water from the soil (Fig. 2d).
The water in the soil can be further divided into capillary and micellar water, the micellar water being between the particles of the clay minerals. When the clay dries out, it shrinks and the space between the particles becomes less. When the soil is rewetted, the entry of water into the spaces becomes very slow.
The third difference is in the use of the programming system. In various monographs of this series the programming language (CSMP) Continuous System Modeling Program has been used. This language was, however, not available for the Controle Data Computer that we used when this programming work started. Moreover, by introducing a few subroutines and organizing the program to ensure that integrations were semi-parallel and rectilinear, we found FORTRAN to be very practical for the present book-keeping program. These subroutines are:
the minimum function, MIN(A, B) which determines the minimum of the values between brackets,
the maximum function, MAX(A, B) which determines the maximum of the values between brackets,
the interpolation function, INPOL(Y, X) which determines by linear interpolation in a graph Y, X, the Y value of the point for which the X value is given. The graph Y, X is given as a table of Y values at equal intervals of X.
The inswitch function, $Y = INSW(X_1, X_2, X_3)$, which means:
$Y = X_2$ when $X_1 < 0$, $Y = X_3$ when $X_1 \geq 0$.
The semi-parallel integration is ensured by distinguishing the contents at time (t − 1) and time t. The rates of transfer are calculated, based on the contents at time (t − 1). Subsequently the integration is done according to

$$CONTENT_t = CONTENT_{t-1} + RATE * DT$$

for all compartments.
This notation is followed in the text, but in the computer program itself the subscripts are omitted.

The relevant rates were converted into amounts of water and totalized and the iteration procedure was repeated. The output was printed out after the rate calculations and before the integration.
The fourth difference is that some processes had to be simplified. In general rate calculations are based on knowledge of the processes involved as far as possible, but here some parameters were taken from field observations and others were calibrated by comparing observed and simulated results.
For this purpose, only the data of 1959 were used, this being a year with wet and dry periods that were long enough. The parameters were calibrated within periods where their influence was decisive.
Without adaptating the parameters further, the whole program was then validated by comparing observed and simulated results for the year 1958, which had quite different weather and another crop. Moreover, the program was evaluated by simulating the water balance in years under grass and its results were compared with observations. Parameters were independently evaluated from a water management study carried out by the Province of Gelderland. In this Province a detailed hydrological study was made of the catchment area of a small river, which is fairly representative for the sandy area in the Eastern part of the Province. The program was the same as that developed for the Rottegats Polder. The 1965 data were used here to calibrate soil parameters and then the program was again evaluated from 1964 data.

2 Program description

2.1 Compartmentalization

The plant soil system is subdivided in compartments for water storage as follows (Fig. 1):

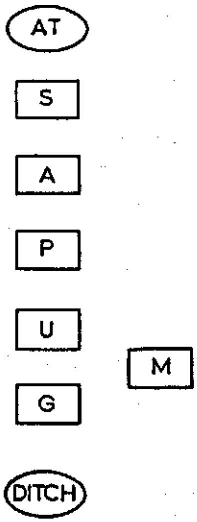

Fig. 1 | Compartments for water storage.

Solid precipitation (S) such as snow and hoary frost. This remains much longer on the field than rain before it ends up in drainage water and prevents evaporation from the bare soil and transpiration from the crop. The capacity of S is unlimited.

Water adhering to the vegetation (A). The adhering water comes from the dew that is formed at night and the part of the precipitation that does not reach the soil. The evaporation of this adhering water reduces transpiration. The capacity of A depends on quantity and type of crop.

Puddles (P) that are frequently formed on heavy clay. They drain also slowly by surface run-off to the ditches. The capacity of P is set at 1.5 mm.

Unsaturated soil (U) is that part of the soil above the watertable. From here the crop removes water for transpiration.
The capacity of U depends on the kind of soil and the depth of the watertable. The depth of the watertable is changing continuously and therefore the capacity of U also changes every time interval.

Saturated soil (G) is that part of the soil beneath the watertable down to an assumed basic surface below the lowest water depth. The content of this part of the soil is required for the calculation of the watertable. The capacity of G is changing for the same reason as for U.

Micellar water (M). In heavy clay water is present in the capillaries and between the particles of the clay minerals. The latter is the micellar water. The flow of micellar water to capillary water is a rapid process, in the opposite direction it is a very slow process (Makkink & van Heemst, 1965). The capacity of M is constant for a specific soil.

Transpiration zone (T) is that part of the unsaturated soil in which the crop is supposed to extract water. The content is required for the calculation of the transpiration. The capacity of T changes with the development of the crop.

Evaporation zone (E) is the bare part of the unsaturated soil which can be depleted by evaporation. The capacity is set at 10 mm.

The available content of the unsaturated soil (UAV) and the transpiration zone (TAV). The content consists of water held at a suction lower than 16 atm. in the unsaturated soil and the transpiration zone. The capacity of UAV is changing with the capacity of U, the capacity of TAV is changing with the capacity of T.

The unavailable content of the unsaturated soil (UNAV) and the transpiration zone (TNAV). The water held at a suction of 16 atm. or more is unavailable for the crop.
The capacity of UNAV is changing with the capacity of U, the

capacity of TNAV is changing with the capacity of T.

The content at hydrostatic equilibrium of the unsaturated soil (UEQC), the transpiration zone (TEQC) and the evaporation zone (EEQC). For a description of the equilibrium content see section 1.3 and Fig. 2a.

The missing water from the unsaturated soil (UEQA), the transpiration zone (TEQA) and the evaporation zone (EEQA) when these compartments are at hydrostatic equilibrium.
For a description of this missing water see Section 1.3. and Fig. 2a.

The deficit (UEQD) and surplus (UEQS) with respect to the equilibrium content of the unsaturated soil. For a description of these compartments see Section 1.3 and Fig. 2b and 2c.

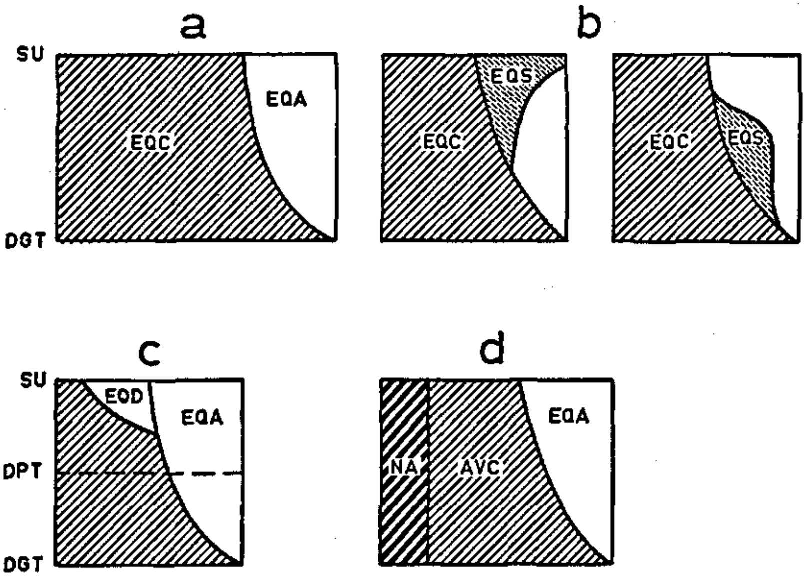

Fig. 2 | The water status in the unsaturated soil. (SU = surface, DGT = depth of watertable, DPT = depth of transpiration zone, EQC = water content at hydrostatic equilibrium, EQA = difference in water content between a soil at saturation and at hydrostatic equilibrium, EQD = deficit above the deficit at hydrostatic equilibrium, NA = not available water, AVC = available water at hydrostatic equilibrium).

The amount of water entering the unsaturated soil at time t (WT). This amount is necessary to calculate the immediate percolations.

The micellar surplus (MS)
This amount of water is necessary to calculate the dehydration.

The water refilling the unsaturated soil (RFU)
This amount is necessary to calculate the rehydration.

2.2 Computation of contents

The symbols of the compartments for waterstorage are used as 'contents' in this chapter.

2.2.1 Snow (S, mm, Fig. 3)

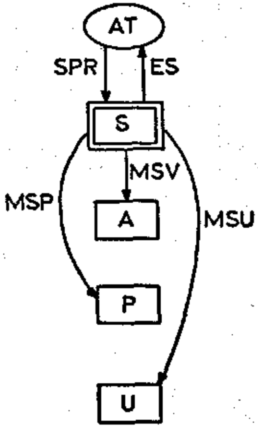

Fig. 3 | Relational diagram for the snow compartment.

The compartment for snow is filled with solid precipitation (SPR) either snow or hoary frost. The snow disappears by evaporation (ES) and by melting. The melting snow ends up as water adhering to the vegetation (MSV), in the pools on the bare soil (MSP) or when there are no pools, in the unsaturated soil (MSU). The balance equation is:

$$S_t = S_{t-1} + DT * (SPR - ES - MSV - MSP - MSU)$$

S_0 being measured or set at zero.

2.2.2 *Adhering water (A, mm, Fig. 4)*

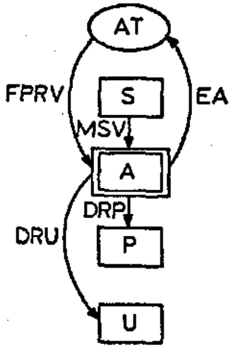

Fig. 4 | Relational diagram for the compartment of adhering water.

The compartment for adhering water is filled by fluid precipitation (FPRV), including dew and by water from the melting snow which may have settled on the vegetation (MSV). The adhering water disappears by evaporation (EA) and by dripping into the pools (DRP), or in the absence of pools in the unsaturated soil (DRU). The balance equation is:

$$A_t = A_{t-1} + DT * (FPRV + MSU - EA - DRP - DRU)$$

With A_0 set at zero.

2.2.3 *Pools (P, mm, Fig. 5)*

The compartment for pools is filled by fluid precipitation, including dew (FPRP), by water from the melting snow (MSP), the water dripping from the vegetation (DRP) and water rising from the saturated soil when the watertable reaches the surface (GP). The content of the pools disappears by evaporation (EP), by surface run-off into the ditch (OFLD) and by infiltration into the unsaturated soil (IU) or when the watertable reaches the surface by infiltration into the saturated soil (IG).

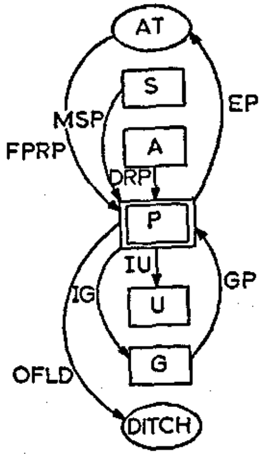

Fig. 5 | Relational diagram for the compartment of the pools.

The balance equation is:

$$P_t = P_{t-1} + DT * (FPRP + MSP + DRP + GP - \\ - OFLG - IU - IG - EP)$$

P_0 being estimated or set at zero.

2.2.4 The unsaturated soil (U, mm, Fig. 6)

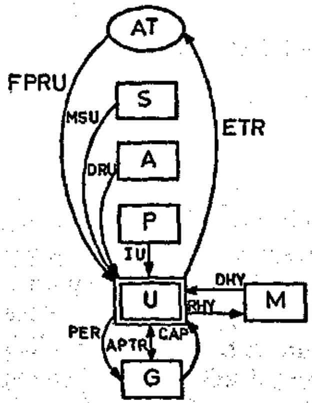

Fig. 6 | Relational diagram for the compartment of the unsaturated soil.

The compartment for the unsaturated soil is filled by fluid precipitation, including dew (FPRU), by melting snow (MSU), by water dripping from the vegetation (DRU), by water infiltrating from the pools (IU), by water from the dehydration of the compartment for micellar water (DHY) and by water from the saturated soil by capillary rise (CAP). When the watertable is falling the remaining water content of the layer between two consecutive watertables is transferred to the unsaturated soil. We assume that this content is at hydrostatic equilibrium. When the watertable is rising the appropriate amount of water is transferrred to the saturated soil. This is an apparent transport (APTR), because the water is not flowing but the boundery line between saturated and unsaturated soil is changing.
When ice forms and melts in the unsaturated soil, the content of the compartment is not changed and there is no transport.
The content of the unsaturated soil disappears by evapotranspiration (ETR), water dehydrating from the capillaries to the compartment for micellar water (RHY) and water percolating to the saturated soil (PER). The balance equation is:

$$U_t = U_{t-1} + DT * (FPRU + MSU + DRU + IU + CAP + \\ + DHY + APTR - ETR - RHY - PER)$$

U_0 is calculated under the assumption that the unsaturated soil is at hydrostatic equilibrium by subtracting the water that is missing at hydrostatic equilibrium (UEQA) from the content at saturation ($CSCU_0$). Where USC_0 is the capacity of the unsaturated soil at time 0, (mm) $UEQA_0$ is the missing water from the unsaturated soil at hydrostatic equilibrium, at time 0, (mm)

$$U_0 = USC_0 - UEQA_0$$

2.2.5 *The saturated soil (G, mm, Fig. 7)*

The compartment of the saturated soil is filled by percolation water from the unsaturated soil (PER) and by water infiltrating from the pools when the watertable is at the surface (IG).
The compartment is emptied by underground flow of water (GFL), by capillary rise into the unsaturated soil (CAP) and by water puddling the land when the watertable reaches the surface (GP). A crop growing with its roots in the groundwater will transport water directly to the

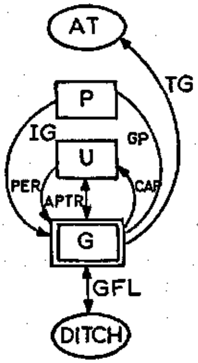

Fig. 7 | Relational diagram for the compartment of the saturated soil.

atmosphere (TG). Then there is the apparent transport (APTR) as discussed under Section 2.2.4. The water balance equation is:

$$G_t = G_{t-1} + DT * (IG + PER - CAP - TG - GP - GFL - APTR)$$

G_0 is calculated as the difference between the capillary capacity of the whole profile and the capillary capacity of the unsaturated soil.

2.2.6 The micellar water (M, mm, Fig. 6)

The compartment of the micellar water is filled by the rehydration water from the unsaturated soil (RHY) and emptied by the dehydration water into the unsaturated soil (DHY).
The balance equation is:

$$M_t = M_{t-1} + DT * (RHY - DHY)$$

M_0 is calculated under the assumption that the water in the compartments of micellar and capillar water are in equilibrium with each other.

$$M_0 = (U_0 + G_0) * FM/FC$$

where
U_0 is the initial water content of unsaturated soil (mm)
G_0 is initial water content of saturated soil (mm)
FM is fraction of micellar capacity of total capacity
FC is fraction of capillar capacity of total capacity

2.2.7 *The whole profile (TP, mm)*

When adding the balance equation of these 6 compartments only the marginal transports remain.

$$TP_t = TP_{t-1} + DT * (SPR + FPRV + FPRP + FPRB - ES - EA - \\ - EP - ETR - TG - OFLD - GFL)$$

The 4 transports containing the symbol PR can be replaced by precipitation PR, the 5 transports whose symbol begins with E or T can be summarized as evaporation E, the 2 remaining symbols containing FL are the surface or underground run-off.

2.2.8 *The watertable (DGT, cm)*

The watertable is found by interpolation of the graph in Fig. 8 with UEQA as the independent variable.

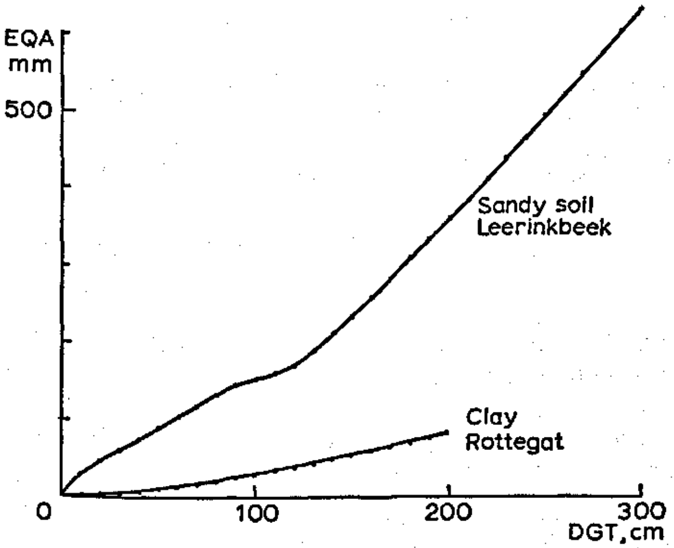

Fig. 8 | The difference in water content between saturation and hydrostatic equilibrium in relation to the depth of the watertable.

2.2.9 The transpiration zone (T, mm)

The content of the transpiration zone is not kept track of, only that of the unsaturated soil. The calculation of the content of transpiration zone differs according to that of the unsaturated soil. If there is a deficit with respect to the hydrostatic equilibrium, this deficit is assumed to be present in the transpiration zone (Fig. 9a), whereas a surplus with respect to the hydrostatic equilibrium may occur in the transpiration zone as well as in the remaining part of the unsaturated soil (Fig. 9b).

$$T = INSW(UEQD, TEQC - UEQD, U_{t-1} * TEQC/UEQC)$$

UEQD is the positive difference between the content of the unsaturated soil at hydrostatic equilibrium and the actual content (mm)
TEQC is the content of the transpiration zone at hydrostatic equilibrium (mm)
UEQC is the content of the unsaturated soil at hydrostatic equilibrium (mm)
U_{t-1} is the content of the unsaturated soil at time $t-1$ (mm)

2.2.10 The evaporation zone (E, mm)

The content of the evaporation zone is calculated in a similar way to the content of the transpiration zone.

$$E = INSW(UEQD, EEQC - UEQD, U_{t-1} * EEQC/UEQC)$$

in which
EEQC is the content of the evaporation zone at hydrostatic equilibrium (mm).

