FLOCR - A simulation model for the calculation of water balance, cracking and surface subsidence of clay soils

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ABSTRACT

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In clay soils swelling and shrinkage have important consequences for water transport. The computer model FLOCR (FLOw in CRacking soils) has been developed to simulate water transport in clay soils. FLOCR simulates one-dimensional vertical water flow through the soil matrix and through the shrinkage cracks in an unsaturated clay soil profile. The model can be used to calculate the water balance, cracking and subsidence of clay soils.

Keywords: computer model, swelling and shrinking, cracking and subsidence, clay soils.

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SUMMARY

In clay soils swelling and shrinkage have important consequences for water transport. The computer model FLOCR (FLOw in CRacking soils) has been developed to simulate water transport in clay soils. FLOCR simulates one-dimensional vertical water flow through the soil matrix and through the shrinkage cracks in an unsaturated clay soil profile. The model can be used to calculate the water balance, cracking and subsidence of clay soils.

Water flow can be simulated in a soil profile consisting of up to 5 horizons with different soil physical properties. To simulate water flow, the profile is divided into compartments. For each compartment the model computes the incoming and outgoing fluxes, the volume change, the crack volume, the change in layer thickness, the pressure head, and the water content. For the complete soil profile, the model computes the total crack volume, the surface subsidence, the bypass flow, the groundwater level, the drain discharge, the actual evapotranspiration and the surface runoff.

The required input data for the model consist of soil properties (e.g. water retention curve, hydraulic conductivity curve, shrinkage characteristic), values for the upper boundary condition (precipitation, potential evapotranspiration) and values for the lower boundary condition (e.g. drain intensities, flux to the deep aquifer). The output is organized in such a way to enable data processing and drawing of graphs with spreadsheet programs.

1 INTRODUCTION

The volume of the soil matrix in a clay soil decreases upon drying. In the field, this process results in shrinkage cracks and in subsidence of the soil surface. Upon wetting, the soil matrix swells, the cracks close and the soil surface moves upward again. This process of the alternate swelling and shrinkage of clay soils has significant consequences.

In agricultural soils, the foremost consequence is the rapid transport of water through the cracks: bypass flow. Part of rain water or irrigation water and dissolved fertilizers flows through these cracks to the deeper subsoil which may lead to drought damage and nutrient deficiency. Significantly this process results in the inevitable consequence of leaching of solutes via cracks to the subsoil and tile drains, contributing to pollution of groundwater and surface water. There are however some favourable effects of swelling and shrinkage. Deep penetration of relatively large amounts of irrigation water in clay soils is possible by shrinkage cracks, whereas in the absence of cracks, very little water would infiltrate in the topsoil. More difficult to observe, yet equally important, is the favourable effect of swelling and shrinkage on the genesis of soil structure.

In civil engineering practice, the vertical movements of the soil are of vital importance. The destruction of buildings, pavements and other constructions situated on heavy clay soils is a well known phenomenon. Furthermore, the occurence of shrinkage cracks is largely as a result of the unwanted transport of water through clay liners above or below waste disposal sites.
The computer simulation model FLOCR has been developed to calculate the water balance, the cracking and the subsidence of clay soils. The phenomena mentioned in the previous paragraph can be calculated and evaluated using this model. FLOCR is a one-dimensional model that calculates the water balances of clay soils producing at the end of each time step: the pressure head, the water content, the crack volume and the compartment thickness of each soil compartment. For the soil as a whole it can produce computations of the surface subsidence, the total crack volume, the groundwater level, the drain discharge, the matrix infiltration, the bypass flow, the surface runoff and the actual evapotranspiration.

2 PRINCIPLES OF FLOCR

The one dimensional model FLOCR is based on the rigid-soils model FLOWEX (Buitendijk, 1984). The adjustments of FLOWEX to enable calculations to be made in swelling and shrinking soils are not restricted to FLOWEX and can, in principle, be applied to any one dimensional simulation model for water transport in the unsaturated zone. The procedure for adapting existing "rigid soil" models for the calculation of water balance, cracking and subsidence of swelling and shrinking clay soils can be summarized as follows (Bronswijk, 1988) (Fig. 1):