2.2.11 The available content of the unsaturated soil (UAV) and of the transpiration zone (TA) (mm)

The available content of a compartment is the actual content of that compartment minus the unavailable content of that compartment.

$$UAV = MAX(0., U_{t-1} - UNAV)$$
$$TAV = MAX(0., T_{t-1} - TNAV)$$

UNAV is unavailable water in the unsaturated soil (mm)
T_{t-1} is content of the transpiration zone at time $t-1$ (mm)

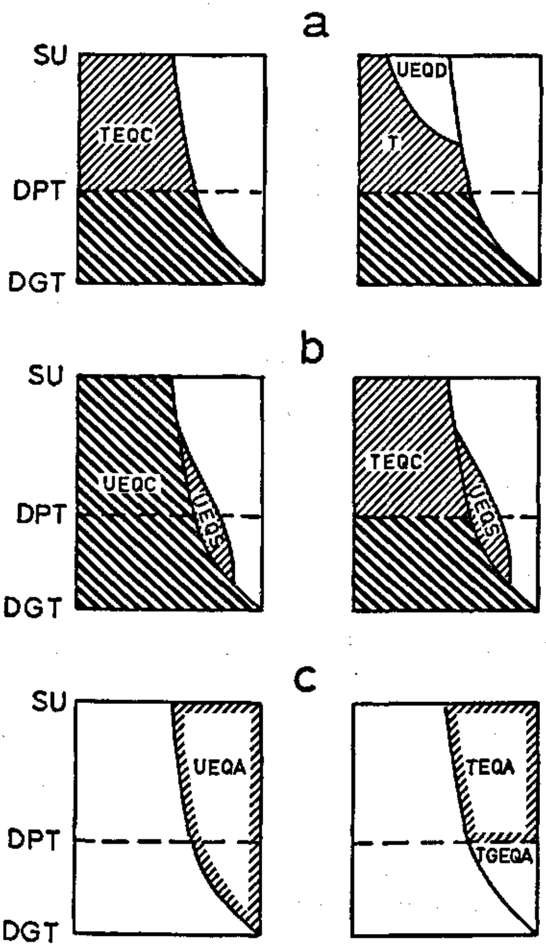

Fig. 9 | The water status in the transpiration zone. (SU = surface, DGT = depth of watertable, DPT = depth of transpiration zone, TEQC = content of the transpiration zone at hydrostatic equilibrium, T = content of the transpiration zone, UEQD = deficit in the unsaturated soil with respect to the content at hydrostatic equilibrium, UEQC = content of the unsaturated soil at hydrostatic equilibrium, UEQS = surplus in the unsaturated soil above the content at hydrostatic equilibrium, UEQA = difference in water content of the unsaturated soil between saturation and hydrostatic equilibrium, partly in the transpiration zone (UEQT) and between DPT and DGT (TGEQA)).

TNAV is unavailable water in the transpiration zone (mm)

2.2.12 The unavailable content of the unsaturated soil (UNAV) and the transpiration zone (TNAV) (mm)

The unavailable content of a compartment is the capacity of the compartment at saturation minus the capacity of the available content.

UNAV = USC − UAVC
TNAV = TSC − TAVC

USC is capacity unsaturated soil (mm)
UAVC is capacity available water in unsaturated soil (mm)
TSC is capacity transpiration zone (mm)
TAVC is capacity available water in transpiration zone (mm)

2.2.13 The content at hydrostatic equilibrium of the unsaturated soil (UEQC, mm), the transpiration zone (TEQC, mm) and the evaporation zone (EEQC, mm)

The content of these compartments is found by subtracting the missing water of the compartment at hydrostatic equilibrium from the capacity of the compartment.

UEQC = USC − UEQA
TEQC = TSC − TEQA
EEQC = ESC − EEQA

where
USC is capacity of the unsaturated soil (mm)
TSC is capacity transpiration zone (mm)
ESC is capacity of the evaporation zone (mm)
UEQA is the difference between the content at saturation and at hydrostatic equilibrium for the unsaturated soil (mm)
TEQA as UEQA, but for the transpiration zone (mm)
EEQA as UEQA, but for the evaporation zone (mm).

2.2.14 The missing water from the unsaturated soil (UEQA, mm), the transpiration zone (TEQA, mm) and the evaporation zone (EEQA, mm) when the content of these compartments is at hydrostatic equilibrium

$UEQA_0$ is found by interpolation of the graph in Fig. 8 with DGT_0 as the independent variable.
The amount of missing water in the unsaturated soil at hydrostatic equilibrium is found by subtracting the water that is responsible for a change in the watertable (DELWG) from the missing water in the unsaturated soil at hydrostatic equilibrium at time t−1.

$$UEQA = UEQA_{t-1} - DT * DELWG$$

The calculation of TEQA is easy when the watertable reaches the transpiration zone. Then the missing water of the transpiration zone at hydrostatic equilibrium equals that of the unsaturated soil. When the watertable is below the transpiration zone, the missing water of the transpiration zone at hydrostatic equilibrium is the missing water of the unsaturated soil at hydrostatic equilibrium (UEQA) minus the missing water at hydrostatic equilibrium of the part of the unsaturated soil between the transpiration zone and the watertable (TGEQA) (Fig. 9c). When the soil is homogeneous the latter can be calculated using the distance between the bottom of the transpiration zone and the level of the watertable as the independent variable by interpolation of the graph in Fig. 8. EEQA is calculated in the same way as TEQA.

$$TEQA = INSW((DGT_{t-1} - DTP_{t-1}), UEQA, UEQA - TGEQA)$$
$$EEQA = INSW((DGT_{t-1} - DEP), UEQA, UEQA - EGEQA)$$

2.2.15 The deficit (UEQD, mm) and surplus (UEQS, mm) with respect to the equilibrium content of the unsaturated soil

The deficit with respect to the equilibrium content of the unsaturated soil is the content of the unsaturated soil minus the actual content.

$$UEQD = MAX(0., UEQC - U_{t-1})$$

The equilibrium surplus is the actual content of the unsaturated soil minus the equilibrium content.

$$UEQS = MAX(0., U_{t-1} - UEQC)$$

2.2.16 *The amount of the newly entered water (WT, mm)*

This is the sum of all the water that the unsatured soil has acquired at time t.

$$WT = DT * (DRU + IU + MSU + FPRU)$$

where
DT is the time interval of integration (day)
DRU is the water dripping from the vegetation onto the unsaturated soil (mm/day)
IU is the infiltration from the pools on the unsaturated soil (mm/day)
MSU is the water from the melting snow on the unsaturated soil (mm/day)
FPRU is the fluid precipitation on the unsaturated soil (mm/day).

2.2.17 *The micellar surplus (MS, mm)*

It has been determined that in the Rottegats Polder 39% of the water capacity of the clay is located between the particles of the clay minerals (Makkink & van Heemst, 1965). The flow of the water between these particles to the capillaries is a rapid process. So when the soil is drying out there is an equilibrium between these two kinds of water. The micellar surplus is the amount of water that flows to the capillaries until the amounts of water in the capillaries and between the particles of the clay minerals are in equilibrium.

$$MS = M_{t-1} - FM * TP_{t-1}$$

M_{t-1} is the content of the compartment of micellar water at time t−1 (mm)
FM is the fraction of micellar capacity of total capacity
TP_{t-1} is the content of the profile at time t−1 (mm)

2.2.18 *Water refilling the unsaturated soil (RFU, mm)*

This is the deficit of the unsaturated soil (DU) subtracted from the maximum deficit of the unsaturated soil (MDU).

$$FRU = MDU - DU$$
$$MDU = MAX(MDU, DU_{t-1})$$

The maximum deficit of the unsaturated soil is the greatest deficit in the course of the season.

2.2.19 Capacities

a *Adhering water capacity (AC, mm)*

$$AC = FRC * FAC * FWC$$

FRC is fraction of coverage of the crop, found by interpolation of the graphs in Fig. 10 or 11, with HC as the independent variable. (crop no. 1: Fig. 10, crop no. 2: Fig. 11)
HC is the height of the crop (cm)
FAC is the fraction adhering water capacity (mm/g)
FWC is the fresh weight crop (kg/m^2)
The capacity of the adhering water is calculated as a fraction of the fresh weight of the crop. According to data of Jagtenberg (1962) the capacity of the grass for adhering water is half that of the fresh weight. The fresh weight is derived from the crop height by interpolation of the graph in Fig. 12.

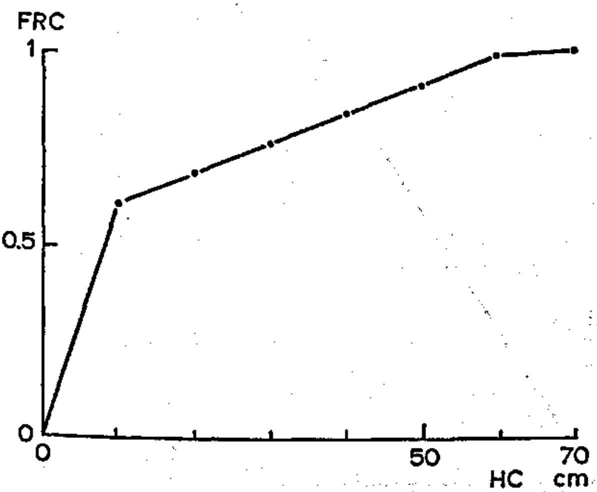

Fig. 10 | Fraction of coverage of Crop 1 in relation to crop height.

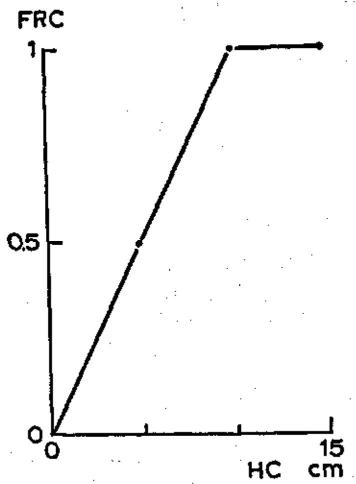

Fig. 11 | Fraction of coverage of Crop 2 in relation to crop height.

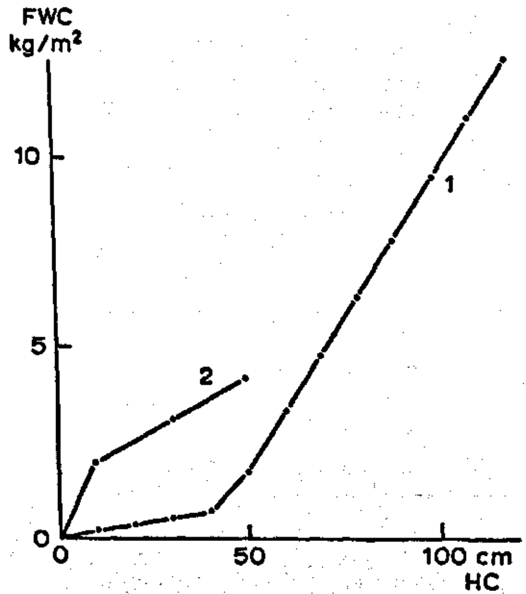

Fig. 12 | Fresh weight of the crop in relation to crop height (1 = Crop 1, 2 = Crop 2).

b *The capacity of the saturated soil (GSC), the unsaturated soil (USC), the transpiration zone (TSC) and the evaporation zone (ESC)* are found by interpolation of the graph in Fig. 27 with DBL, DGT_{t-1}, DTP_{t-1} or DEP as independent variable. The result is then increased by CIPL.
DBL is the depth of basic level (cm)
DGT_{t-1} is the depth of watertable at time t − 1 (cm)
DTP_{t-1} is the depth of transpiration zone at time t − 1 (cm)
DEP is the depth of evaporation zone (cm)

c *Capacity increase by ploughing (CIPL, mm)*
There is the possibility to include a capacity increase as a result of ploughing. On the ploughing date a number of mm are added to the capacity, which during a period of weeks gradually decreases to zero.

CIPL = MAX(0., CIPLM * (1. − (DAY − DAYPL)/DPLEF))

where
CIPLM is the maximum capacity increase by ploughing (mm)
DAY concerns day (day)
DAYPL is the day of ploughing (day)
DPLEF is the duration of the effect of ploughing (day)

d *Capacity of available moisture in unsaturated soil (UAVC, mm) and transpiration zone (TAVC, mm)* are found by interpolation of the graph in Fig. 13 with DGT_{t-1} or DPT_{t-1} as the independent variable and then increased by CIPL.
DGT_{t-1} is the depth watertable at time t − 1 (cm)
DTP_{t-1} is the depth transpiration zone at time t − 1 (cm)
CIPL is the capacity increase by ploughing (mm)

2.3 Computation of rates

For the calculation of potential evaporation of crop and wet soil a modification of the formula of Penman for open water is used, taking into account the following factors:
a the reflection coefficient of the evaporating surface,
b the surface roughness of the crop in relation to crop height and wind velocity,
c the influence of light intensity on the stomatal opening.

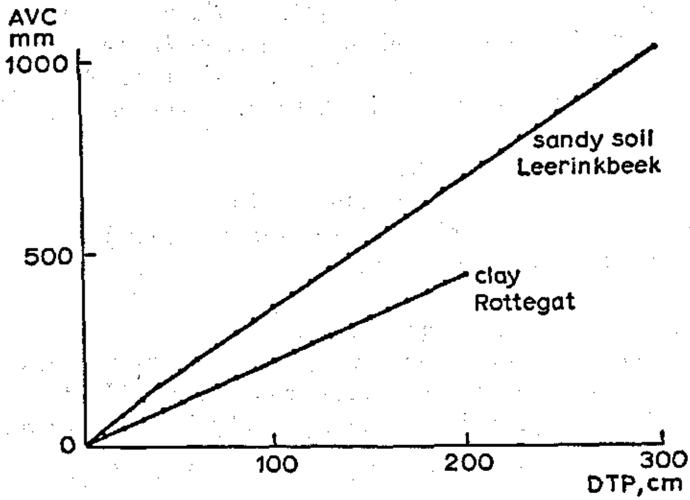

Fig. 13 | Capacity of available moisture in the soil in relation to depth.

The formula used is:

EO = (DEL * NRAD/LHV + GAM * FZO * VPD)/(DEL +
+ GAM * (1. + FZO * W * RSC))

EO is the potential evaporation (mm/day) (EOS for snow, EOA for adhering water, EOB for bare soil, PTR for vegetation)
NRAD is the net radiation (cal/(cm^2.day))
LHV is the latent heat of evaporation, equal to 590 cal/cm^3
GAM is the constant of wet and dry bulb hygrometer equation (psychrometer constant) (mm Hg/C°)
FZO is the factor related to ZO (ZO is roughness length of the evaporating surface) (cm)
W is the wind velocity at 2 m height (m/sec) (data per day)
VPD is the vapour pressure deficit (mm Hg)
RSC is the apparent diffusion resistance of the crop (h.atm/mm Hg), found by interpolation of the graph in Fig. 14 with RGINT as independent variable (Rijtema, 1965)
RGINT is the global radiation calculated per minute as intensity (cal/min.cm^2)

RGINT = RG/(DAYL * 60.)

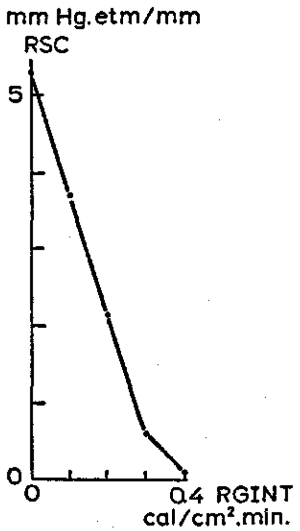

Fig. 14 | Apparent diffusion resistance of the crop in relation to radiation intensity.

RG is the global radiation (cal/(day.cm^2)) (data per day)
DAYL is daylength (h) found by interpolation of the graph in Fig. 15 with QN as the independent variable
QN is radiation outside the atmosphere (cal/(day.cm^2)) (data per day)
DEL is the slope of the curve of temperature against vapour pressure at air temperature (mm Hg/C°), found by interpolation of the graph in Fig. 16 with TEMP as the independent variable.
TEMP is the temperature average per 24 hours at 2 m height (C°) (data per day).

NRAD = IN − OUT

IN is the incoming radiation (cal/(day.cm^2))
OUT is the outgoing radiation (cal/(day.cm^2))

IN = RG * (1. − RC)

RG is the global radiation (cal/(day.cm^2)) (data per day)
RC is the reflection coefficient (RCS for snow, RCB for bare soil, RCC for a crop)

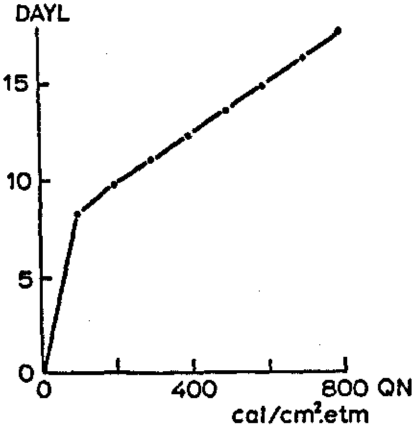

Fig. 15 | Daylength in relation to radiation outside the atmosphere.

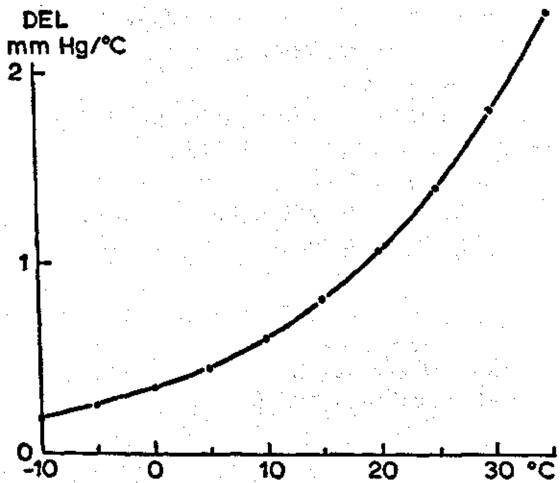

Fig. 16 | Slope of the temperature-vapour pressure curve in relation to temperature.

$$OUT = 118. * 10^{-9} * (273. + TEMP)^4 *$$
$$* (MAX(.10, (1.27 * RG/QN - .27))) * (.56 - .092 * AVP)$$

QN is the radiation outside the atmosphere (cal/(day.cm^2)) (data per day)
AVP is the actual vapour pressure (mm Hg), found by interpolation of the graph in Fig. 17 with DEWT as the independent variable
DEWT is the dew point temperature (C°) (data per day)

$$FZO = 13.65/(LOGN((200. - ZPD)/ZO))^2$$

LOGN is the natural logarithmic function
ZPD is the zero plane displacement (cm)
ZO is the roughness length of the evaporating surface (cm)

$$ZPD = H * FZPD$$

H is the height of the evaporating body (cm) (HS = height of snow, HC = height of crop)
FZPD is found by interpolation of the graph in Fig. 18 with W as the independent variable (Makkink & van Heemst, 1970)
W is the wind velocity at 2 m height (m/sec)

$$ZO = CZO * H$$

where
CZO is the constant for ZO of the evaporating body (CZOS for snow,

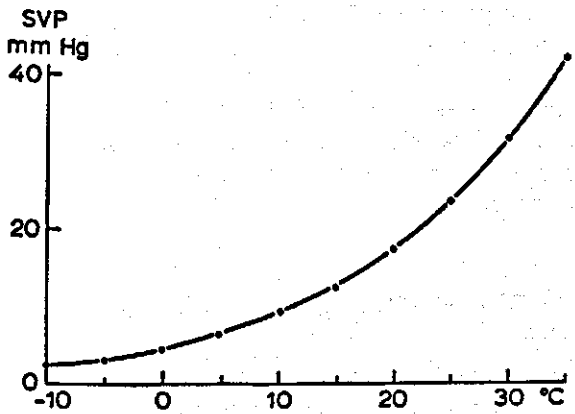

Fig. 17 | Saturated vapour pressure in relation to temperature.

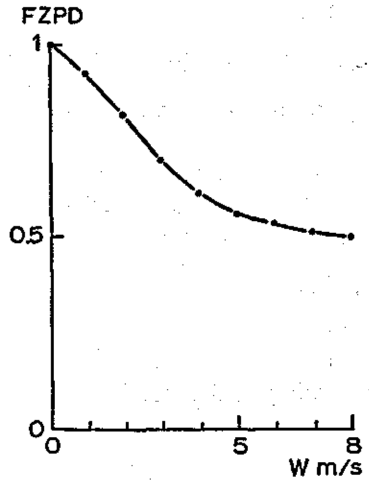

Fig. 18 | Factor of zeroplane displacement in relation to wind speed.

CZOC for a crop)

VPD = SVP − AVP

SVP is the saturated vapour pressure at air temperature (mm Hg), found by interpolation in the graph of Fig. 17, using TEMP as the independent variable
AVP is the actual vapour pressure at 2 m height (mm Hg)
TEMP is the temperature average per 24 hours at 2 m height (C°) (data per day)

For some years the local measurements of global radiation were not recorded. For these years data of the Royal Meteorological Office at The Bilt are used. The calculated potential evaporation for these years are multiplied by a place factor.

EO = PLF * EO

EO is the potential evaporation (mm/day)
PLF is the place factor

The place factor can be read from the isolines of evaporation of a free water surface which have been drawn on maps of the Netherlands. These isolines are based on monthly values of EO for some 20 places.

EO ratios will only slightly differ from R ratios. The place factor is set at 1 if the meteorological data were collected locally.

2.3.1 Evaporation of snow (ES, mm/day)

The potential evaporation of snow is also calculated according to Penman's formula (EOS).
The reflection coefficient for snow (RCS) is set at 0.80, the constant for the roughness height of the snow (CZOS) is set at 0.1, the height of the snow (HS, cm) is calculated with:

$$HS = 0.07 * S_{t-1}$$

There is only evaporation of snow if the amount of snow is sufficient to meet the calculated requirement and if there is no hoary frost (i.e. if the potential evaporation of the snow has a positive value).

$$ES = MIN(S_{t-1}/DT, MAX(0., EOS))$$

ES is the evaporation of snow (mm/day)
S_{t-1} is the content of the compartment of snow at time $t-1$ (mm)
DT is the time interval of integration (day)
EOS is the potential evaporation of snow (mm/day)

2.3.2 Evaporation of adhering water (EA, mm/day)

The potential evaporation of adhering water is again calculated according to Penman's formula (EOA).
The reflection coefficient for the crop (RCC) is set at 0.23, the constant for the roughness height of the crop (CZOC) at 0.1 and the height of the crop (HC) is given as a daily input.
When the crop does not cover the soil completely, the potential evaporation is multiplied by the fraction of the soil that is covered (FRC).

$$EOA = FRC * EOA$$

Evaporation occurs only when there is no snow.

$$IF(S_{t-1}.GT.O.)\ EA = 0.$$

i.e., when the content of the compartment for snow has a positive value, the evaporation of adhering water is zero. Otherwise the evaporation of adhering water is calculated as:

$$EA = MIN(MAX(0., MIN(AC, A_{t-1})/DT), MAX(0., EOA))$$

AC is the adhering water capacity (mm)
A_{t-1} is the content of compartment of adhering water at time $t-1$ (mm)
There is only evaporation from the adhering water if there is enough water to meet the calculated requirement. The amount of water which is allowed to evaporate is limited by the capacity.

2.3.3 Evaporation from pools (EP, mm/day)

The potential evaporation from pools is calculated according to Penman's formula (EOB).
The reflection coefficient for a wet, bare soil (RCB) is set at 0.21, the constant for the roughness height (CZOB) is not used. Here the roughness height itself (ZOB) is set at 1.0, because the height of the pools is assumed to be zero.
The evaporation takes place only from the uncovered soil, so the potential evaporation has to be multiplied by the fraction of the soil that is not covered by the crop.

$$EOB = (1. - FRC) * EOB$$

FRC is the fraction of coverage of the crop
Evaporation occurs only when there is no snow.

$$IF(S_{t-1}.GT.0.)\ EP = 0.$$

i.e. when the content of the compartment of snow has a positive value, the evaporation from pools is zero. Otherwise the evaporation of pools is calculated as:

$$EP = MIN(MAX(0., P_{t-1}/DT), MAX(0., EOB))$$

There is only evaporation from the pools if the amount of water is sufficient to meet the calculated requirement.

2.3.4 Evaporation from the unsaturated soil (ETR, mm/day)

The water lost by the unsaturated soil to the atmosphere with a crop partly covering the soil, consists of two components: that of the covered

fraction and that of the bare fraction.
The unsaturated soil is subdivided in two parts, the part in which the crop has roots (transpiration zone) and the part between this zone and the freatic level. When the soil is bare there is a division between the evaporation zone (capacity about 10 mm) which can be completely emptied by evaporation and the remainder of the unsaturated soil.
The capacity of the transpiration zone is given for each crop as a function of time.

The potential transpiration (PTR) is calculated according to Penman's formula. The reflection coefficient for the crop is set at 0.23, the constant for the roughness height of the crop (CZOC) is set at 0.1, the height of the crop are data per day.

When the crop does not cover the soil completely, the potential transpiration is multiplied by the fraction of the soil that is covered. The potential transpiration is multiplied by a maturity factor which ranges from 1.0 for a totally green crop to 0.4 for a completely dead crop. The factor does not reach the value zero because it is assumed that as the crop matures weeds will partly take over the transpiration.

$$PTR = FRC * FDC * PTR$$

FRC is the fraction of coverage of the crop
FDC is the maturity factor of the crop
Transpiration from the covered part of the soil occurs only when snow and adhering water are absent.

$$IF(S_{t-1}.GT.0..AND.\ A_{t-1}.GT.0.)\ ETA = 0.$$

S_{t-1} is the content of compartment of snow at time $t-1$ (mm)
A_{t-1} is the content of compartment of adhering water at time $t-1$ (mm)
ETA is the actual transpiration of the covered part of the soil (mm/day)
Otherwise ETA is calculated according to

$$ETA = FPTR * RPTR + MIN(PU, PTR)$$

FPTR is the reduction factor for the potential transpiration
RPTR is the remainder of PTR after part of the precipitation has evaporated (mm/day)
PU is the precipitation on the unsaturated soil (mm/day)

$$RPTR = MAX(0., PTR - PU)$$

The reduction factor FPTR is dependent on the available moisture content in the transpiration zone. Precipitation falling on a partly dried out soil, but not increasing the content of the transpiration zone to the critical value for potential use, leads to sub-potential transpiration. This is not correct, because this precipitation water is not equally distributed over the transpiration zone, but remains in the top layer of the soil, which attains a higher moisture content than the rest of the soil. The water in this wet part of the transpiration zone will be used for potential transpiration. Therefore depletion of precipitation falling on the soil has priority: irrespective of the moisture content of the soil this precipitation is used for potential transpiration. The precipitation included is related to the whole surface of the soil, because it is assumed that also with partly covered soil the roots of the crop will be able to reach the precipitation throughout the soil. When this precipitation is not sufficient for complete potential transpiration, the available content of the transpiration zone is used for the remaining transpiration.

With respect to the reduction factor FPTR, we assume that in a not fully saturated soil, there is still potential transpiration until a certain

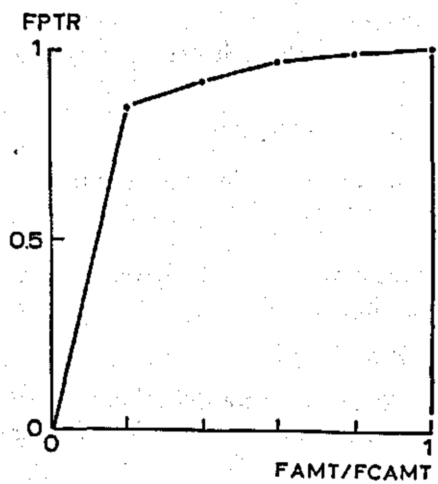

Fig. 19 | Reduction factor for transpiration in relation to the quotient of the fraction of actual and critical available moisture in the soil.

fraction of critical available moisture, which is found by interpolation of the graph in Fig. 19 with FAMT/FCAMT as the independent variable.

FAMT is the fraction of available moisture in the transpiration zone

FCAMT is the fraction of critical available moisture in the transpiration zone, found by interpolation of the graph in Fig. 20, using RPTR as the independent variable

FAMT = TAV/TAVC

TAV is the available content of the transpiration zone (mm)

TAVC is the capacity of available moisture of the transpiration zone (mm)

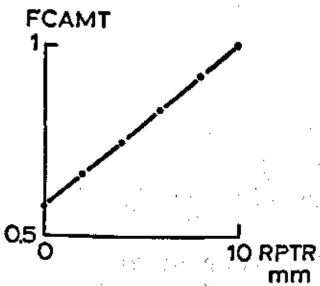

Fig. 20 | Fraction of critical available moisture in the soil in relation to the evaporation power of the atmosphere.

The actual evaporation of the uncovered part of the soil is calculated in a similar way to transpiration of the covered part of the soil. The corresponding equations have a corresponding letter.

The potential evaporation (EOB) is calculated according to Penman's formula. See evaporation from pools, Section 2.3.3.

EOB = (1. − FRC) * EOB

FRC is the fraction of coverage of the crop.

Evaporation from the bare part of the soil occurs only when snow and pools are absent.

IF(S_{t-1}.GT.0..AND.P_{t-1}.GT.0.) EBA = 0.

S_{t-1} is the content of compartment of snow at time $t-1$ (mm)
P_{t-1} is the content of compartment of pools at time $t-1$ (mm)
EBA is the actual evaporation of the uncovered part of the soil (mm/day)

Otherwise EBA is calculated according to

$$EBA = FEOB * REOB + MIN(PRB, EOB)$$

FEOB is the reduction factor potential evaporation, found by interpolation of the graph in Fig. 19 with FME/FCME as the independent variable
FME is the fraction of moisture in the evaporation zone
FCME is the fraction of critical moisture in the evaporation zone, found by interpolation in the graph of Fig. 20 with REOB as the independent variable

$$FME = E/ESC$$

E is the content of evaporation zone (mm)
ESC is the capacity of evaporation zone (mm)
REOB is the remainder of EOB after part of the precipitation has evaporated (mm/day)
PRB is the precipitation on bare part of the soil (mm/day)
EOB is the potential evaporation of the bare part of the soil (mm/day)

$$REOB = MAX(0., EOB - PRB)$$
$$PRB = MAX(0., PU - ETA)$$

where
PRB is precipitation on bare part of the soil (mm/day)
PU is precipitation on unsaturated soil (mm/day)
ETA is actual transpiration of the covered part of the soil (mm/day)

As said before, the precipitation falling on the soil is potentially used for the transpiration of the crop. Only when there is a surplus of precipitation, is there precipitation left for potential use in evaporation.

$$ETR = ETA + EBA$$

ETR is the evapotranspiration from the unsaturated soil (mm/day)
ETA is the transpiration from the unsaturated soil (mm/day)
EBA is the evaporation from the unsaturated soil (mm/day)

2.3.5 Evaporation from the saturated soil (TG, mm/day)

It is assumed that evaporation from the saturated soil only occurs when the watertable reaches the surface. Then the evaporation from the unsaturated soil becomes zero.

$$TG = INSW(DGT_{t-1}, ETR, 0.)$$
$$ETR = INSW(DGT_{t-1}, 0., ETR)$$

2.3.6 Solid precipitation (SPR, mm/day)

Solid precipitation, intercepted when the average temperature at 2 m height ≤ 0 C°, is considered to be snow. When the potential evaporation from the snow has a negative value and the average temperature at 2 m height ≤ 0 C°, the absolute value of this evaporation is considered as hoary frost.

$$SPR = SN + HF$$

where
SN is snow (mm/day)
HF is hoary frost (mm/day)

$$SN = INSW(TEMP, PR, 0.)$$

PR is measured precipitation (mm/day) (data per day)
TEMP is average temperature at 2 m height (C°) (data per day)

$$HF = INSW(TEMP, -MIN(0., EOS), 0.)$$

EOS is the potential evaporation from snow (mm/day)

2.3.7 Fluid precipitation on the vegetation (FPRV, mm/day)

Rainfall and dew occur only when the average temperature at 2 m height is above 0 C°.

$$RF = INSW(TEMP, 0., PR)$$
$$DWV = INSW(TEMP, 0., -MIN(EOA, 0.))$$

where
TEMP is average temperature at 2 m height (C°) (data per day)
RF is rainfall (mm day)

DWV is dew on vegetation (mm/day)
PR is precipitation (mm/day) (data per day)
EOA is potential evaporation of adhering water (mm/day)

$$FPRV = DWV + RF * FRC$$

FRC is the fraction of coverage of the crop

2.3.8 Fluid precipitation into the pools (FPRP, mm/day) and fluid precipitation into the unsaturated soil (FPRU, mm/day)

Dew on the bare soil or the pools occur only at temperatures above 0 C°.

$$DWB = INSW(TEMP, 0., -MIN(EOB, 0.))$$

TEMP is the temperature at 2 m height (C°) (data per day)
DWB is dew on bare soil (mm/day)
EOB is potential evaporation of the bare soil (mm/day)
The fluid precipitation falls into the pools only when the soil is saturated, otherwise it falls on the unsaturated soil.

$$FPRP = INSW(G_{t-1} - GSC, 0., DWB + RF * (1. - FRC))$$
$$FPRU = INSW(G_{t-1} - GSC, DWB + RF * (1. - FRC), 0.)$$

G_{t-1} is the content saturated soil at time t−1 (mm)
GSC is the capacity of the soil (mm)
RF is the rainfall (mm/day)
FRC is the fraction of coverage of the soil

2.3.9 Water dripping from the vegetation into the pools (DRP, mm/day) or onto the unsaturated soil (DRU, mm/day)

Dripping water from the vegetation falls into the pools only when the soil is saturated, otherwise it falls on the unsaturated soil and occurs when the temperature is above 0 C°.

$$DRV = INSW(TEMP, 0., MAX(0., (A_{t-1} - AC)/DT))$$

TEMP is the average temperature at 2 m height (C°) (data per day)
DRV is dripping water from vegetation (mm/day)
A_{t-1} is the content of compartment of adhering water (mm)
AC is adhering water capacity (mm)

DT is time interval of integration (day)

$$DRP = INSW(G_{t-1} - GSC, 0., DRV)$$
$$DRU = INSW(G_{t-1} - GSC, DRV, 0.)$$

G_{t-1} is the content saturated soil at time t−1 (mm)
GSC is the capacity of the soil (mm)

2.3.10 Surface run-off to the ditch (OFLD, mm/day)

When the content of the pools exceeds a certain capacity, it will run off to the ditch. It is assumed that this does not take place in one time interval, but with a delay with time constant of .6 day.

$$OFLD = MAX(0., (P_{t-1} - PC)/TCD)$$

P_{t-1} is the pool compartment content (mm)
PC is the pool compartment capacity (mm)
TCD is the time constant (day)

2.3.11 Underground vertical flow of water (GFL, mm/day)

The underground vertical flow of water is found by interpolation of the graph in Fig. 21, with DGT_{t-1} as the independent variable. This graph is constructed by calculating the underground vertical flow of water according to the formula of Hooghoudt but for high watertables the formula underestimates the flow, probably because of water standing above the drains. Therefore for the 1959 run the figures at high watertables were adapted. The formula of Hooghoudt (1940) is

$$S = (8.k.d.m_0 + 4.k.m_0^2)/l^2$$

S is the underground vertical flow of water (m/day)
k is the hydraulic conductivity (m/day)
m_0 is the distance between the watertable and the middle of the drains (m)
l is the distance between the drains (m)
d is the thickness of the layer in which the flow take place (m) (Hooghoudt, 1940, Table 5)

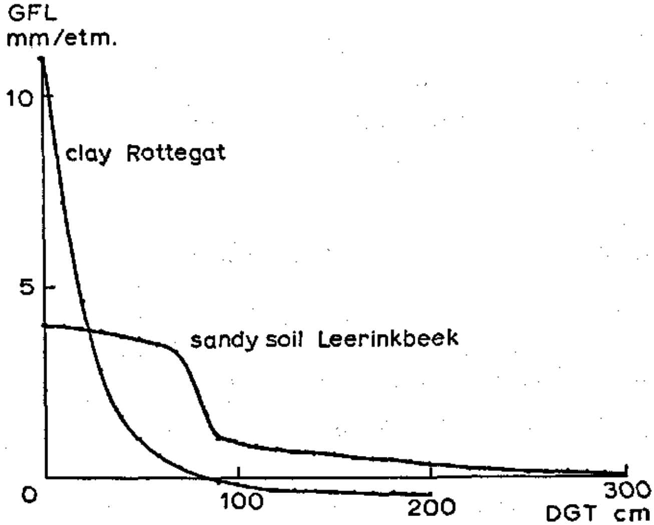

Fig. 21 | Underground vertical flow of water in relation to the depth of the watertable.

2.3.12 Infiltration from the pools into the unsaturated soil (IU, mm/day) or into the saturated soil (IG, mm/day)

The infiltration from the pools into the unsaturated soil occurs when the profile is not saturated.

$$IU = INSW(G_{t-1} - GSC, IP, 0.)$$
$$IG = INSW(G_{t-1} - GSC, 0., IP)$$

G_{t-1} is the content of the saturated soil at time $t-1$ (mm)
GSC is the capacity of the soil (mm)
IP is the infiltration from the pools (mm/day)

$$IP = MIN(KO * 10., MAX(0., P_{t-1}/TCI))$$

KO is the hydraulic conductivity of the saturated soil (cm/day)
P_{t-1} is the content of pools at time $t-1$ (mm)
TCI is time constant (day) (set at .2 day)

2.3.13 Pools created by groundwater (GP, mm/day)

$$GP = MAX(0.,(G_{t-1} - GSC)/TCG)$$

G_{t-1} is the content saturated soil at time $t-1$ (mm)
GSC is the capacity of the soil (mm)
TCG is the time constant, (day) (set at .2 day)

2.3.14 Percolation from the unsaturated soil to the saturated soil (PER, mm/day)

It was found in the Rottegats Polder that at a maximum 10% of the precipitation infiltrates immediately into the saturated soil. We, however, assume that this percolation decreases as the saturation of the soil decreases. A saturation factor (FFIL) is therefore used, which depends on the fraction of the positive difference between the content of the unsaturated soil and the content at hydrostatic equilibrium (UEQD), which is filled by precipitation. This is found by interpolation of the graph in Fig. 22 with WT/UEQD as the independent variable.