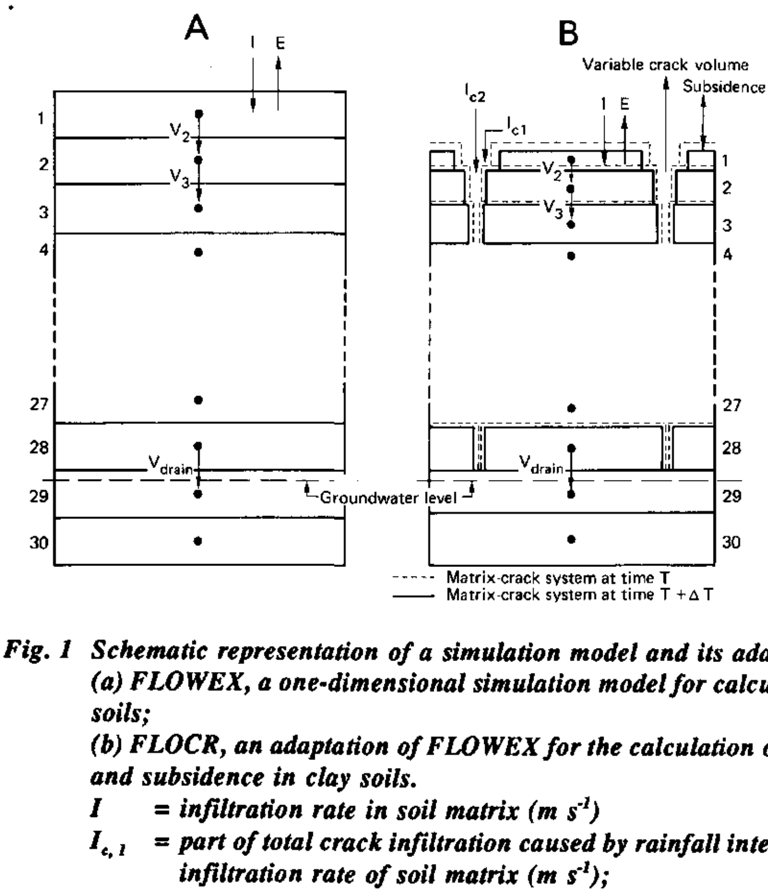

***Fig. 1** Schematic representation of a simulation model and its adapted version*
(a) FLOWEX, a one-dimensional simulation model for calculation of water balance of soils;
(b) FLOCR, an adaptation of FLOWEX for the calculation of water balance, cracking and subsidence in clay soils.
I = infiltration rate in soil matrix ($m\ s^{-1}$)
$I_{c,1}$ = part of total crack infiltration caused by rainfall intensity exceeding maximum infiltration rate of soil matrix ($m\ s^{-1}$);
$I_{c,2}$ = part of total crack infiltration caused by rainfall directly into the cracks ($m\ s^{-1}$);
E = actual evapotranspiration ($m\ s^{-1}$);
V = Darcy flux between two nodal points ($m\ s^{-1}$);
V_{drain} = drain discharge ($m\ s^{-1}$). Matrix-crack system at time T is indicated by a broken line, matrix-crack system at time T + ΔT is indicated by a solid line.

- The soil is divided into soil matrix and cracks.
- The rainfall is divided into matrix infiltration and crack infiltration.
- The crack infiltration is added to the bottom of the cracks, and to the water content of the soil matrix at that depth.
- The matrix infiltration is added to the top compartment of the soil matrix.

- The vertical water flow between the compartments of the soil matrix and the resulting h(z), θ(z) and k(z) profiles of the soil matrix is calculated in the same manner as in the original "rigid soils" model, in this case FLOWEX. The distances between nodal points are held constant within one time step but are adapted when the next time step starts.
- The shrinkage characteristics can be used to give the new θ(z) profile a new volume of soil matrix at each depth.
- The dimensionless geometry factor r_s can be used to convert, volume changes of the soil matrix into volume changes of the thicknesses and the cracks of the compartments at each depth.
- This procedure is repeated in the next time step.

The soil profile is divided into 30 numerical compartments at the maximum. FLOCR is also applicable to soils with several soil horizons. A single soil profile may contain up to 5 different horizons with different soil physical properties such as water retention curve, k(h) relation etc. In the following, the principles of FLOCR will be outlined briefly.

2.1 Unsaturated flow through the soil matrix

Combining the Darcy-equation and the continuity equation gives:

$$\frac{\partial\theta}{\partial t} = \frac{\partial}{\delta z}\left[k(h)\left(\frac{\partial h}{\partial z}+1\right)\right] \qquad (1)$$

with:
θ = Volumetric water content
t = Time (s)
h = Pressure head (cm)
z = Distance (cm)
k(h) = Hydraulic conductivity ($cm.d^{-1}$)

In FLOWEX and FLOCR, the exponential relation between k(h) en h, $k(h)=k_0.e^{\alpha h}$, with k_0 being the saturated hydraulic conductivity, is the basis for an integrated solution of the Darcy-equation (Wind and Van Doorne, 1975), describing vertical water flow between two points in the soil , i and i-1 :

$$v = -\frac{k_i - k_{i-1}}{e^{\alpha\Delta Z}-1} - k_{i-1} \qquad (2)$$

with :
v = Water flow ($cm.d^{-1}$)
α = Soil constant (cm^{-1})

2.2 Calculation of subsidence and cracking

The shrinkage characteristic is defined here as the relationship between moisture ratio (volume of moisture/volume of solids) and void ratio (volume of voids/volume of solids) of the soil. Introducing the shrinkage characteristic of a soil into model calculations allows each soil compartment to have its own relationship with water content, pressure head, hydraulic conductivity and matrix volume. The shrinkage characteristic is described by a table of points. An example of a shrinkage characteristic is presented in Figure 2. Each water content change (in comparison with saturation) in the model can be converted into a volume change of the soil matrix ΔV using the shrinkage characteristic. ΔV can then be converted into a change in compartment thickness and a change in crack volume (Bronswijk, 1989) by:

$$\Delta z = z_1 - \left[\left(\frac{V2}{V1}\right)^{\frac{1}{r_s}}\right] z_1 \tag{3}$$

$$\Delta V_{cr} = \Delta V - z_1^2 \, \Delta z \tag{4}$$

with:
ΔV = Change in soil matrix volume (m^3)
Δz = Change in compartment thickness due to shrinkage (m)
ΔV_{cr} = Change in crack volume (m^3)
V_1, V_2 = Volume of cube of soil matrix at saturation and after shrinkage (m^3)
z_1 = Compartment thickness at saturation (m)
r_s = Geometry factor (-)