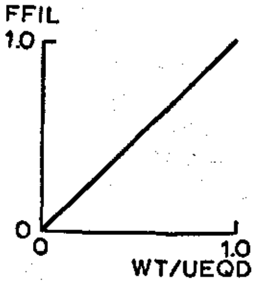

Fig. 22 | Saturation factor in relation to the fraction of the deficit that is refilled by precipitation.

$$PU = DRU + IU + MSU + FPRU$$
$$IPER = PU * FIPER * FFIL$$

IPER is the immediate percolation (mm/day)
DRU is the water dripping from the vegetation on the unsaturated soil (mm/day)

IU is the infiltration from the pools on the unsaturated soil (mm/day)
MSU is the melting water from the snow on the unsaturated soil (mm/day)
FPRU is the fluid precipitation on the unsaturated soil (mm/day)
FIPER is the factor immediate percolation (set at 0.1)
UEQD is the positive difference between the content of the unsaturated soil at hydrostatic equilibrium and the actual content (mm)
The water available for normal percolation is the amount of water above the content of the compartment at hydrostatic equilibrium. A delay is used for this water which increases when the distance to the watertable is greater. The delay corresponds with the fraction of the percolating water reaching the saturated soil in the first DT.

NPER = UEQS/TCP

NPER is normal percolation (mm/day)
UEQS is the difference between the content of the unsaturated soil and the content at hydrostatic equilibrium (mm)
TCP is the time constant (day)
TCP is the reciprocal of the interpolation of the graph in Fig. 23,with HFV as the independent variable.

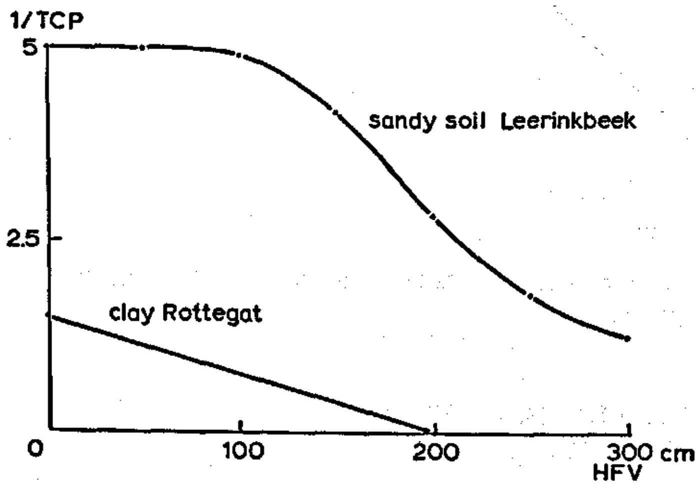

Fig. 23 | Reciprocal of the time constant for percolation in relation to the height of the collected water surplus above the watertable.

HFV is the height above the freatic level of UEQS when it is collected for saturation at the top of the profile (cm)

The distance to the freatic level (HFV) is assumed to be the distance between this level and the bottom of the layer in which the surplus water above the hydrostatic equilibrium could be distributed and saturate all the pores in that layer (Fig. 24a). Beneath the bottom of this layer the water is at hydrostatic equilibrium.

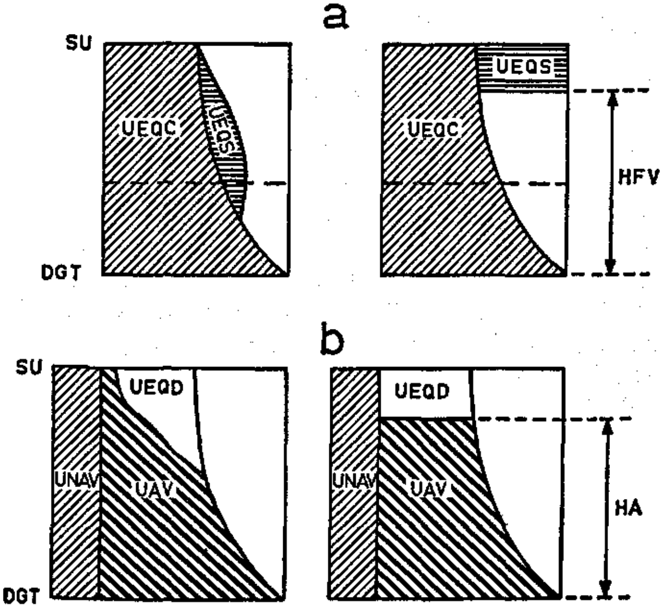

Fig. 24a | Example of how the surplus water is collected at the top of the profile to compute the height of the collected surplus water above the water-table. (SU = surface, DGT = depth of watertable, UEQC = content of the unsaturated soil at hydrostatic equilibrium, UEQS = surplus in the unsaturated soil above the content at hydrostatic equilibrium, HFV = height of the collected surplus water above the watertable).

Fig. 24b | Example of how the deficit above the deficit at hydrostatic equilibrium is collected at the top of the profile to compute the height of the collected deficit above the watertable. (UNAV = not available water in the unsaturated soil, UAV = available water content of the unsaturated soil, UEQD = deficit in the unsaturated soil above the deficit at hydrostatic equilibrium, HA = height of the collected deficit above the watertable).

HFV is found by interpolation of the graph in Fig. 8, with USC $-U_{t-1}$ as the independent variable.

USC is the capacity of the unsaturated soil (mm)
U_{t-1} is the content of the unsaturated soil (mm)

The percolation is NPER or IPER depending on whether there is a surplus above hydrostatic equilibrium or not.

PER = INSW(UEQS, IPER, NPER)

2.3.15 Capillary rise (CAP, mm/day)

The deficit that is made up filled by capillary rise is the missing water from the hydrostatic equilibrium in the unsaturated soil. This deficit is not allowed to fill up in one time interval, but a delay is used.
The delay is dependent on the distance of the dried-out zone above the freatic level. This distance is assumed to be the height of the bottom of a layer that is dried out to wilting point above the watertable. Below this layer the water is at hydrostatic equilibrium (Fig. 24b).
This height (HAINP) is found by interpolation of the graph in Fig. 25 with UAV as the independent variable.

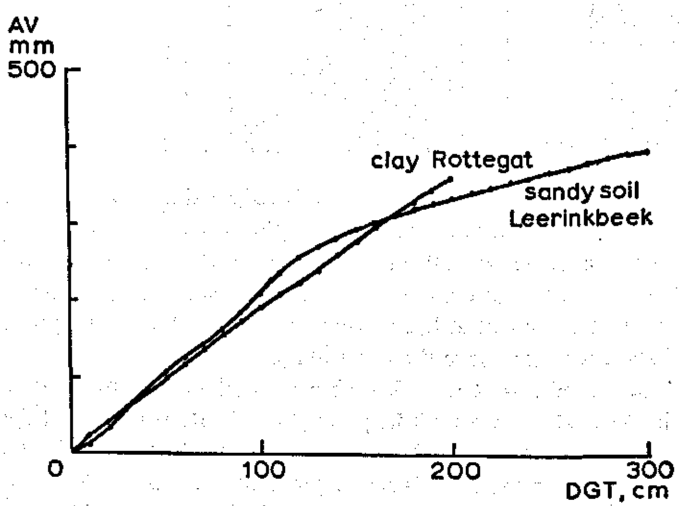

Fig. 25 | Available water in relation to the depth of the watertable.

UAV is the available water in the unsaturated soil (mm)
The capillary rise, however, only starts when the height of the dried-out zone above the watertable has exceeded a certain critical value (CHA). The rise continues, even if there is a supply of fresh precipitation, because this wets the top soil and does not alter the distance between the bottom of the dry layer and the watertable. The rise stops when the content of the unsaturated soil exceeds the content at hydrostatic equilibrium.

$$HAP = MAX(HA_{t-1}, HAINP)$$
$$HA = INSW(UEQD, 0.,(INSW(HAP-CHA, 0., HAP))$$

HA_{t-1} is the height of the missing available water that is collected from the available content at hydrostatic equilibrium, above the watertable (cm)

$$CAP = UEQD/TCC$$

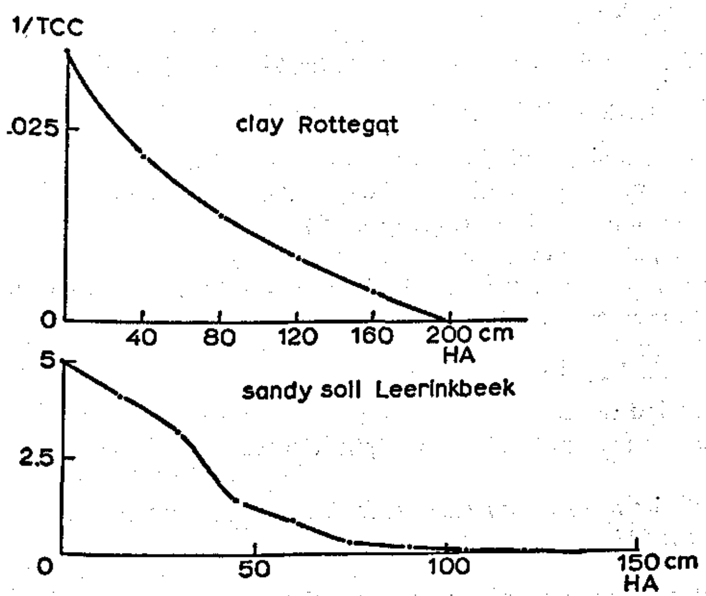

Fig. 26 | Reciprocal of the delay of capillary rise in relation to the height of the collected deficit above the watertable.

TCC is the time constant (day), the reciprocal of the interpolation of the graph in Fig. 26 with HA as the independent variable.
UEQD is the deficit in the unsaturated soil with respect to the hydrostatic equilibrium (mm)

2.3.16 Melting snow on the vegetation (MSV, mm/day)

The rate at which snow melts is determined by the amount of heat supplied. In the calculation only the heat supplied from above is assumed to be relevant. However, no more snow can melt than is present on that fraction of the crop, which covers the soil.

$$MSV = FRC * MIN(MSA, MAX(0., S_{t-1}/TCS))$$

FRC is the fraction of coverage of the crop
MSA is snow melted by heat from above (mm/day)
S_{t-1} is the content of the compartment of snow at time t−1 (mm)
TCS is the time constant (day) (set at 0.2 day)

$$MSA = MAX(0., MSHB)$$

MSHB is the melting snow according to heat balance (mm/day)

$$MSHB = (INS + COV - OUT - 59. * EOS)/8.$$

INS is the incoming radiation for snow (cal/(day.cm^2))
OUT is the outgoing radiation (cal/(day.cm^2))
COV is the convected heat (cal/(day.cm^2))
EOS is the potential evaporation snow (mm/day)
The amount of convected heat is derived from the heat exchange coefficient (Penman, 1948).

$$COV = (10.1 + 5.4 * W) * TEMP$$

W is the wind velocity at 2 m height (m/sec) (data per day)
TEMP is the temperature at 2 m height (C°) (data per day)

2.3.17 Snow melting into pools (MSP, mm/day) or onto the unsaturated soil (MSU, mm/day)

The water of the melting snow lying on the bare part of the soil will run-off to the pools when the profile is saturated, otherwise into the soil.

$$MSU = INSW(G_{t-1} - GSC, (1. - FRC) * MIN(MSA, MAX(0., S_{t-1}/TSC)), 0.)$$

$$MSP = INSW(G_{t-1} - GSC, 0., (1. - FRC) * MIN(MSA, MAX(0., S_{t-1}/TSC)))$$

G_{t-1} is the content saturated soil at time $t-1$ (mm)
GSC is the capacity saturated soil (mm)
FRC is the fraction of coverage of the soil
MSA is the melting snow with heat from above (mm/day)
S_{t-1} is the content compartment of snow at time $t-1$ (mm)
TCS is the time constant (day) (set at .2 day)

2.3.18 Dehydration (DHY, mm/day)

This is the flow of water from the micellar compartment into the capillaries. The compartments of micellar and capillar water may be compared to two communicating vessels. When extracting water from the capillar compartment, water is flowing from the micellar compartment to the capillar compartment, until the content of the two compartments are in equilibrium with each other. The amount of flowing water is the micellar surplus (MS).

$$DHY = MAX(0., MS/TC)$$

TC is the time constant (day) (set at .2)

2.3.19 Rehydration (RHY, mm/day)

The flow of water from the capillar compartment to the micellar compartment is a slow process. Rehydration occurs at a constant rate for each mm of capillar water supplied in the soil after a dry period (Makkink & van Heemst, 1965). No more water is allowed to enter the micellar compartment than this compartment may contain.

$$RHY = MAX(0., MIN(-MS/TC, RHYR * RFU))$$

$-MS$ is the micellar deficit (mm)
TC is the time constant (day) (set at .2)
RHYR is the rehydration rate (mm/(mm.day)) (set at 0.0036)
RFU is the water refilling the unsaturated soil (mm)

2.3.20 *Apparent transport of water (APTR, mm/day)*

When the watertable is falling, a layer of soil passed by the watertable, till now saturated, becomes unsaturated, because some water is removed from it. The water remaining in that layer now belongs to the unsaturated soil; before the moving of the freatic level, this water was part of the content of the saturated soil. This water itself did not move but the boundary line did. The same holds in the opposite direction. This transport is called apparent transport of water.

The saturation content of that incremental layer can be found by subtracting the capacity of the unsaturated soil at time t−1 from the capacity at time t (SCL). These capacities are found by interpolation of the graph in Fig. 27 with DGT_{t-1} or DGT_t as the independent variable.

ATPR is the apparent transport of this water in one time step minus the transport that is responsible for the change in the watertable (DELWG).

$$ATPR = SCL/DT - DELWG$$

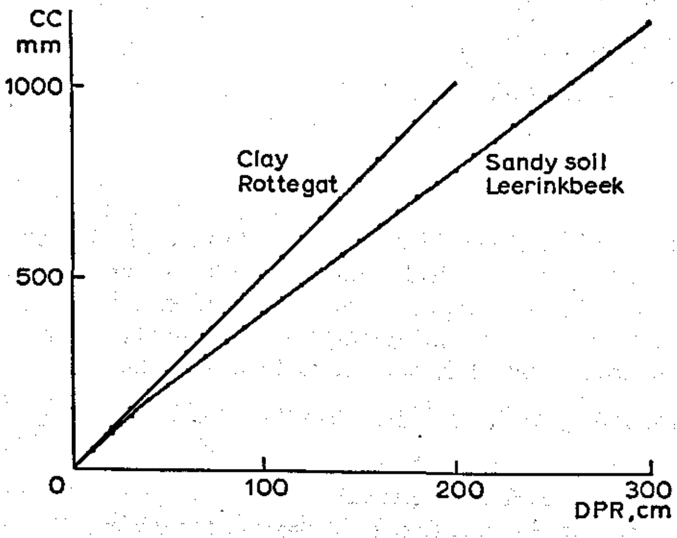

Fig. 27 | The water capacity of the soil in relation to its depth.

The water transports changing the watertable are percolation (PER), capillary rise (CAP), run-off and infiltration from below (GFL), water moving from the pools to the saturated soil (IG), water moving from the saturated soil to the pools (GP) and water evaporating from the saturated soil (TG).

DELWG = IG + PER − CAP − GP − TG − GFL

2.4 The program

The program in its final form is given on page 65, a list of names of variables and their dimensions is given on page 72. The executable part of the program is divided in sections. Constants, initial capacities and initial contents are computed in the initial part of the program.
The inputs are: the last day of the balance period of observation (DAYBP), the precipitation (ERG), the correction for the precipitation (CPR), the global radiation (RG), the radiation outside the atmosphere (QN), the place factor (PLF), the temperature (TEMP), the dew point temperature (DEWT) or the relative humidity (RH), the wind speed (W), the height of the crop (HC), the depth of the transpiration zone (DPT), the date (IDAT) and the day concerned (DAY)
In the 'Penman' section, potential evaporation and transpiration for the day are computed.
The dynamic part is passed through every DT. In this part the rates are computed: precipitation, evaporation, percolation and underground infiltration, dehydration and rehydration and subsequently the watertable, the apparent transport, the capacities and the contents.
Transfer occurs to the first statement in the dynamic section, unless the day is finished, then transfer occurs to the first statement in the input section.
To save computer time the daily run-off (RUN), the change of the moisture content of the soil at the end of the day (CUMM), the depth of the watertable at the end of the day (FREA), the daily transpiration (TRAN) and evapotranspiration (ETRA) are temporarily stored in an array (OUT). This array is printed every 15 days, which is organized in the terminal section.
At the end of a balance period are printed: the totals for the balance period of underground run-off (RUNO) and infiltration (UNDI), of surface run-off (SRUN), of evapotranspiration (EVATR), of the

change in moisture content of the soil (MOISCH) and the water content of the unsaturated soil (U1), of the saturated soil (G1), of the micellar soil (M1) and of the total profile (TP1). The depth of the watertable(DGT1), the change in moisture content of the soil from the beginning of the simulation (SMOISC) and the date are also printed. After printing-out, transfer occurs to the first statement in the input section, or when the simulation is finished to the END statement. The main program is followed by the function subroutines.

3 The evaluation of the program

3.1 Introduction

According to Wigan (1972) and van Keulen (1974), proper evaluation of models should consist of two distinct phases: calibration and validation. The calibration procedure is better described by the term curve-fitting. One set of data is used to calibrate, within reasonable limits, weak or unknown parameters or relations, to obtain the best overall agreement between simulated and observed results. Such a procedure is practically impossible if a large number of parameters have to be calibrated in this way.

In the present simulation model, calibration of a large number of parameters is not necessary because many parameters were obtained from plant physiological and physical soil measurements and hydrologic considerations. Moreover by selecting the proper year for calibration, periods can be distinguished where different parameters have decisive influence on the output. Then calibration is a relatively simple operation. At the end of the calibration the simulation program is identified with the data used.

For validation other sets of completely independent data must be used to show that the model yields correct results under different conditions. With many models this full procedure is not possible because of lack of data. Then all or parts of the same data are used in both the calibration and validation phase. Thus the most that can be concluded from the model is that historical events under a given set of conditions may be described by the generated set of equations. However, there is no guarantee at all that the dynamics of the process are correctly formulated.

Another evaluation technique is sensitivity analysis, which is most conveniently described as: a test on the relative influence of changes in input data and parameters on the relative output of models (van Keulen, 1974). Some simulation runs are done within a range of input data or parameters and the output values are compared. This is most helpful when it must be decided which subsystem should receive most attention; relations with the strongest impact on the final results should be studied most thoroughly, while those showing only little influence, may be left alone. Sensitivity analysis is often done parallel to calibration, but the results are presented separately, for convenience.

3.2 Sensitivity analysis

It is practically impossible to present results of a sensitivity analysis for all parameters and input data. In this section the influence of some of the main parameters and data is briefly analysed. Special attention is given to those characteristics that changed during the long history of the field. The outputs that are compared are mainly the change in the watertable and the evapotranspiration. The parameters that did not change during the sensitivity analysis are set at the value that gave the best overall fit at the end of the calibration procedure.