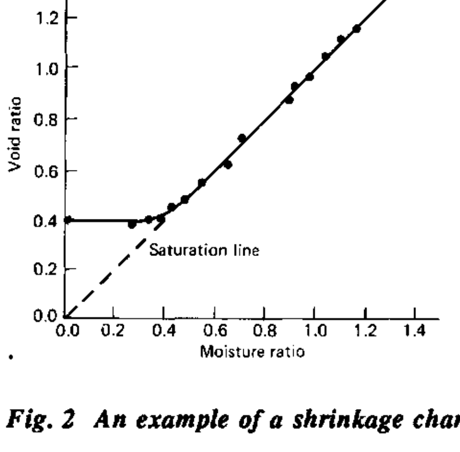

Fig. 2 An example of a shrinkage characteristic of soil aggregates

The dimensionless geometry factor r_s determines the partition of total volume change over change in compartment thickness and change in crack volume. For three dimensional isotropic shrinkage: $r_s = 3$, for one dimensional subsidence: $r_s = 1$. Factor r_s depends on sedimentation, development stage, water content and load. For most well developed soils, $r_s = 3$. Surface subsidence and total crack volume of the soil are calculated by adding up the changes in compartment thicknesses and crack volumes of the individual soil compartments.

2.3 Boundary condition at the top of the soil profile

The water balance of the soil surface within one timestep is as follows:

$$S = (P - E) - R - V \tag{5}$$

With :
V = Flux through the soil surface with: $V = V_{matrix} + V_{crack}$ (m)
S = Storage of water at soil surface (thickness of the pool) (m)
P = Precipitation (m)
E = Actual Evapotranspiration (m)
R = Runoff (m)

2.3.1 Evapotranspiration

In FLOCR, water extraction from the soil profile by evapotranspiration is limited to the top compartment. The model is therefore suitable for bare soils and shallow rooted crops. When the top compartment dries, evapotranspiration is reduced in the following way:

$$\begin{aligned} &\text{For } h > a \quad E_r = E_p \\ &\text{For } h < a \quad E_r = E_p \left(1 + \frac{h - a}{\frac{1}{b} + a}\right) \end{aligned} \tag{6}$$

in which:
E_p = Potential evapotranspiration (input) (cm.d^{-1})
E_r = Reduced evapotranspiration (cm.d^{-1})
h = Pressure head of the top compartment (cm)
a = Pressure head above which $E_r = E_p$ (cm) (in the present model a = -320 cm)
b = Soil parameter (cm^{-1}). The value - 1/b describes the pressure head which below no water is extracted from the soil profile.

In Figure 3 an example of the reduction of evapotranspiration dependant on soil water pressure head is presented.

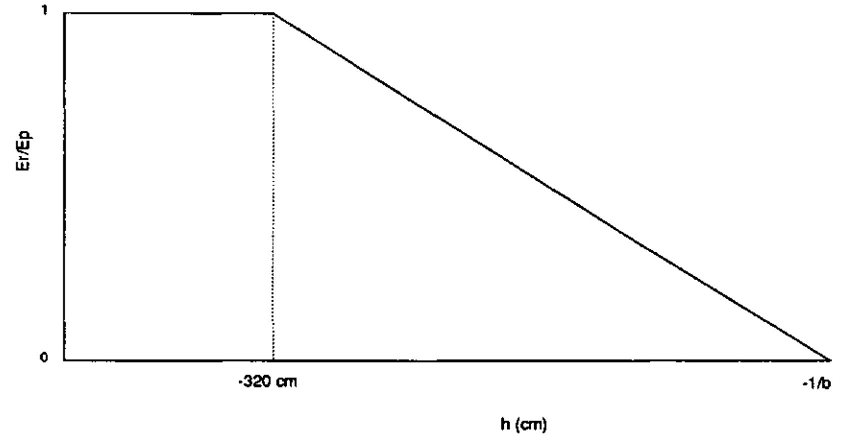

Fig. 3 The reduction of the evapotranspiration

2.3.2 Surface runoff

Surface runoff is only possible when cracks are closed. When cracks are closed runoff occurs after a certain threshold value (i.e. maximum surface storage) is exceeded.

$$R = S - S_{max} \tag{7}$$

in which:

R = Surface runoff (cm)
S = Computed storage of water at soil surface (cm)
S_{max} = Maximum storage of water at soil surface (cm)

2.3.3 Infiltration into matrix and cracks

When rain water reaches the surface of a cracked clay soil, part of the water infiltrates into the soil matrix and part of it flows into the cracks. Therefor adaptation of the top boundary condition of simulation models is necessary. The water content of the top compartment generally, of simulation models, corresponds with a certain maximum infiltration rate into the soil. When rainfall exceeds this maximum, surface runoff occurs. A similar procedure can be used to calculate the bypass flow of cracked soils: when rainfall exceeds the maximum infiltration rate of soil matrix, water flows into the cracks. In addition, a certain amount of rain falls directly in the cracks. Surface runoff only occurs when cracks are closed. Matrix infiltration and crack infiltration at a given rainfall intensity can be calculated as follows:

$$\begin{aligned} - P < I_{max} : I &= A_m * P \\ I_c &= A_c * P \\ - P > I_{max} : I &= A_m * I_{max} \\ I_{c,1} &= A_m * (P - I_{max}) \end{aligned} \tag{8}$$

$$I_{c,2} = A_c * P$$
$$I_c = I_{c,1} + I_{c,2}$$

in which:

P = Rainfall intensity ($m.s^{-1}$)
I_{max} = Maximum infiltration rate of soil matrix ($m.s^{-1}$)
I = Infiltration rate in soil matrix ($m.s^{-1}$)
I_c = Infiltration rate in cracks (bypass flow) ($m.s^{-1}$)
A_m,A_c = Relative areas of soil matrix and cracks respectively (-)
$I_{c,1}$ = The part of total crack infiltration caused by rainfall intensity exceeding maximum infiltration rate of soil matrix ($m.s^{-1}$)
$I_{c,2}$ = The part of total crack infiltration caused by rain falling directly into the cracks ($m.s^{-1}$)

Defined in this way, all infiltration rates are based on total surface area.

2.3.4 Calculation of maximum infiltration rate

When infiltration occurs, the pressure head at the soil surface is 0, therefore $k = k_0$. At the top nodal point, $k = k(h1)$. Then I_{max} is equal to the maximum possible flux between the soil surface and the top nodal point. This flux is calculated with equation 2.

2.4 Boundary condition at the bottom of the soil profile

2.4.1 Ground water level above drainage system

The boundary condition at the bottom of the soil profile is defined by a flux to the open water system (V_d) via drains and a flux to the underlying aquifer (V_a) (Van Bakel, 1986) :

$$V_b = V_d + V_a \qquad (9)$$

in which :
V_b = bottom boundary flux ($cm.d^{-1}$)
V_d = flux to the open water system via drains ($cm.d^{-1}$)
V_a = flux to the aquifer ($cm.d^{-1}$)

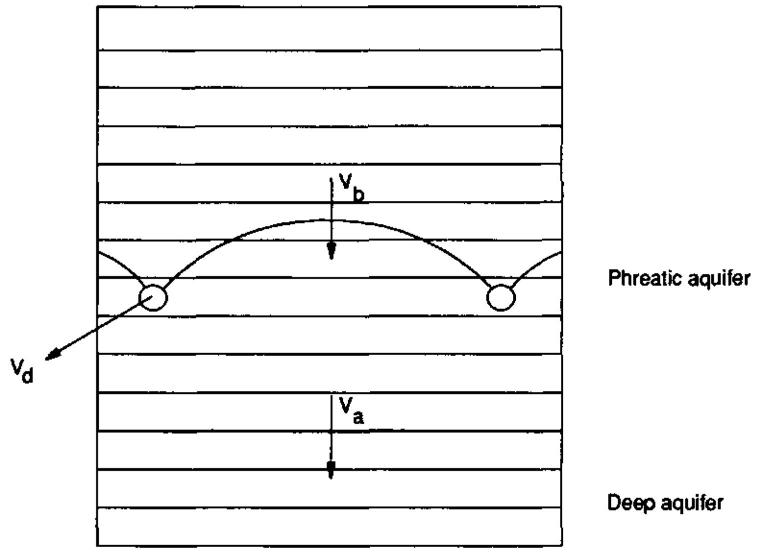

Fig. 4 Schematic representation of the bottom boundary flux V_b. This flux consists of a flux to drains V_d and a flux to or from the deep aquifer V_a

The situation is schematically illustrated in Figure 4. The drain outflow can be written as:

$$V_d = - \frac{1}{\dfrac{1}{k_0} + \dfrac{1}{A.z_g}} \tag{10}$$

in which:
V_d = Drain outflow (cm.d^{-1})
A = Drainage intensity (d^{-1})
k_0 = Saturated hydraulic conductivity (cm.d^{-1})
z_g = Groundwater level above drain depth (cm)

A, the drain intensity, is defined as:

$$A = \frac{8\ k_0\ d}{L^2} \tag{11}$$

with:
L = Distance between the drains (cm)
d = Thickness of the compartment through which horizontal flow to drains takes place (cm)

The flux from the bottom unsaturated nodal point to the groundwater table can be written as:

$$V_b = -\bar{k}\left[\frac{h_n - h_g}{z_n - z_g} + 1\right] \tag{12}$$

with:

k = Average value of hydraulic conductivities at the deepest unsaturated compartment and at the groudwater level ($k = k_0$) ($cm.d^{-1}$)

h_n,h_g = Pressure heads at the deepest unsaturated nodal point and the groundwater level respectively (cm)

z_n = Height of the lowest unsaturated nodal point above drain depth (cm)

When V_a is given as input, z_g can be solved combining 9 - 12:

$$-\bar{k}\left[\frac{h_n - h_g}{z_n - z_g} + 1\right] = -\frac{1}{\frac{1}{k_0} + \frac{1}{A\ z_g}} + V_a \tag{13}$$

this yields:

$$b = t\left[\bar{k}\ (h_n + z_n - A'\ k_0) - k_0\ z_n - A'\ k_0\ V_a + z_n\ V_a\right] \tag{14}$$

$$c = A'\ k_0\ t\left[\bar{k}\ (h_n + z_n) + z_n V_a\right] \tag{15}$$

$$t = \frac{1}{k_0 - \bar{k} - V_a} \tag{16}$$

$$A' = \frac{1}{A} \tag{17}$$

$$z_g = \frac{-b - \sqrt{b^2 - 4c}}{2} \text{ applies when } t > 0 \tag{18a}$$

$$z_g = \frac{-b + \sqrt{b^2 - 4c}}{2} \text{ applies when } t \le 0 \tag{18b}$$

When V_a is unknown this flux can be calculated by the equation:

$$V_a = -k_0 \left[\frac{z_g + d - H_a}{z_g + d} \right] \tag{19}$$

where,
H_a = hydraulic head of deep aquifer (cm)
d = distance between drainage level and deep aquifer (cm)