3.2.1 The pF function

Until 1959 the lysimeter plots in the Rottegats Polder were used as arable land and after that as pasture. As will be shown later the difference in waterholding capacity between arable land and pasture was at least 60 mm. With the pF function of the arable land in 1959 the run-off and evapotranspiration calculated for the pasture in 1969 were 54 mm more and 102 mm less respectively than the measured results. A calculation with a readjusted pF function for the top 25 cm of the soil resulted in 4 mm less run-off and 29 mm less evapotranspiration than the measured results. This difference reflects the influence of the improvement in structure, characterized by the pF function. It shows also that a good knowledge of this function is necessary to obtain reasonable results.
The year 1969 was very suitable for a sensitivity analysis because the summer was dry and evapotranspiration was indeed chiefly dependent on the soil water. In wet summers the evapotranspiration is mainly rainfed, so that the influence of a smaller waterholding capacity of the soil is not discovered. Indeed the calculation of run-off and evapotranspiration for the wet summer 1965 gave te same results whether the pF function for the arable land or pasture was used.

3.2.2 *Underground run-off and infiltration*

As will be shown later the physical characteristics of soil under arable land and pasture differ also in respect to underground run-off and infiltration as is illustrated in Fig. 28, where Curve 1 is given for arable land, and the points and Curve 2 for pasture. Comparison of the 1969 data with results of simulations based on the 1969 and the 1959 curves show that there are considerable differences in groundwater depths (Fig. 29a and b), but total run-off and evapotranspiration are hardly affected. The reason is that run-off is mainly determined by the depth of the watertable and therefore subject to a rapid feedback. An excessive run-off in a given time interval is followed by an excessive drop in the watertable and then followed by an extremely small run-off. Consequently another relation between run-off and watertable changes the pattern of the run-off, but not the total amount.

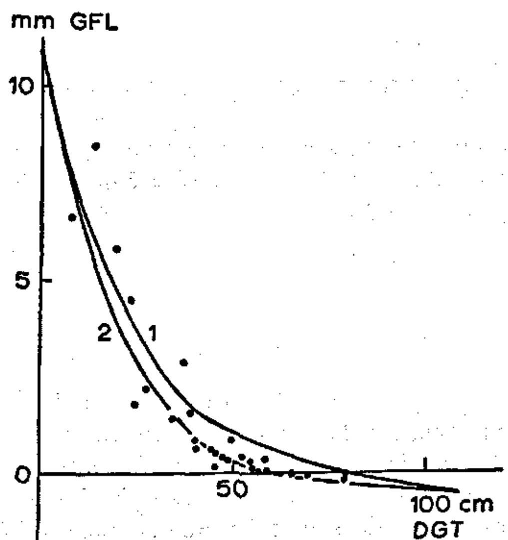

Fig. 28 | Underground flow of water in relation to the depth of the watertable. Line 1: curve for arable land, line 2: curve for pasture. The dots are observations for pasture.

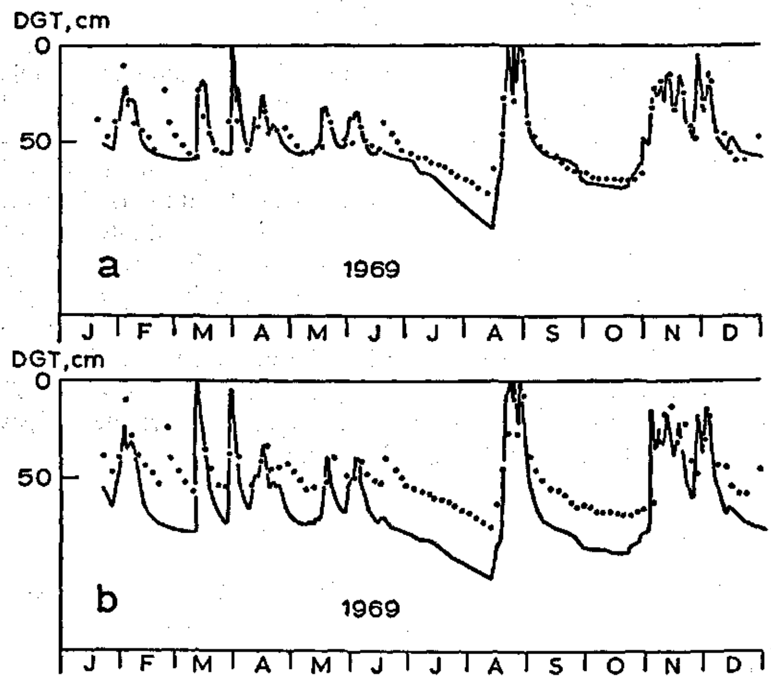

Fig. 29 | Watertable depths in 1969 for the Rottegats Polder, observed (dots) and simulated (line). a. With the curve for pasture (line 2 of Fig. 28). b. With the curve for arable land (line 1 of Fig. 28).

3.2.3 *Micellar capacity*

The fraction of micellar capacity is normally set at 0.39 but the influence of a change to 0.25 has been evaluated. Fig. 30 shows a decrease of the watertable of about 10 cm in summer. This caused a somewhat greater infiltration and a negligible change in evapotranspiration with a somewhat smaller water deficit in the soil at the end of the year 1959. With a smaller micellar fraction, the fraction of the capillaries is greater and after a drought period the soil can take up more water immediately. As a result the watertable by the end of the year was less high and run-off was decreased. The time of run-off shifted as well.

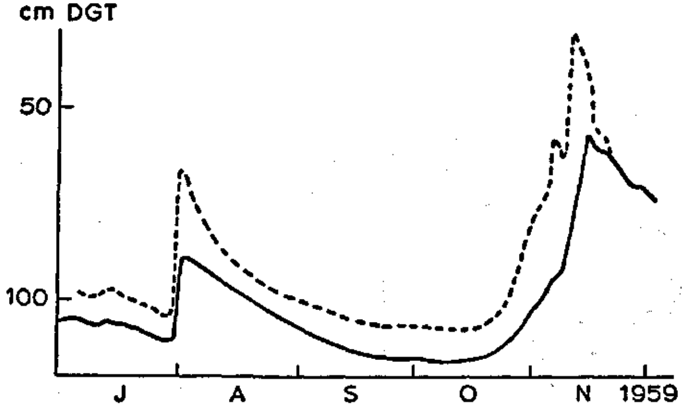

Fig. 30 | The effect of the fraction of micellar capacity on the depth of the watertable (- - - FM = 0.39, ——— FM = 0.25).

3.2.4 *The delay of capillary rise*

The delay of capillary rise is in the present program dependent on the distance between the water deficit collected in the upper layer of the soil and the watertable, but was a constant in earlier programs and then its relative influence on the results was evaluated. This factor only has effect in a dry summer. Decreasing the value causes greater infiltration because the watertable dropped and evapotranspiration increased. For instance a tenfold decrease of the delay time from 500 to 50 days in June of the year 1959, increased the evapotranspiration from 34 to 98 mm, while underground infiltration increased from 7 to 42 mm. The effect on the watertable is shown in Fig. 31.

3.2.5 *The delay of percolation*

The delay of percolation was also a constant in earlier programs and then the effect of changing from 3 into 5 or 2 days was small. A smaller delay caused a change from underground run-off to overflow in winter, because the groundwater reached the surface sooner.

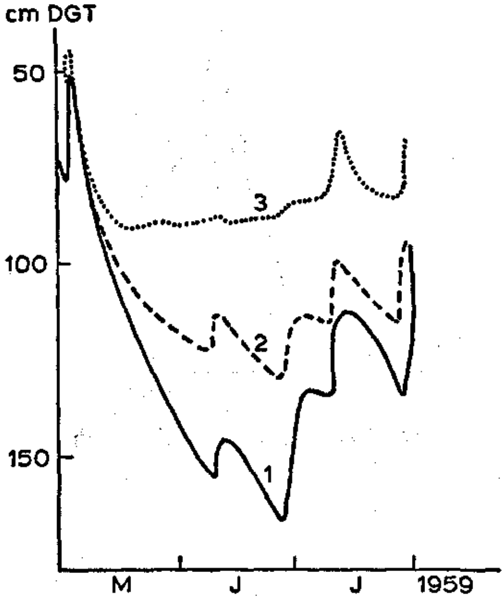

Fig. 31 | The effect of the delay of capillary rise on the depth of the watertable (1: TCC = 50 days, 2: TCC = 100 days, 3: TCC = 500 days).

3.2.6 *Ploughing*

Ploughing increases the capacity of the soil for water, but the effect is temporary. As a result the watertable receives less percolation water resulting in a slightly deeper watertable and less underground run-off. Since the effect disappears after some time, the water that is stored temporarily benefits the groundwater later but the total run-off is not affected. The effect on the terms of the water balance is therefore negligible.

3.2.7 *Frost*

In the model, precipitation during frost is indicated as snow, which results in a decrease of the watertable due to reduced percolation and underground run-off. The snow melts at the end of the frost period and due to the melting water the watertable is increased. Snow therefore affects the watertable, changes the run-off pattern, but does not affect the total run-off.

3.2.8 Depth of the transpiration zone

The transpiration zone is that layer of the soil in which the plant has roots. The effect of increasing the thickness of that layer is comparable with the effect of increasing the waterholding capacity of the subsoil as described in Section 3.2.1.

3.2.9 Coverage of the soil

An increase in winter and spring of 1965 of the fraction of coverage of the soil by the crop from 0.2 to 1.0 induced a considerable decrease of evaporation and increase of transpiration. But evaporation of a wet bare soil in winter is larger than transpiration at low light intensity of short dry grass. Therefore an increase of the coverage of the soil resulted in a decrease of the evapotranspiration, so that the watertable and the run-off increased.

3.2.10 Capacity of adhering water

An increase of the interception capacity in winter and spring of 1965 increased the evapotranspiration because evaporation of the adhering water is not limited by the stomata that are partly closed due to low light intensity. As a result the watertable and the run-off decreased.

3.3 Calibration

As said before the data recorded in 1959 in the Rottegats Polder were used to calibrate the values of various parameters and curves. In 1959 first flax and then grass and clover were grown.
First reasonable estimations of parameters were made on basis of literature and earlier reports. For calibration of parameters those periods were selected in which the relevant output depended mainly on the estimate of a specific parameter. For instance, after a long dry period when there remains little moisture in the soil, the evapotranspiration depends mainly on the water due to capillary rise; the percolation during a dry period following a shower of rain depends mainly

on immediate percolation.
The final results of the calibration process are presented in Fig. 32. The calculated changes in water content of the profile per balance period correspond well with the measured changes (Fig. 32d). The calculated and the measured run-off and underground infiltration (Fig. 32b) and the calculated evapotranspiration and that determined from the water balance experiment (Fig. 32c) deviate in January + February and November. These observations are presented by open dots. In

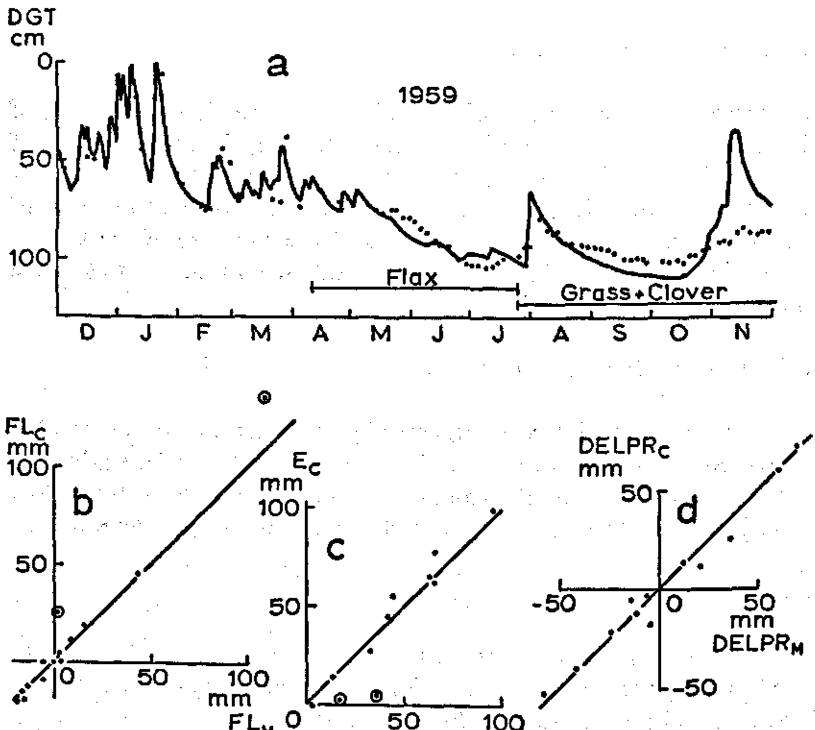

Fig. 32 | Results for the year 1959 for the Rottegats Polder. a. Simulated (line) and observed (dots) depth of the watertable, b. Simulated against observed underground flow of water, c. Simulated against observed evapotranspiration, d. Simulated against observed change of water content of the profile.

January + February evapotranspiration is 36 mm but calculated at 4 mm. The measured evapotranspiration of 36 mm is in good agreement with the evapotranspiration of 33 mm in the same period from clay lysimeters in Wageningen covered with grass.

If the simulation had been done for a soil covered with weed rather than a bare soil, transpiration values of the same magnitude, rather than 4 mm, would have been found. This might explain the difference between the measured and the calculated results, but no information on weed coverage is available.

This explanation might contradict the remarks in Section 3.2.9. There is said that in the wet winter and spring of 1965 an increase of the coverage of the soil induced a decrease of the evapotranspiration. But during a great part of January + February of 1959 no appreciable amount of rain had fallen. The total rainfall in February was only 8 mm. Through that, the upper layer of the soil was dry and evaporation was negligible. In that case a weed canopy will increase evapotranspiration.

In November the calculated evapotranspiration and the calculated supply of the groundwater are lower than the measured evapotranspiration so that the watertable is too high and there is too much underground run-off. After the very dry late summer of 1959, temperature in the autumn was fairly high and the resulting high temperature of the soil in November, also at night, may have limited condensation. Therefore actual evapotranspiration may have been higher than calculated, because the average 24-hour temperature was used as soil temperature during simulation.

The calculated watertable (Fig. 32a) is somewhat too low from August to the end of October, and is completely wrong in November. The overall results are, however, good and justify continued calculations with the calibrated parameters and curves.

The model is also calibrated for more sandy soil by means of the results obtained from the management study of the Province of Gelderland. The procedure of calibrating the parameters is the same as for the clay soil, data of 1965 being used. The crop was rye, followed by turnips. The only other data available were sowing and harvesting data, so that an estimated mean curve for the height of the crop was used. It appears that after calibration the calculated watertable is in good agreement with the measured watertable, although the calculated fluctuation is less, as demonstrated in Fig. 33. The dots are measure-

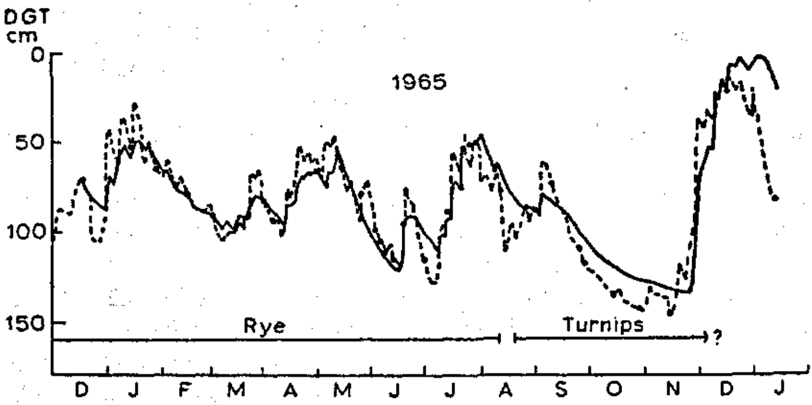

Fig. 33 | Simulated (line) and observed (dots) depth of the watertable for 1965 for the Leerinkbeek region.

ments in the field itself, the broken line is interpolated from data recorded at a distance of 100 m from the field and on a level 1.5 m below the field where the other measurements were done.
Only the change in water content of the profile is determined as a term

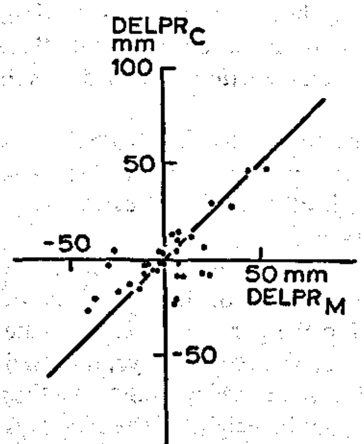

Fig. 34 | Simulated against observed change in water content of the profile for 1965 for the Leerinkbeek region.

of the water balance. There are some doubts about the precision of the measured values. In the permanent saturated layers below the lowest level of the groundwater in summer, the soil moisture content should be constant, yet there were changes in the layers on 230–270 cm of +13 to −10 mm water per balance period. Moreover the measurement of the water content at a depth of 20 cm is considered to represent the water content in the layer 0–20 cm. Hence, the agreement between calculated and measured change in water content is acceptable (Fig. 34).

3.4 Validation

The Rottegats Polder simulation was validated by comparing the simulated results with the observed results in 1958, this being the only year in which the watertable was measured and a crop other than grass was cultivated. In that year winterwheat was grown.
The results of the validation are shown in Fig. 35. The results for the watertable are in reasonable agreement but are about 5 cm too high in July through to half August (Fig. 35a). Since underground run-off is determined by the height of the watertable, the agreement between measured and simulated underground run-off and infiltration in Fig. 35b is very good. The scatter is larger in Figs. 35c and d, which concern the evapotranspiration and the change of the soil moisture. The main reason is that the experimentally determined evapotranspiration is dependent on het measured soil moisture change, which was determined gravimetrically outside the lysimeter plots. However, in general the results are in good agreement with the measurements.
The observation field was covered with grass from the year 1959 until 1964 during which time it was used for grazing and haymaking. From 1964 until the end of the experiment in 1971 it was treated as a lawn. The grass was kept very short and the cuttings stayed on the field. The year 1969 was used for validation, because it was one of the driest of the series with grass.
The results shown in Figs. 36 and 37 are disappointing. There is too much underground run-off, too little evapotranspiration and too deep a watertable. Either the model is wrong which is unlikely because of the good results for 1958, or the properties of the soil altered. The latter is most likely. The maximum water content of the profile in winter or spring above the water content at the start of the experiment in 1951 is presented against time in Fig. 38. Till 1959, the last arable

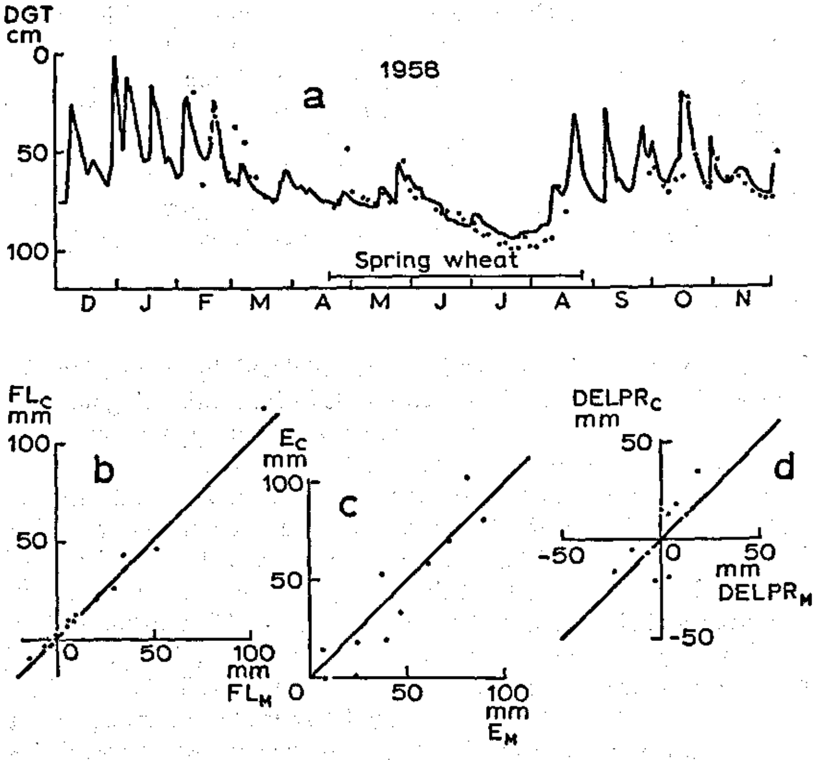

Fig. 35 | Results for the year 1958 for the Rottegats Polder. a. Simulated (line) and observed (dots) depth of the watertable, b. Simulated against observed underground flow of water, c. Simulated against observed evapotranspiration, d. Simulated against observed change of water content of the profile.

year, the values are 50 mm or less. Less, when the rain was not sufficient to refill the soil completely. From 1960, the first grass year, the values increase, and in the last years they reach a value of about 110 mm. The difference in waterholding capacity between arable and pasture land is therefore at least 60 mm and this must be reflected in a rather different pF function.