Combining eq. 9 - 12 with eq. 19, z_g can be solved:

$$-\bar{k} \left[\frac{h_n - h_g}{z_n - z_g} + 1 \right] = -\frac{1}{\frac{1}{k_0} + \frac{1}{A\, z_g}} - k_0 \left[\frac{z_g + d - H_a}{z_g + d} \right] \tag{20}$$

This results in a third degree equation.

2.4.2 Ground water level above drainage system with various horizons

Equation 10 is only valid when z_g is in the same horizon as the drainage system. When a profile consists of several horizons and z_g rises above the transition of two horizons with different saturated hydraulic conductivities, then the resistance for vertical flow must be taken into account. Equation 10 can be rewritten as follows:

$$z_g = -V_d \left[\frac{z_g}{k_0} + \frac{1}{A} \right] \tag{21}$$

For a profile of two horizons with the drainage system in the lower horizon and the groundwaterlevel in the upper horizon equation 21 changes into:

$$z_g = -V_d \left[\frac{1}{A} + \frac{D}{k_{01}} + \frac{z_g - D}{k_{02}} \right] \tag{22}$$

or with:

$$B = \frac{D}{k_{01}} - \frac{D}{k_{02}} \text{ and } A' = \frac{1}{A}$$

$$z_g = -V_d \left[A' + B + \frac{z_g}{k_{02}} \right] \tag{23}$$

where,
D = distance between drain depth and the transition of the two horizons (cm).
k_{01},k_{02} = saturated hydraulic conductivity of the lower and upper horizon respectively ($cm.d^{-1}$)

Rewriting this equation to V_d:

$$V_d = -\frac{z_g}{\frac{z_g}{k_{02}} + A' + B} \tag{24}$$

If the groundwater level of soil profiles with three horizons and a drainage system in the lower horizon is in the lower or second horizon, then equations 10 and 24 apply respectively.
In case the groundwater level is in the upper horizon, equation 24 changes into:

$$V_d = -\frac{z_g}{\frac{z_g}{k_{03}} + A' + B}$$

with:

$$B = \frac{D_1}{k_{01}} + \frac{D_2}{k_{02}} - \frac{D_1 + D_2}{k_{03}}$$

where,
D_1 = distance between the drain depth and the transition of the lower and the second horizon (cm)
D_2 = thickness of the second horizon (cm)
k_{01},k_{02},k_{03} = saturated hydraulic conductivity of the lower, second and upper horizon respectively ($cm.d^{-1}$)

2.4.3 Ground water level below the drainage system

If the groundwater level is below drainage system, the flux to the open water system (see eq. 9) is zero. If V_a is input, combination of eq. 9 and 12 yields:

$$V_a = -\bar{k}\left[\frac{h_n - h_g}{z_n - z_g} + 1\right] \qquad (25)$$

or:

$$z_g = \frac{V_a z_n + \bar{k}\, h_n + \bar{k}\, z_n}{V_a + \bar{k}} \qquad (26)$$

When V_a is unknown, this flux can be computed by the equation:

$$V_a = -k_0\left[\frac{z_g^{'} - H_a}{z_g^{'}}\right] \qquad (27)$$

where,
$z_g^{'}$ = height of the ground water level above the deep aquifer (cm)
H_a = hydraulic head of the deep aquifer (cm)

The combination of eq. 9 and 12 with 27 yields:

$$-\bar{k}\left[\frac{h_n - h_g}{z_n - z_g} + 1\right] = -k_0\left[\frac{z_g^{'} - H_a}{z_g^{'}}\right] \qquad (28)$$

2.5 Soil physical properties

k(h) relation
To enable the analytical solution of the Darcy equation, the k(h) relation is presented by an exponential relation. For many soils, an exponential k(h) relation is valid only for a narrow range of pressure heads. Therefore in the model FLOCR, one k(h) relation is described by three different exponential k(h) sections (See Fig. 5). If the pressure heads are very negative care should be taken that the expontial k(h) does not deflect too much from the true k(h). Each line segment can be described by:

$$k(h) = k_0\, e^{\alpha h} \qquad (29)$$

in which,
k = calculated hydraulic conductivity ($cm.d^{-1}$)
α = gradient
h = pressure head (cm)
k_0 = saturated hydraulic conductivity ($cm.d^{-1}$)

The range of pressure heads that each line segment covers must be specified. Therefore, the model input is the intersection of the first and second line segment and the intersection of the second and third line segment. In Figure 5 the transition of the first line segment to the second one takes place at a pressure head of -27 cm. Evenso there is a transition between the second and third line segment at a pressure head of -159 cm.

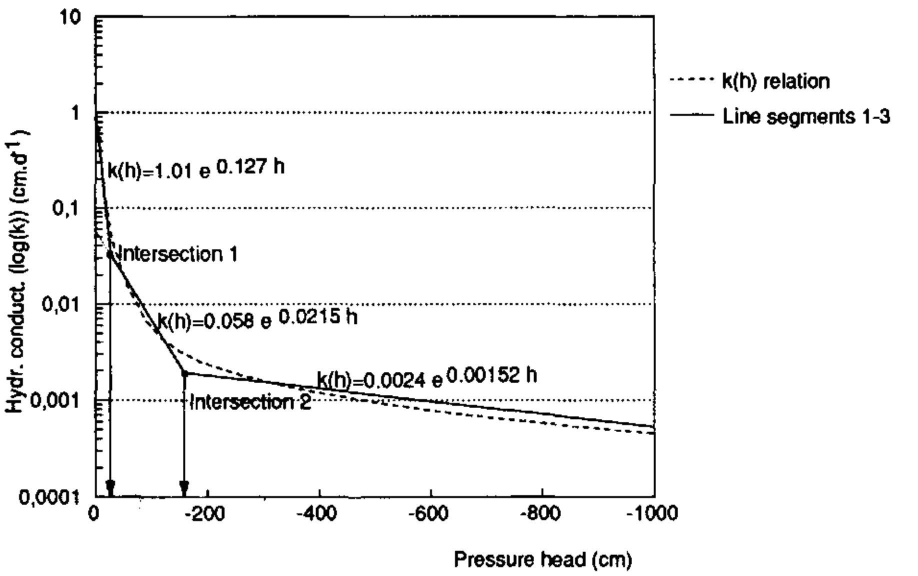

Fig. 5 An example of a k(h) relation described by three different line segments

Water retention curve

The water retention curve, i.e. the relationship between soil water pressure head and volumetric water content, is shown in a table (appendix 1)

Shrinkage characteristic and shrinkage geometry

The shrinkage characteristic is also shown in a table (appendix 1). The void ratio and the geometry factor (r_s) must be defined for each moisture ratio. Values in between are computed by the model by means of interpolation. The volumetric water contents must correspond with the moisture ratio. The relation between volumetric water content (θ), moisture ratio (ϑ) and void ratio (e) is:

$$\theta = \frac{\vartheta}{(1+e)} \tag{30}$$

2.6 Model time step

The computer model computes the maximum allowable time step. The time step depends on the wet range of the hydraulic conductivity curve. The critical value for the time step according to Wind and van Doorne (1975) is:

$$\Delta t < \frac{\partial \theta}{\partial k} \left(\frac{e^{\alpha \Delta z} - 1}{e^{\alpha \Delta z} + 1} \right) \Delta z \tag{31}$$

Choosing model time steps larger than those calculated from eq. 31 may result in serious simulation errors.

3 DESCRIPTION OF THE PROGRAM AND ITS SUBROUTINES

In this section the computer program of the model (version 2.0) will be outlined briefly. The program consists of several routines. Each routine has its own unique function. The model is programmed in Fortran and is available in a PC-version and a VAX-version. A variable list and a reference map is provided in the appendices 10 and 11. The program flow is presented in Figure 6. The routines with their specific functions are:

FLOCR	The main program that takes care of the program flow and in which output is written to file.
ALGEM	Calculates an average value for ALFA when the pressure heads of two successive compartments are not on the same line segment of the exponential k(h) relation.
ALGEMI	See ALGEM. ALGEMI is only called up at the transition of two horizons.
CRACKING	Calculates crack volume and subsidence per compartment.
CRINFIL	Calculates the infiltration into cracks at the soil surface.
DELTIM	Calculates the time step.
FLUX	Calculates all the vertical fluxes in the soil matrix between the unsaturated compartments. This routines checks whether the pressure heads of the successive compartments are on the same k(h) line segment. If not, an average value is calculated for ALFA by routine ALGEM.
GWS2	Calculates groundwater level below drain level and flux to deep aquifer.
GWST	Calculates groundwater level above drain level, drain outflow and flux to deep aquifer.
INFIL	Calculates the infiltration into the soil matrix at the soil surface. Furthermore, INFIL calculates which part of the precipitation falls directly in the cracks, the total amount of bypass flow and the amount of runoff. In case of evapotranspiration, the reduced evapotranspiration is calculated.
INIFLW	This routine reads the input files and assigns initial values to each variable. All constants are calculated. All variables are stored in the memory, the compartment numbers are being used as indices.

INTPOL Interpolates the values of the table containing the shrinkage characteristic and the shrinkage geometry factor.

ITERA Iteration routine to calculate the pressure head at the transition of two compartments with different soil physical properties. When the calculated pressure head of the upper compartment is not on the same line segment of the k(h) relation as the pressure head of the compartment directly below the transition, ALGEMI is called up to calculate an average value for ALFA. Finally, the flux over the transition is calculated.

KPSI Following calculation of the pressure head at a given water content for each unsaturated compartment by calling up subroutine TETPSI, KPSI then identifies the k(h) line segment to which the calculated pressure head belongs and computes the correct hydraulic conductivity.

ROOTS Iteration procedure to solve a third degree equation.

TETPSI Uses the water retention curve to calculate the pressure head at a given water content by linear interpolation. When the water content exceeds the water retention curve range, the model types an error message and stops.

THETA Calculates the change in water content for each compartment dependant on the fluxes and counts the number of unsaturated compartments.