Unfortunately the experiment was terminated in 1971 so that the pF function under grass could not be determined. However, reasonable estimates can be made from the change of the waterholding capacity.

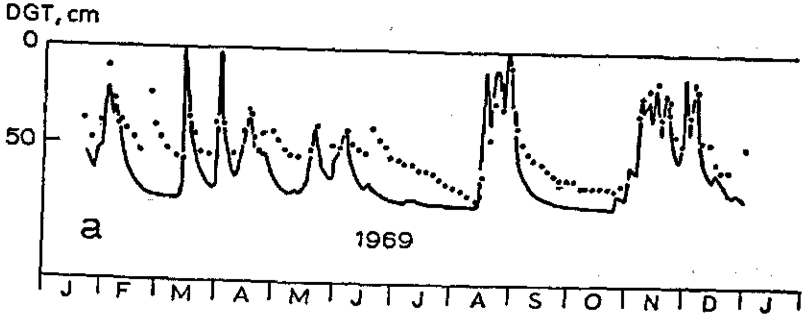

Fig. 36 | Simulated (line) and observed (dots) depth of the watertable for 1969 for the Rottegats Polder.

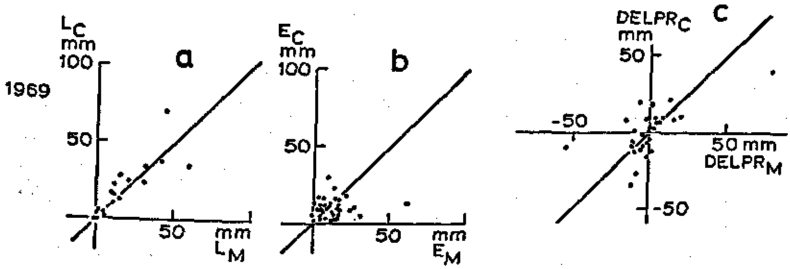

Fig. 37 | Results for the year 1969 for the Rottegats Polder. a. Simulated against observed underground flow of water, b. Simulated against observed evapotranspiration, c. Simulated against observed change of water content of the profile.

Another change concerns the run-off and infiltration. The latter changed probably because the drain tubes were partly blocked and the first because of change in soil characteristics. As for the curves for arable land those for pasture were determined by plotting measured underground run-off against measured groundwater depths as given in Fig. 28. Repeating the simulations with the new pF function for the upper 25 cm of the soil and the other curve for the underground run-off, gave a good agreement between the measured and calculated quantities of the terms of the water balance as is shown in Fig. 39. The calculated watertable is now also acceptable (Fig. 29a).

The model adjusted for the management study of the Province of

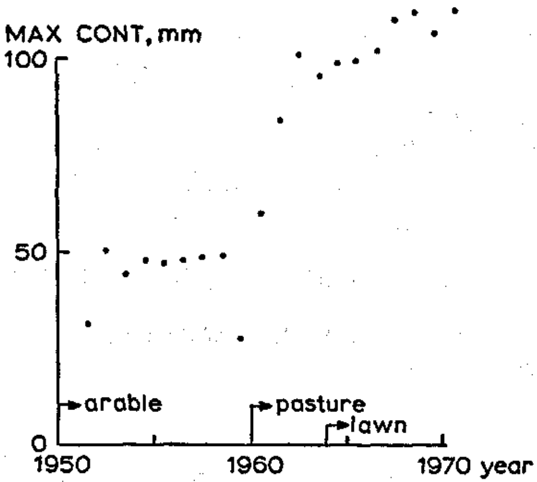

Fig. 38 | Maximum water content of the profile in winter or spring above the content at the start of the experiment from 1951 until 1971.

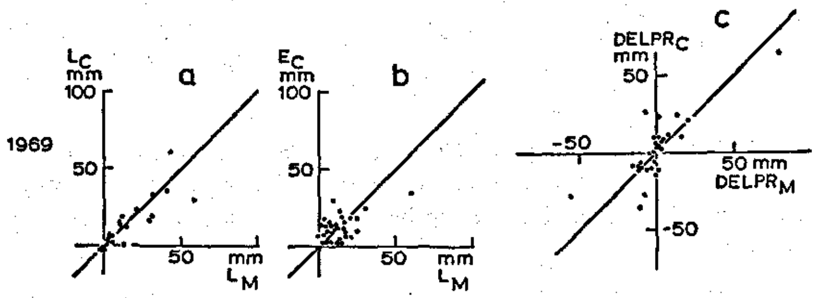

Fig. 39 | Results for the year 1969 for the Rottegats Polder with the pF function and the curve for underground flow of water for pasture. a. Simulated against observed underground flow of water, b. Simulated against observed evapotranspiration, c. Simulated against observed change of water content of the profile.

Gelderland was validated for the year 1964. The crop was oats, followed by winter rye. The results are shown in Figs. 40 and 41. The scatter in Fig. 41 where the calculated change in water content of the soil is plotted against the measured values is acceptable. The calculated watertable is somewhat too high in summer (Fig. 40).

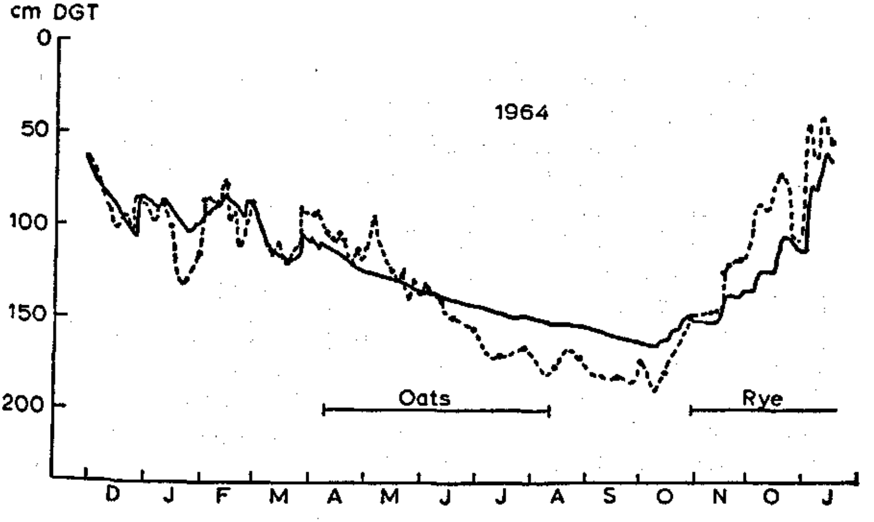

Fig. 40 | Simulated (line) and observed (dots) depth of the watertable for 1964 for the Leerinkbeek region.

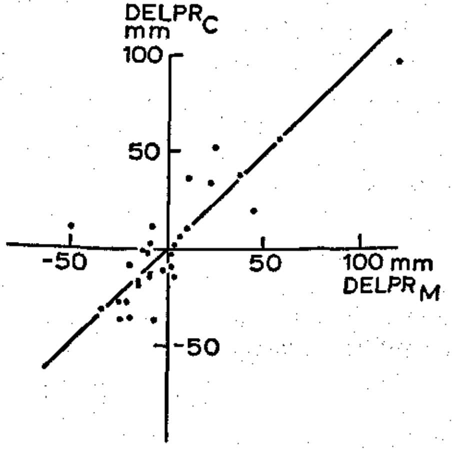

Fig. 41 | Simulated against observed change in water content of the profile for 1964 for the Leerinkbeek region.

3.5 Conclusions

To arrive at a workable simulation program it was often necessary to use simplified presentations of the physical and physiological processes that occur. Inspite of this, the validation shows that reasonable calculations of the terms of the water balance and of the depth of the groundwater may be made based on macrometeorological data, some crop characteristics and the main soil characteristics.
Although there is always room for improvement, the present program is suitable for water balance studies in catchment areas and for management purposes. Rather than measuring the evapotranspiration, water content of the soil and the watertable in a drainage basin or catchment area, its quantities may be simulated, although it is prudent to have an experimental control at crucial points. Especially measurements of the depth of the groundwater about four times a year is suitable for this purpose.

The simulation program may be used for management studies too. By simulating a large series of years, frequencies of water shortage or water surplus may be determined. The provisions that have to be made and their returns can be calculated from these frequencies. The water level in the waterways may be adjusted also on basis of the result of a simulation for the various fields in that area, or decisions for the necessity of additional sprinkling or infiltration of water may be judged.
Obviously the program is made for conditions where the groundwater may be within the reach of the roots of the crop directly or by means of capillary rise. There are many situations where this is not so. One of these is considered by van Keulen (1975), who developed a program for evaporation, evapotranspiration, water relations and crop growth under arid and semi-arid conditions. This program is described in another monograph of this series. Combination of elements of both simulation programs may lead to a program which is suitable for temporate humid climats and soils without a watertable. The development of such a program has not yet been attempted.

Program

```
      PROGRAM ROTTEGAT
C
      DIMENSION OUTP(75),FCDAT(250),ICDAT(10),KU(6)
      DIMENSION RUN(15),FREA(15),CUMM(15),TRAN(15),ETRA(15)
C
      REAL INPOL,INSN,MAX,MIN,M,MS,MDU,INS,INB,INC,MSHB,MSA,MSV,MSU,MSP, REAL
     1 IP,IU,IG,IPER,NPER,INF,MOISCH,M1,KO                              REAL
      INTEGER DAY,DAYPL,DAYPR,DAYD,DAYD1,DAYD2,DAYC2,DAYBP
C
      COMMON/DATA/ DT,RCB,RCS,TCS,DBL,GAM,PC,DAYLTB(9),VPTB(10),        COM-DT
     1DELTB(10)                                                         COM-DT
      COMMON/DATA/ AWTB(21),ACTB(21),AITB(21),SCTB(21),FFILTB(2),       COM-AWT
     1TCPTB(2),TCCTB(6),GFLTB(21),FCTTB(6),DPLEF,CIPLM,FIPER,KO,ZOB,FM, COM-AWT
     2 RHYR,CHAP,DEP,TCI,TCD,TCC,TC,TCG                                 COM-AWT
      COMMON/DATA/FRCTB1(8),FRCTB2(4),FWCTB1(13),FWCTB2(13),FDCTB(2),   CON-FRC
     1 FAC1,FAC2,RCC,CZOC,ZPDTB(9),RSCTB(5),FPTRTB(6)                   COM-FRC
      COMMON/DATA/HC1,DTP1,DGT
      COMMON/DATA/DAY,DAYPL,DAYD1,DAYD2,DAYC2,DAYPR,IA,KA,MAXI,KRV
C
      EQUIVALENCE (OUTP,RUN),(OUTP(16),CUMM),(OUTP(31),FREA),(OUTP(46), EQUIV
     1 TRAN),(OUTP(61),ETRA),(DT,FCDAT),(DAY,ICDAT)                     EQUIV
C
      DATA (DT=.2),(RCB=.09),(RCS=.8),(TCS=.2),(DBL=200.),(GAM=.485),   DT
     1 (PC=1.5), (DAYLTB=0.,8.1,9.7,11.1,12.4,13.7,15.1,16.4,17.7),     DT
     2 (VPTB=2.15,3.16,4.58,6.54,9.20,12.78,17.53,23.75,31.82,42.00),   DT
     3 (DELTB=.18,.25,.36,.45,.61,.81,1.07,1.40,1.80,2.31)              DT
      DATA (AWTB=0.,  .6, 2.1,  4.3,  6.9,  9.9, 13.2, 16.9, 20.8, 25.0, AWTB
     1 29.4, 34.0, 38.8, 43.8, 48.9, 54.1, 59.5, 65.0, 70.6, 76.4, 82.2) AWTB
      DATA (AITB=0.,21.8,42.1, 62.0, 81.5,100.6,119.4,137.8,156.0,173.9, AITB
     1191.6,209.1,226.4,243.5,260.5,277.4,294.1,310.7,327.2,343.5,359.8) AITB
      DATA (ACTB=0.,22.1,44.2, 66.3, 88.4,110.5,132.6,154.7,176.8,198.9, ACTB
     1221.0,243.1,265.2,287.3,309.4,331.5,353.6,375.7,397.8,419.9,442.0) ACTB
      DATA(SCTB=0.,50.6,101.2,151.8,202.4,253.0,303.6,354.2,404.8,455.4, SCTB
     1506.0,556.6,607.2,657.8,708.4,759.0,809.6,860.2,910.8,961.4,1012.) SCTB
      DATA (FFILTB=0.,1.),(TCPTB=1.5,0.)
      DATA (TCCTB=.0350,.0215,.0140,.0085,.0040,.0)
      DATA (GFLTB=11.,7.2,4.6,2.8,1.6,1.0,.6,.3,0.,-.2,-.4,-.5,-.6,-.6,  GFLTB
     1 -.7,4(-.8),-.9,-.9)                                              GFLTB
      DATA (FCTTB =.57,.63,.70,.83,.92,1.0)
      DATA (DPLEF=90.),(CIPLM=20.),(FIPER=.3),(KO=1.5),(ZOB=1.),(FM=.39) DPLEF
     1 ,(RHYR=.0036),(CHAP=35.0),(DEP=9.),(TCI=.2),(TCD=4.),(TCC=.2),   DPLEF
     2 (TC=.2),(TCG=3.33),                                              DPLEF
     3 (FRCTB1=0.,.61,.69,.76,.84,.91,.99,1.),(FRCTB2=0.,1.0,1.0,1.),   DPLEF
     4(FWCTB1=0.,.17,.35,.52,.70,1.65,3.20,4.74,6.30,7.87,9.40,11.,12.5) DPLEF
     5 ,(FWCTB2=0.,1.,2.,2.3,2.6,2.8,3.1,3.3,3.6,3.8,4.1,4.3,4.6)       DPLEF
      DATA (FDCTB=1.,.4),(FAC1=.3),(FAC2=.2),(RCC=.23),(CZOC=.1),       FDCTB
     1 (ZPDTB=1.,.93,.82,.70,.61,.56,.53,.51,.50),                      FDCTB
     2 (RSCTB=8.25,3.70,2.15,.60,.11),(FPTRTB=0.,.85,.92,.97,.99,1.)    FDCTB
      DATA (HC1=0.),(DTP1=0.),(DGT=50.)
      DATA (DAY=0),(DAYPL=-32),(DAYD1=209),(DAYD2=365),(DAYC2=231),     DAY
     1 (DAYPR=15),(IA=0),(KA=1),(MAXI=364),(KRV=0)                      DAY
C
C     INITIAL
C
      MAM=0.
      RUNO=UNDI=SRUN=EVATR=TRANS=MOISCH=SMOISC=0.
      CHA=CHAP
      FC=1.-FM
      FZOB=13.65/(ALOG(200./ZOB))**2
      DO 100 I=1,21
      AWTB(I)=FC*AWTB(I)
      ACTB(I)=FC*ACTB(I)
      AITB(I)=FC*AITB(I)
  100 SCTB(I)=FC*SCTB(I)
      KU(1)=4H RUN
      KU(2)=4HCUMM
      KU(3)=4HFREA
      KU(4)=4HTRAN
      KU(5)=4HETRA
C
```

```
C       CAPACITIES
C
        CIPL=MAX(0.,CIPLM*(1.-(DAY-DAYPL)/DPLEF))
        IF(DAY.LT.DAYPL) CIPL=0.
        USC=INPOL(21,SCTB,DGT,0.,200.,10.)+CIPL
        TSC=INPOL(21,SCTB,DTP1,0.,200.,10.)+CIPL
        GSCP=INPOL(21,SCTB,DBL,0.,200.,10.)
        GSC=GSCP+CIPL
        ESCP=INPOL(21,SCTB,DEP,0.,200.,10.)
        ESC=ESCP+CIPL
        UAVC=INPOL(21,ACTB,DGT,0.,200.,10.)+CIPL
        TAVC=INPOL(21,ACTB,DTP1,0.,200.,10.)+CIPL
        IF(DAY.LT.DAYC2) 101,102
  101   FRC=INPOL(8,FRCTB1,HC1,0.,70.,10.)
        FAC=FAC1
        DAYD=DAYD1
        FWC=INPOL(13,FWCTB1,HC1,0.,120.,10.)
        GO TO 103
  102   FRC=INPOL(4,FRCTB2,HC1,0.,15.,5.)
        FAC=FAC2
        DAYD=DAYD2
        FWC=INPOL(13,FWCTB2,HC1,0.,60.,5.)
  103   TIMED=DAY-DAYD
        FDC=INPOL(2,FDCTB,TIMED,0.,25.,25.)
        AC=FRC*FAC*FWC
C
C       CONTENTS
C
        UEQA=INPOL(21,AWTB,DGT,0.,200.,10.)
        TGEQA=INPOL(21,AWTB,MAX(0.,DGT-DTP1),0.,200.,10.)
        TEQA=UEQA-TGEQA
        EGEQA=INPOL(21,AWTB,MAX(0.,DGT-DEP),0.,200.,10.)
        EEQA=UEQA-EGEQA
        UEQC=USC-UEQA
        TEQC=TSC-TEQA
        EEQC=ESC-EEQA
        U=USC-UEQA
        G=GSC-USC
        M=(U+G)*FM/FC
        TP=U+G+M
        UEQD=UEQS=MS=0.
        T=U*TEQC/UEQC
        E=U*EEQC/UEQC
        UNAV=USC-UAVC
        TNAV=TSC-TAVC
        UAV=MAX(0.,U-UNAV)
        TAV=MAX(0.,T-TNAV)
        MDU=UEQA
        RFU=0.
        S=P=A=0.
C
C       INPUT
C
  199   IA=IA+1
        SDT=0.
        READ 200,DAYBP,ERG,CPR,RG,QN,PLF,TEMP,DEWT,RH,W,HC ,DTP ,IDAT,DAY
  200   FORMAT (I3,5X,F6.1,F5.2,2F6.0,F5.2,2F6.1,F5.2,F5.1,2F5.0,I7,I5)
        PR=CPR*ERG
        W=.75*W
C
C       PENMAN
C
        SVP=INPOL(10,VPTB,TEMP,-10.,35.,5.)
        AVP=INSW(KRV,RH*SVP,INPOL(10,VPTB,DEWT,-10.,35.,5.))
        VPD=SVP-AVP
        ED=W*VPD*GAM
        DEL=INPOL(10,DELTB,TEMP,-10.,35.,5.)
        FRT=DEL/59.
        DLGM=DEL+GAM
        OUT=118.E-9*((273.+TEMP)**4)*(MAX(.10,(1.27*RG/QN-.27)))*(.56-.092 OUT
       1 *SQRTF(AVP))                                                      OUT
        DAYL=INPOL(9,DAYLTB,QN,0.,800.,100.)
        RGINT=RG/(DAYL*60.)
        INS=RG*(1.-RCS)
        INB=RG*(1.-RCB)
```

```
      INC=RG*(1.-RCC)
      RTS=(INS-OUT)*FRT
      RTB=(INB-OUT)*FRT
      RTC=(INC-OUT)*FRT
      WTB=FZOB*ED
      EOB=(1.-FRC)*PLF*(RTB+WTB)/DLGN
      PEV=MAX(0.,EOB)
      WB=MAX(0.,W*(1.-.1*HC))
      COV=TEMP*(10.1+5.4*WB)
      ZOA=CZOC*HC
      IF(HC)300,300,301
 300  EOA=PTR=0.
      GO TO 302
 301  ZPD=HC*INPOL(9,ZPDTB,W,0.,8.,1.)
      FZOA=13.65/(ALOG((200.-ZPD)/ZOA))**2
      WTC=FZOA*ED
      EOA=FRC*PLF*(RTC+WTC)/DLGN
      RSC=INPOL(5,RSCTB,RGINT,0.,.4,.1)
      EOC=FRC*FDC*PLF*(RTC+WTC)/(DEL+GAM*(1.+FZOA*W*RSC))
      PTR=MAX(0.,EOC)
C
 302  SINF=SDRAI=SOFLD=SEC=SEV=SDELP=0.
C
C     DYNAMIC
C
 303  HS=.07*S
      FZOS=13.65/(ALOG((200.-HS)/ZOB))**2
      WTS=FZOS*ED
      EOS=PLF*(RTS+WTS)/DLGN
C
C     PRECIPITATION
C
      IF(TEMP)304,304,305
 304  SPR=PR-MIN(0.,EOS)
      RF=DWV=DWB=DRV=0.
      GO TO 306
 305  SPR=0.
      RF=PR
      DWV=-MIN(EOA,0.)
      DWB=-MIN(EOB,0.)
      DRV=MAX(0.,(A-AC)/DT)
 306  FPRV=DWV+RF*FRC
      FPRP=INSW(G-GSC,0.,DWB+RF*(1.-FRC))
      FPRU=INSW(G-GSC,DWB+RF*(1.-FRC),0.)
      DRP=INSW(G-GSC,0.,DRV)
      DRU=INSW(G-GSC,DRV,0.)
      MSHB=(INS+COV-OUT-59.*EOS)/8.
      MSA=MAX(0.,MSHB)
      MSV=FRC*MIN(MSA,MAX(0.,S/TCS))
      MSU=INSW(G-GSC,(1.-FRC)*MIN(MSA,MAX(0.,S/TCS)),0.)
      MSP=INSW(G-GSC,0.,(1.-FRC)*MIN(MSA,MAX(0.,S/TCS)))
      IP=MIN(KD*10.,MAX(0.,P/TCI))
      IF(DGT)307,307,308
 307  IU=0.
      IG=IP
      GO TO 309
 308  IU=IP
      IG=0.
 309  PU=DRU+IU+MSU+FPRU
C
C     EVAPORATION
C
      ES=MIN(MAX(0.,S/TCS),MAX(0.,EOS))
      EA=MIN(MAX(0.,MIN(AC,A)/DT),MAX(0.,EOA))
      EP=MIN(MAX(0.,P/DT),MAX(0.,EOB))
      IF(S.GT.0.) EA=EP=0.
      RPTR=MAX(0.,PTR-PU)
      FAMT=TAV/TAVC
      FCAMT=INPOL(6,FCTTB,RPTR,0.,10.,2.)
      FPTR=INPOL(6,FPTRTB,FAMT/FCAMT,0.,1.,.2)
      EC=FPTR*RPTR+MIN(PU,PTR)
      PRB=MAX(0.,PU-EC)
      REOB=MAX(0.,PEV-PRB)
      FME=E/ESC
```

```
      FCME=INPOL(6,FCTTB,REOB,0.,10.,2.)
      FEOB=INPOL(6,FPTRTB,FME/FCME,0.,1.,.2)
      EB=FEOB*REOB*MIN(PRB,PEV)
      IF(S.GT.0.)EB=EC=0.
      IF(P.GT.0.) EB=0.
      IF(A.GT.0.)EC=0.
      IF(DGT)314,314,313
  313 ETR=EC+EB
      TG=0.
      GO TO 315
  314 ETR=0.
      TG=EC+EB
C
  315 OFLD=MAX(0.,(P-PC)/TCD)
      IF(DGT)316,316,317
  316 GFL=GFLTB(1)+P/TCG
      GO TO 318
  317 GFL=INPOL(21,GFLTB,DGT,0.,200.,10.)
  318 GP=MAX(0.,(G-GSC)/TCC)
C
C     PERCOLATION AND UNDERGROUND INFILTRATION
C
      WT=DT*PU
      IF(UEQD)405,405,400
  400 FFIL=INPOL(2,FFILTB,WT/UEQD,0.,1.,1.)
      IPER=PU*FIPER*FFIL
      PER=IPER
      DO 401 I=1,21
      IF(UAV-AITB(I))402,401,401
  401 CONTINUE
  402 XI=I
      HAV=10.*((XI-1.)+(UAV-AITB(I))/(AITB(I)-AITB(I-1)))
      HAINP=DGT-HAV
      IF(HAINP.GT.HAM) HAM=HAINP
      HA=DGT-HAM
      IF(UEQD.GT.CHA)404,403
  403 CAP=0.
      GO TO 408
  404 CHA=0.
      TCCR=INPOL(6,TCCTB,HA,0.,100.,20.)
      CAP=UEQD*TCCR
      GO TO 408
  405 CAP=0.
      HAM=0.
      CHA=CHAP
      DO 406 I=1,21
      IF(MAX(0.,USC-U)-ANTB(I))407,406,406
  406 CONTINUE
  407 XI=I
      HFV=10.*((XI-1.)+(MAX(0.,USC-U)-ANTB(I))/(ANTB(I)-ANTB(I-1)))
      TCPR=INPOL(2,TCPTB,HFV,0.,200.,200.)
      NPER=UEQS*TCPR
      PER=NPER
C
C     DEHYDRATION AND REHYDRATION
C
  408 DHY=MAX(0.,MS/TC)
      RHY=MAX(0.,MIN(-MS/TC,RHYR*RFU))
C
C     GROUNDWATERTABLE AND APPARENT TRANSPORT
C
      DGT1=DGT
      DELGW=IG+PER-CAP-GP-TG-GFL
      UEQA=MAX(0.,UEQA-DT*DELGW)
      DO 500 I=1,21
      XI=I
      IF(UEQA-ANTB(I))501,500,500
  500 CONTINUE
  501 DGT=10.*((XI-1.)+(UEQA-ANTB(I))/(ANTB(I)-ANTB(I-1)))
      USCP=INPOL(21,SCTB,DGT,0.,200.,10.)
      SCL=USCP-(USC-CIPL)
      APTR=SCL/DT+DELGW
C
```

```
C       CAPACITIES
C
        CIPL=MAX(0.,CIPLM*(1.-(DAY-DAYPL)/DPLEF))
        IF(DAY.LT.DAYPL) CIPL=0.
        USC=USCP+CIPL
        TSC=INPOL(21,SCTB,DTP,0.,200.,10.)+CIPL
        GSC=GSCP+CIPL
        ESC=ESCP+CIPL
        UAVC=INPOL(21,ACTB,DGT,0.,200.,10.)+CIPL
        TAVC=INPOL(21,ACTB,DTP,0.,200.,10.)+CIPL
        IF(DAY.LT.DAYC2)502,503
  502   FRC=INPOL(8,FRCTB1,HC,0.,70.,10.)
        FAC=FAC1
        DAYD=DAYD1
        FWC=INPOL(13,FWCTB1,HC,0.,120.,10.)
        GO TO 504
  503   FRC=INPOL(4,FRCTB2,HC,0.,15.,5.)
        FAC=FAC2
        DAYD=DAYD2
        FWC=INPOL(13,FWCTB2,HC,0.,60.,5.)
  504   TIMED=DAY-DAYD
        FDC=INPOL(2,FDCTB,TIMED,0.,25.,25.)
        AC=FRC*FAC*FWC
C
C       CONTENTS
C
        TGEQA=INPOL(21,AWTB,MAX(0.,DGT-DTP),0.,200.,10.)
        TEQA=UEQA-TGEQA
        EGEQA=INPOL(21,AWTB,MAX(0.,DGT-DEP),0.,200.,10.)
        EEQA=UEQA-EGEQA
        UEQC=USC-UEQA
        TEQC=TSC-TEQA
        EEQC=ESC-EEQA
        U1=U
        G1=G
        M1=M
        TP1=TP
        U=U+DT*(PU+CAP+DHY+APTR-ETR-RHY-PER)
        G=G+DT*(DELGW-APTR)
        M=M+DT*(RHY-DHY)
        EV=ES+EA+EP+ETR+TG
        DELP=PU+IG-ETR-TG-GP-GFL
        TP=TP+DT*DELP
        UEQD=MAX(0.,UEQC-U)
        UEQS=MAX(0.,U-UEQC)
        MS=M-FM*TP
        IF(UEQD)506,506,505
  505   T=TEQC-UEQD
        E=EEQC-UEQD
        GO TO 509
  506   IF(UEQC)507,507,508
  507   T=TSC
        E=ESC
        GO TO 509
  508   T=U*TEQC/UEQC
        E=U*EEQC/UEQC
  509   UNAV=USC-UAVC
        TNAV=TSC-TAVC
        UAV=MAX(0.,U-UNAV)
        TAV=MAX(0.,T-TNAV)
        S=S+DT*(SPR-ES-MSV-MSP-MSU)
        A=A+DT*(FPRV+MSV-EA-DRP-DRU)
        P=P+DT*(FPRP+MSP+DRP+GP-OFLD-IU-IG-EP)
        DU=GSC-G-U
        MDU=MAX(MDU,DU)
        RFU=MDU-DU
C
        IF(GFL)600,600,601
  600   INF=-GFL
        DRAI=0.
        GO TO 602
  601   DRAI=GFL
        INF=0.
  602   SINF=SINF+DT*INF
        SDRAI=SDRAI+DT*DRAI
```

```
      SOFLD=SOFLD+DT*OFLD
      SEC=SEC+DT*EC
      SEV=SEV+DT*EV
      SDELP=SDELP+DT*DELP
      SDT=SDT+DT
      IF(SDT-1.)303,700,700
C
C     TERMINAL
C
  700 RUNO=RUNO+SDRAI
      UNDI=UNDI+SINF
      SRUN=SRUN+SOFLD
      EVATR=EVATR+SEV
      TRANS=TRANS+SEC
      MOISCH=MOISCH+SDELP
      SMOISC=SMOISC+SDELP
C
C     OUTPUT PER BALANSPERIOD
C
      IF(DAY-DAYBP)802,800,800
  800 PRINT 801,DGT1,RUNO,UNDI,SRUN,EVATR,MOISCH,SMOISC,UEQC,MDU,U1,G1,     PRINT
     1 M1,TP1,IDAT                                                          PRINT
  801 FORMAT (1H ,13F8.2,I6)
      RUNO=UNDI=SRUN=EVATR=MOISCH=TRANS=0.
  802 RUN(KA)=SINF-SDRAI-SOFLD
      FREA(KA)=DGT1
      CUMM(KA)=SMOISC
      TRAN(KA)=SEC
      ETRA(KA)=SEV
      IF(DGT-DBL)804,803,803
  803 IA=MAXI
      GO TO 806
  804 IF(DAY-DAYPR)805,807,807
  805 KA=KA+1
      IF(IA-MAXI)199,806,806
  806 KA=KA-1
C
C     OUTPUT EVERY 15 DAYS
C
  807 DO 900 I1=1,5
      I=(I1-1)*15+1
      J=I+KA-1
  900 PRINT 901,IDAT,KU(I1),(OUTP(K),K=I,J)
      PRINT 902
  901 FORMAT (1H ,I6,2X,A4,2X,15F8.2)
  902 FORMAT (/)
      DAYPR=DAYPR+KA
      KA=1
      IF(IA-MAXI)199,903,903
  903 END

      FUNCTION INPOL(N,TAB,DAT,LOW,TOP,STEP)
C
      DIMENSION TAB(25)
      REAL INPOL,LOW
C
      I=0
      TRAJ=(TOP-LOW)/STEP
      XI=(DAT-LOW)/STEP
      IF(XI)6,6,1
    1 IF(TRAJ-XI)2,2,3
    2 XI=TRAJ
    3 I=XI
      IF(I+1-N)4,5,5
    4 A=I
      A=XI-A
      IF(A)6,6,7
    5 I=N-1
    6 INPOL=TAB(I+1)
      RETURN
    7 INPOL=TAB(I+1)*(1.-A)+TAB(I+2)*A
      RETURN
      END
```

```
      FUNCTION INSW(NUMB1,NUMB2,NUMB3)
C
      REAL INSW,NUMB1,NUMB2,NUMB3
C
      IF(NUMB1)1,2,2
 1    INSW=NUMB2
      RETURN
 2    INSW=NUMB3
      RETURN
      END

      FUNCTION MAX(NUMB1,NUMB2)
C
      REAL MAX,NUMB1,NUMB2
C
      IF(NUMB1-NUMB2)1,2,2
 1    MAX=NUMB2
      RETURN
 2    MAX=NUMB1
      RETURN
      END

      FUNCTION MIN(NUMB1,NUMB2)
C
      REAL MIN,NUMB1,NUMB2
C
      IF(NUMB1-NUMB2)1,1,2
 1    MIN=NUMB1
      RETURN
 2    MIN=NUMB2
      RETURN
      END
```