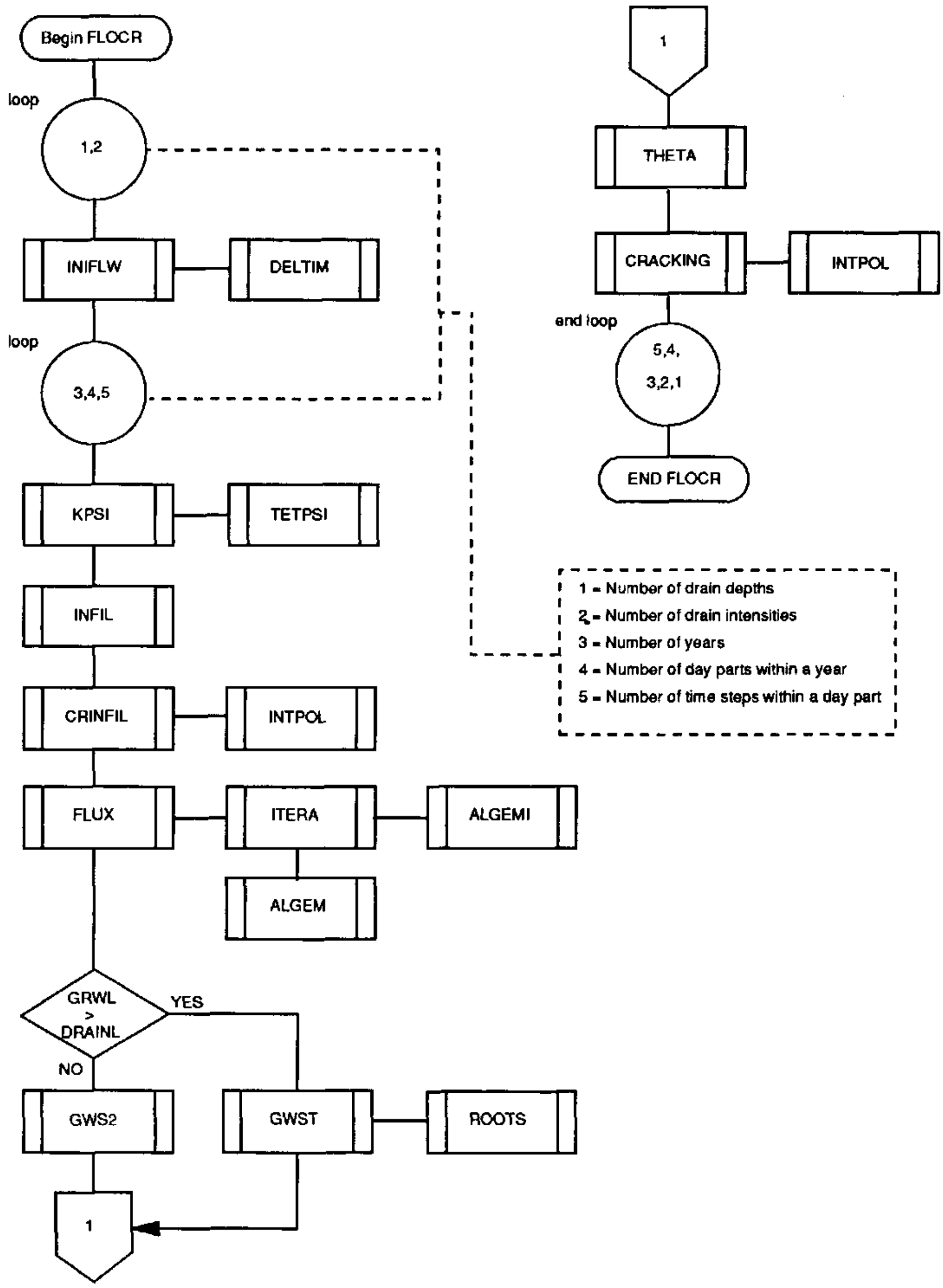

Fig. 6 Program flow chart of the model FLOCR

4 INPUT AND OUTPUT

The computer model FLOCR uses two kinds of input files: a file with meteorological data (METEO-file) and fluxes to the aquifer and a file containing information about the physical properties of the considered soil profile together with some general information on the simulation period, the time step etc (INFO-file) (See also the example in appendix 1).

4.1 METEO files

The first record in this file contains the total number of day parts and an identifier which may be zero or one. The identifier informs the program on how the folowing records in the meteo files are to be read, i.e. with or without the duration of the precipitation. When the identifier has the value one, the duration of the precipitation will be read from the meteo file. Otherwise no duration of precipitation will be read. The duration will then be equal to the length of a daypart. Each subsequent record in this file contains for every daypart:

. the precipitation (cm)

. the potential evapotranspiration (cm)

. the flux to or from the deep aquifer ($cm.d^{-1}$) or,
. the hydraulic head of the deep aquifer (cm) and

. the duration of the precipitation (hr)

A part of this file is given in appendix 2.

4.2 INFOrmation files

In this section the INFO file for a soil profile with one horizon will be presented. The INFO file consists of comments and parameter values. The comments consist of information about the parameters that are to be defined in the next record. The comment lines are numbered between parenthesis and correspond with the numbered lines in the example of appendix 1. The input parameters are specified as follows:

- Comment line (01)
- Header
- Comment line (02)
- Number of years to simulate, number of drain depths and number of drain intensities.