List of names of variables and their dimensions

```
C      A        = ADHERING WATER CONTENT,MM
C      AC       = ADHERING WATER CAPACITY,MM
C      ACTB     = AVAILABLE CAPACITY TABLE,MM
C      AITB     = AVAILABLE CONTENT TABLE,MM
C      APTR     = APPARENT TRANSPORT OF WATER,MM/DAY
C      AVP      = ACTUAL VAPOUR PRESSURE,MM HG
C      AWTB     = ABSENT WATER TABLE,MM
C      CAP      = CAPILLARY RISE,MM/DAY
C      CHA      = CRITICAL DEFICIT OF THE DRIEDOUT ZONE ABOVE THE GROUNDWATER,MM
C      CIPL     = CAPACITY INCREASE BY PLOUGHING,MM
C      CIPLM    = MAXIMAL CIPL,MM
C      COV      = CONVECTED HEAT,CAL/(DAY,CM**2)
C      CPR      = CORRECTION FOR ERG
C      CUMM     = TABLE OF SMOISC AT THE END OF EACH DAY,MM
C      CZOC,S,B = CONSTANT FOR THE ROUGHNESS HEIGHT OF THE EVAPORATING BODY,C OF
C               = THE CROP,S OF THE SNOW,B OF THE SOIL
C      DAY      = CONCERNING DAY,DAY
C      DAYBP    = LAST DAY OF THE BALANCE PERIOD,DAY
C      DAYC2    = DAY OF SHOWING UP OF THE SECOND CROP,DAY
C      DAYD1,2  = DAY OF DYING OF THE CROP,1 FIRST CROP,2 SECOND CROP,DAY
C      DAYL     = DAYLENTH,HOURS
C      DAYLTB   = DAYLENGTH-TABLE,H
C      DAYPL    = DAY OF PLOUGHING,DAY
C      DAYPR    = DAY OF OUTPUT
C      DBL      = DEPTH OF BASIC LEVEL,CM
C      DEL,TB   = SLOPE OF THE TEMPERATURE-VAPOUR PRESSURE CURVE AT TEMPERATURE
C               = OF THE AIR,TB TABLE,MM HG/DEGREE C
C      DELWG    = TRANSPORT RESPONSIBLE FOR THE CHANGE OF THE GROUNDWATER TABLE
C               = ,MM/DAY
C      DELP     = CHANGE OF MOISTURE CONTENT OF THE PROFILE,MM/DAY
C      DEP      = DEPTH EVAPORATION ZONE,CM
C      DEWT     = DEWPOINT TEMPERATURE,DEGREE C
C      DGT,1    = DEPTH GROUNDWATER TABLE,1 AT TIME T,CM
C      DHY      = DEHYDRATION,MM/DAY
C      DPLEF    = DURATION OF THE EFFECT OF PLOUGHING,DAY
C      DRAI     = UNDERGROUND RUNOFF,MM/DAY
C      DR,P,U   = RATE OF WATER DRIPPING FROM THE VEGETATION,P INTO THE POOLS,
C               = U ON THE UNSATURATED SOIL,MM/DAY
C      DT       = TIME OF INTEGRATION,DAY
C      DTP,1    = DEPTH TRANSPIRATION ZONE,1 AT TIME T,CM
C      DU       = DEFICIT IN THE UNSATURATED SOIL,MM
C      DW,B,V   = DEW,B ON THE BARE SOIL,V ON THE VEGETATION,MM/DAY
C      E,A,B,C,P= EVAPORATION,A OF ADHERING WATER,B OF BARE SOIL,C OF THE CROP,
C      ,S,V     = P FROM POOLS,S OF SNOW, V FROM THE PROFILE,MM/DAY
C      EEQA     = MISSING WATER FROM THE EVAPORATION ZONE AT HYDROSTATIC
C               = EQUILIBRIUM,MM
C      EEQC     = CONTENT OF THE EVAPORATION ZONE AT HYDROSTATIC EQUILIBRIUM,MM
C      EGEQA    = MISSING WATER IN THE LAYER BETWEEN DEP AND DGT AT HYDROSTATIC
C               = EQUILIBRIUM,MM
C      EO,A,B,S = POTENTIAL EVAPORATION,A OF ADHERING WATER,B FROM BARE SOIL,S OF
C               = SNOW,MM/DAY
C      ERG      = PRECIPITATION IN RAINGAUGE IN ENLISH POSITION,MM/DAY
C      ESC      = CAPACITY OF THE EVAPORATION ZONE,MM
C      ETR      = EVAPOTRANSPIRATION OF THE UNSATURATED SOIL,MM/DAY
C      ETRA     = TABLE OF THE DAYLY SUM OF THE EVAPOTRANSPIRATION,MM
C      EVATR    = EVAPOTRANSPIRATION PER BALANCE PERIOD,MM
C      FAC,1,2  = FRACTION ADHERING WATER CAPACITY,1 OF CROP 1,2 OF CROP 2,MM/G
C      FC       = FRACTION OF CAPILLAR CAPACITY OF TOTAL CAPACITY
C      FCAMT    = FRACTION OF CRITICAL AVAILABLE MOISTURE IN THE TRANSPIRATION
C               = ZONE
C      FCME     = FRACTION OF CRITICAL AVAILABLE MOISTURE IN THE EVAPORATION ZONE
C      FDC      = MATURING FACTOR
C      FEOB     = REDUCTION FACTOR POTENTIAL EVAPORATION
C      FFIL,TB  = SATURATION FACTOR,TB TABLE
C      FIPER    = FACTOR IMMEDIATE PERCOLATION
C      FM       = FRACTION OF MICELLAR CAPACITY OF TOTAL CAPACITY
C      FAMT     = FRACTION OF AVAILABLE WATER IN THE TRANSPIRATIN ZONE
C      FME      = FRACTION OF MOISTURE IN THE EVAPORATION ZONE
C      FPR,P,U,V= FLUID PRECIPITATION,P INTO THE POOLS,U ON THE UNSATURATED SOIL,
C               = V ON THE VEGETATION,MM/DAY
```

```
C       FPTR      = REDUCTION FACTOR POTENTIAL TRANSPIRATION
C       FRC       = FRACTION OF COVERAGE OF THE CROP
C       FREA      = TABLE OF DGT AT THE END OF EACH DAY,CM
C       FWC,TB1-2= FRESH WEIGHT CROP,TB1 TABLE CROP 1,TB2 TABLE CROP 2,KG/M**2
C       FZOA,S    = FACTOR CONCERNING THE ROUGHNESS HEIGHT OF THE EVAPORATING
C                 = SURFACE,A OF ADHERING WATER,S OF SNOW,CM
C       G         = WATER CONTENT OF THE SATURATED SOIL,MM
C       GAM       = CONSTANT OF WET AND DRY BULB HYGROMETER EQUATION,MM HG/DEGREE C
C       GFL       = UNDERGROUND VERTICAL FLOW OF WATER,MM/DAY
C       GP        = GROUNDWATER CREATING POOLS,MM/DAY
C       GSC       = CAPACITY OF THE SOIL,MM
C       H,C,S     = HEIGHT OF THE EVAPORATING BODY,C OF CROP,S OF SNOW,CM
C       HAINP     = HEIGHT OF THE COLLECTED MISSING AVAILABLE WATER FROM THE
C                 = AVAILABLE CONTENT AT HYDROSTATIC EQUILIBRIUM,ABOVE THE
C                 = GROUNDWATER TABLE,CM
C       HAM       = MAXIMAL HAINP,CM
C       HFV       = HEIGHT ABOVE THE WATERTABLE OF THE UEOS IF IT WOULD BE
C                 = COLLECTED FOR SATURATION IN TOP OF THE PROFILE,CM
C       IA        = NUMBER OF COMPUTATED DAYS
C       IDAT      = DATE
C       IG        = INFILTRATION FROM THE POOLS INTO THE UNSATURATED SOIL,MM/DAY
C       IN,S,B,C  = INCOMING RADIATION,S FOR SNOW,B FOR BARE SOIL,C FOR CROP,
C                 = CAL/(DAY,CM**2)
C       INF       = UNDERGROUND INFILTRATION,MM/DAY
C       IP        = INFILTRATION FROM THE POOLS,MM/DAY
C       IPER      = IMMEDIATE PERCOLATION,MM/DAY
C       IU        = INFILTRATION FROM THE POOLS TO THE UNSATURATED SOIL,MM/DAY
C       KO        = HYDRAULIC CONDUCTIVITY OF THE SATURATED SOIL,CM/DAY
C       KRV       = SWITCH PARAMETER (NEG FOR USING RH,ZERO OR POSITIVE FOR USING
C                 = DEWT)
C       M         = CONTENT OF MICELLAR WATER,MM
C       MAXI      = NUMBER OF DAYS TO RUN,DAY
C       MDU       = GREATEST DEFICIT IN THE COURSE OF THE SEASON,MM
C       MOISCH    = CHANGE OF MOISTURE CONTENT OF THE PROFILE AT THE END OF THE
C                 = BALANCE PERIOD,MM
C       MS        = MICELLAR WATER SURPLUS,MM
C       MS,P,U,V  = MELTING SNOW,P INTO POOLS,U ON THE UNSATURATED SOIL,V ON THE
C                 = VEGETATION,MM/DAY
C       NPER      = NORMAL PERCOLATION,MM/DAY
C       OFLD      = SURFACE RUNOFF TO THE DITCH,MM/DAY
C       OUT       = OUTGOING RADIATION,CAL/(DAY,CM**2)
C       P         = WATER CONTENT OF THE POOLS,MM
C       PC        = POOL CAPACITY,MM
C       PER       = PERCOLATION FROM THE UNSATURATED TO THE SATURATED SOIL,MM/DAY
C       PLF       = PLACE FACTOR
C       PR        = MEASURED PRECIPITATION,MM/DAY
C       PTR       = POTENTIAL TRANSPIRATION,MM/DAY
C       PU        = PRECIPITATION ON THE UNSATURATED SOIL,MM/DAY
C       PRB       = PRECIPITATION ON THE BARE PART OF THE SOIL,MM/DAY
C       QN        = RADIATION OUTSIDE THE ATMOSPHERE,CAL/(DAY,CM**2)
C       RC,R,C,S  = REFLECTION COEFFICIENT,B FOR BARE SOIL,C FOR CROP,S FOR SNOW
C       REOB      = REMAINDER OF EVAPORATION FROM THE BARE SOIL AFTER PART OF
C                 = THE PRECIPITATION HAS EVAPORATED,MM/DAY
C       RF        = RAINFALL,MM/DAY
C       RFU       = WATER REFILLING THE UNSATURATED SOIL,MM
C       RG        = GLOBAL RADIATION,CAL/(DAY,CM**2)
C       RGINT     = INTENSITY OF GLOBAL RADIATION,CAL/(MIN,CM**2)
C       RH        = RELATIVE HUMIDITY
C       RHY       = REHYDRATION,MM/DAY
C       RHYR      = RECIPROKE OF REHYDRATION DELAY,MM/(DAY,MM)
C       RPTR      = REMAINDER OF PTR AFTER  PART OF THE PRECIPITATION HAS
C                 = EVAPORATED,MM/DAY
C       RSC       = APPARENT DIFFUSION RESISTENCE OF THE CROP,H,ATM/MM HG
C       RUNO      = UNDERGROUND RUNOFF PER BALANCE PERIOD,MM
C       S         = WATER CONTENT OF THE SNOW COMPARTMENT,MM
C       SCL       = CAPACITY OF THE SOIL LAYER BETWEEN DGT AND DGT1,MM
C       SCTB      = SATURATION CAPACITY TABLE,MM
C       SDELP     = CHANGE IN WATERCONTENT OF THE PROFILE PER DAY,MM/DAY
C       SDRAI     = DAILY SUM OF UNDERGROUND RUNOFF,MM/DAY
C       SDT       = SUM OF DT,DAY
C       SEC       = DAILY SUM OF TRANSPIRATION,MM/DAY
C       SEV       = DAILY SUM OF EVAPOTRANSPIRATION,MM/DAY
C       SINF      = DAILY SUM OF UNDERGROUND INFILTRATION,MM/DAY
C       SMOISC    = CUMULATIVE SUM OF MOISCH,MM
C       SOFLD     = DAILY SUM OF SURFACE RUNOFF,MM/DAY
```

```
C       SPR       = SOLID PRECIPITATION,MM/DAY
C       SPRE      = DAILY SUM OF PRECIPITATION,MM/DAY
C       SRUN      = SURFACE RUNOFF PER BALANCE PERIOD,MM
C       SVP       = SATURATION VAPOURPRESSURE AT TEMPERATURE OF THE AIR,MM HG
C       T         = WATER CONTENT OF THE TRANSPIRATION ZONE,MM
C       TAV       = AVAILABLE CONTENT OF THE TRANSPIRATION ZONE,MM
C       TAVC      = CAPACITY OF AVAILABLE WATER IN THE TRANSPIRATION ZONE,MM
C       TC        = TIME CONSTANT DEHYDRATION,DAY
C       TCCP      = RECIPROCAL OF THE TIME CONSTANT CAPILLARY RISE,1/DAY
C       TCD       = TIME CONSTANT OF THE SURFACE RUNOFF,DAY
C       TCG       = TIME CONSTANT OF THE GROUNDWATER CREATING POOLS,DAY
C       TCI       = TIME CONSTANT INFILTRATION FROM POOLS,DAY
C       TCPR      = RECIPROCAL TIME CONSTANT PERCOLATION,1/DAY
C       TCS       = TIME CONSTANT MELTING SNOW,DAY
C       TEMP      = 24-AVERAGE OF THE AIR TEMPERATURE AT 2 M HEIGHT,DEGREE C
C       TEQA      = MISSING WATER FROM THE TRANSPIRATION ZONE AT HYDROSTATIC
C                 = EQUILIBRIUM,MM
C       TEQC      = CONTENT OF THE TRANSPIRATION ZONE AT HYDROSTATIC EQUILIBRIUM,MM
C       TG        = EVAPORATION FROM THE SATURATED SOIL,MM/DAY
C       TGEQA     = MISSING WATER IN THE LAYER BETWEEN DPT AND DGT AT HYDROSTATIC
C                 = EQUILIBRIUM,MM
C       TIMED     = DURATION OF MATURING,DAY
C       TNAV      = UNAVAILABLE CONTENT OF THE TRANSPIRATION ZONE,MM
C       TP        = CONTENT OF THE PROFILE,MM
C       TRAN      = TABLE OF THE DAYLY SUM OF THE EVAPORATION,MM
C       TRANS     = TRANSPIRATION PER BALANCE PERIOD,MM
C       TSC       = CAPACITY OF THE TRANSPIRATION ZONE,MM
C       U         = WATER CONTENT OF THE UNSATURATED SOIL,1 AT TIME T,MM
C       UAV       = AVAILABLE CONTENT OF THE UNSATURATED SOIL,MM
C       UAVC      = CAPACITY AVAILABLE WATER IN THE UNSATURATED SOIL,MM
C       UEQA      = MISSING WATER FROM THE UNSATURATED SOIL AT HYDROSTATIC
C                 = EQUILIBRIUM,MM
C       UEQC      = CONTENT OF THE UNSATURATED SOIL AT HYDROSTATIC EQUILIBRIUM,MM
C       UEQD      = DEFICIT WITH RESPECT TO THE EQUILIBRIUM CONTENT OF THE
C                 = UNSATURATED SOIL,MM
C       UEQS      = SURPLUS WITH RESPECT TO THE EQUILIBRIUM CONTENT OF THE
C                 = UNSATURATED SOIL,MM
C       UNAV      = UNAVAILABLE CONTENT OF THE UNSATURATED SOIL,MM
C       UNDI      = UNDERGROUND INFILTRATION PER BALANCE PERIOD,MM
C       USC       = CAPACITY OF THE UNSATURATED SOIL,MM
C       VPD       = VAPOUR PRESSURE DEFICIT,MM HG
C       VPTB      = VAPOUR PRESSURE TABLE,MM HG
C       W         = WIND SPEED AT 2 M HEIGHT,M/SEC
C       WT        = AMOUNT OF NEWLY ENTERED WATER,MM
C       ZPD       = ZERO PLANE DISPLACEMENT,CM
C       ZO,A,B    = ROUGHNESS LENGHT OF THE EVAPORATING SURFACE,A ADHERING WATER,
C                 = B BARE SOIL,CM
```

Acknowledgement

The authors express their gratitude to Professor C. T. de Wit for the critical reading of the manuscript and to Mrs. Brouns for correcting it.

References

Bloemen, G. W., 1966. The calculation of evapotranspiration from groundwater depth observations. Versl. Meded. Comm. Hydr. Onderz. TNO 12, 45–71.

Braak, C. and S. W. Visser, 1941. Grondtemperatuur te Groningen. Versl. landbouwk. Onderz. 47 (9) A: 817–895.

Deij, L. J. L., 1955. Evaporation research in the Rottegatspolder (Holland). Publication no. 38 de l'Association Internationale d'Hydrologie, 237–240.

Deij, L. J. L., S. B. Hooghoudt, J. H. M. Latour, P. K. Peerlkamp, A. H. Stam, 1955. Het verdampingsonderzoek in de Rottegatspolder gedurende de jaren 1947–1952. Versl. Meded. Comm. Hydr. Onderz. TNO 2, 211–255.

Ernst, L. F., 1956. Calculation of the steady flow of ground water in vertical cross sections. Neth. J. Agr. Sci. 4: 126–131.

Forrester, J. W., 1961. Industrial dynamics. Massachusetts, New York, London.

Forrester, J. W., 1970. Urban dynamics. Massachusetts, New York, London.

Hooghoudt, S. B., 1940. Bijdragen tot de kennis van eenige natuurkundige grootheden van den grond. No. 7 Versl. landbouwk. Onderz. 46 (14) B: 515–707.

Hooghoudt, S. B., 1952. Enkele opmerkingen over de bepaling van de grondwaterberging en over het gebruik van lysimeters in verband met de voorgenomen onderzoekingen in de Rottegatspolder. Versl. Techn. Bijeenkomsten 1–6, 20–31.

Impens, I. I., D. W. Stewart, L. H. Allen Jr. & E. R. Lemon, 1966. Diffusive resistances at, and transpiration rates from leaves in situ within the vegetative canopy of a corn crop. U.S.D.A. interim rep. 66.1 research rep. 386.

Jagtenberg, W. D., 1962. Droge-stofgehalten van gras. Meded. 62 Proefstation voor de Akker- en Weidebouw, Wageningen.

Keulen, H. Van, 1974. Evaluation of Models. Proc. of the first Int. Congress Ecology, the Hague.

Keulen, H. Van, 1975. Simulation of water use and herbage growth in arid regions. Simulation Monographs, Pudoc, Wageningen.

Kraijenhoff Van De Leur, D. A., 1956. Studieopdracht Lammingafonds. Aantekening 5a.

Makkink, G. F., 1957. Graslengte en droge-stofopbrengst (with summary). Jaarboek IBS, 73–77.

Makkink, G.F., 1962. Vijf jaren lysimeteronderzoek. Versl. landbouwk. Onderz. 68.1.

Makkink, G. F. & H. D. J. Van Heemst, 1965. Uitdroging en rehydratie van een zware bebouwde kleigrond. Landbouwk. Tijdschr. 77, 77–87.

Makkink, G. F., 1965. Berekening van de evapotranspiratie uit de Rottegatspolder en uit het drainage-lysimeterveld. 15e verslag Werkcommissie voor Verdampingsonderzoek, 's-Gravenhage, Rijkswaterstaat, 80–102.

Makkink, G. F. & H. D. J. Van Heemst, 1966. Waterbalance and waterbookkeeping of regions. Versl. Meded. Comm. Hydr. Onderz. TNO 12, 90–112.

Makkink, G. F. & H. D. J. Van Heemst, 1967. De potentiële verdamping van kort gras en water. Jaarboek IBS, 89–96.

Makkink, G. F. & H. D. J. Van Heemst, 1970. De potentiële verdampingsfactor van een gewas. Meded. 417 Inst. v. Biol. en Scheik. Onderz. v. Landbouwgewassen, Wageningen.

Makkink, G. F. & H. D. J. Van Heemst, 1970. Berekening van de waterbalans van een perceel volgens de methode der dynamische digitale imitatie. Deelrapport 10 in Hydrologisch Onderzoek in het Leerinkbeekgebied. Arnhem 195–208.

Peerlkamp, P. K., 1944. Bodemmeteorologische onderzoekingen te Wageningen. Meded. Landbouwhogesch. 47 (3) 1–96.

Peerlkamp, P. K. 1955. Evaporation research with four drainage-lysimeter plots in the Rottegatspolder (Netherlands). Annual Bulletin 1955 of the international Commission on Irrigation and Drainage.

Penman, H. L., 1941. Laboratory experiments on evaporation from fallow soil. J. Agric. Sci. 31, 454–456.

Reever, R. C. & D. Kirkham, 1951. Soil anisotropy and some field methods for measuring permeability. Trans. Am. Geophys. Un. 32, 582–590.

Rijkoort, P. J., 1964. De vorstdiepte in de bodem gedurende de winter 1962–1963. W.R. 64–2, KNMI, De Bilt.

Rijtema, P. E., 1965. An analysis of actual evapotranspiration. Agric. Res. Rep. 659.

Rijtema, P. E. & A. H. Ryhiner, 1968. De lysimeters in Nederland (III). Versl. Meded. Comm. Hydr. Onderz. TNO, 14, 86–149.

Rijtema, P. E., 1969. Soil moisture forecasting. Nota ICW, Wageningen nr. 513.

Stam, A. H., 1946. Een verdampingsonderzoek in de Rottegatspolder in de gemeente Ten Boer van de provincie Groningen. Ingenieur vol. 58, no. 45.

Stam, A. H., 1952. Het verdampingsonderzoek in de Rottegatspolder. Versl. Techn. Bijeenkomsten 1–6, 13–18.

Vries, D. A. & H. J. Venema, 1954. Some considerations on the behaviour of the Piche evaporimeter. Vegetatio 5/6, 225–234.

Wigan, M. R., 1972. The fitting, calibration and validation of simulation models. Simulation 18 (5): 188–192.

Wind, G. P., 1960. Capillary rise and some applications of the theory of moisture movement in unsaturated soils. Versl. Meded. Comm. Hydrol. Onderz. TNO 5, 186–199.

Wind, R., 1958. The lysimeters in the Netherlands. Versl. Meded. Comm. Hydr.

Wijk, W. R. Van, 1963. Physics of plant environment, Amsterdam.

Wit, C. T. De & J. Goudriaan, 1974. Simulation of ecological processes. Simulation Monographs, Pudoc, Wageningen.

Although this paper appears in English, the first author wonders why scientific organizations and institutions still continue to neglect the politically neutral, precise and efficient auxilliary language Esperanto. An obligatory mastering of it for each student entering any university would put an end to the language chaos, in which French and Russian never will give way to English, and Chinese and Arabian soon will claim their places. Esperanto can replace Latin as a universal scientific language and prevent provincialism in science.