Each combination of drain depth and drain intensity needs a different INFO file. The first INFO file is called INFO01.DAT, the second INFO02.DAT and so on. The example in appendix 1 will need only one INFO file because both the number of drain depths and the number of drain intensities is 1.

- Comment line (03)
- Starting day number, number of the compartment containing the drain, number of horizons in the soil profile (maximum 5), for each horizon the number of compartments (up to 5 horizons), number of day parts within one day. Total number of compartments may not be over 30.
- Comment line (04)
- Table containing for each individual compartment: the compartment number, compartment thickness and the saturated volumetric water content.
- Comment line (05)
- Maximum thickness of the pool before runoff takes place (cm), thickness of the pool at the start of the simulation (cm), reduction factor for calculating the reduction of the potential evapotranspiration.
- Comment line (06)
- Drain depth (cm), drain intensity (d^{-1}), initial groundwater level (cm), depth of the deep aquifer (cm) and a indicator (0 or 1). The fluxes to or from the deep aquifer are computed when this indicator is one and are given as input when this indicator is zero. Besides, the indicator determines what the contents of the meteo file should be. The meteo file also contains the hydraulic heads when the indicator is one, and fluxes when the indicator is zero (see also paragraph 4.1).
- Comment line (07)
- Table of water content, pressure head (cm), void ratio, moisture ratio and geometry factor r_s.

The table consists of a maximum of forty lines. Furthermore, the water contents in the table should be in ascending order. A record with all negative values indicates the end of the table.

- Comment line (08)
- k_0 values for the three line segments of the exponential k(h) relation (from wet to dry) ($cm.d^{-1}$).
- Comment line (09)
- Alfa values for the three line segments of the exponential k(h) relation (from wet to dry) (cm^{-1}).
- Comment line (10)
- Pressure heads at the intersections of the three line segments of the exponential k(h) relation (from wet to dry) (cm).

If more than one horizon has to be defined, steps 7 until 10 must be repeated for each additional required horizon, up to 5 horizons.

- Comment line (11)
- Name of the first meteo file.

One year of meteo data are collected into one file. All years to be computed should have a separate meteo file. The name of the first meteo file should be:

Azz.AAA

where,
A = alphanumerical character
zz = the first year to be simulated

For example, if the first year to be simulated is 1978, the first meteo file could be R78.DAT. When more years are to be simulated, the second meteo file name becomes automatically R79.DAT.

- Comment line (12)
- Output identification code.

This identification code is used to name the output files. The code consists of a maximum of four characters.
- Comment line (13)
- Output selection.

In this line the user can choose the desired output files. The available output files just are: water balance (WB), water contents per compartment (MP), pressure heads per compartment (PH), compartment thicknesses (LT), crack volume per compartment (CV), summarized data for the whole soil profile (SC) and the info file (IN). For each file a one for yes or a zero for no must be specified. The output file names consist of a two character code, which is the code between parenthesis, and the output identification appended to it. The extension for each file is .DAT. According to appendix 1 the water balance data are written to the file WBRP47.DAT.

- Comment line (14)
- Frequency of writing output.

The user can select one of three different output writing frequencies:
. 1 = output per fifth of a day
. 2 = output once per day
. 3 = output once per week

- Comment line (15)
- Put down a Y for compute time step or a N for don't compute the time step
- Comment line (16)
- Give the desired model time step. In case the time step is calculated, this may be a dummy value.

4.3 Output files

The user can select the desired model output. Seven output files are possible. These seven output files with their contents are:

1) Water balance:
   . time (d)
   . groundwater level (cm).
   . cumulative actual evapotranspiration since start of simulation (cm).
   . cumulative potential evapotranspiration since start of simulation (cm).
   . cumulative flux through the lower boundary since start of simulation (cm).
   . cumulative drain outflow since start of simulation (cm).
   . cumulative flux to aquifer since start of simulation (cm).
   . cumulative matrix infiltration since start of simulation (cm).
   . cumulative crack infiltration since start of simulation (cm).
   . cumulative precipitation since start of simulation (cm).
   . cumulative surface runoff since start of simulation (cm).
   . thickness of the pool (cm)
   . change of water content of the soil compared to the start of the simulation (cm). (decrease in water content is positive)

2) Water contents:
   . time (d);
   . number of unsaturated compartments (-);
   . groundwater level (cm);
   . volume percentage of liquid of the unsaturated compartments (-).

3) Pressure heads:
   . time (d);
   . number of unsaturated compartments (-);
   . groundwater level (cm);
   . pressure heads of the unsaturated compartments (cm).

4) Compartment thicknesses:
   . time (d);
   . number of unsaturated compartments (-);
   . thicknesses of the unsaturated compartments (cm).

5) Crack volumes:
   . time (d);
   . number of unsaturated compartments (-);
   . crack volumes of the unsaturated compartments (cm).

6) Water content and volume change for the whole soil profile:
   . time (d);
   . change of water content compared to start of simulation (cm);
   . change of volume compared to start of simulation (cm);
   . subsidence of the soil surface compared to start of simulation (cm);

. change in crack volume compared to start of simulation (cm).

7) A copy of the input file.

Examples of the output files are given in the appendices 3-9. The various output files are organized in such a way to enable data processing and drawing of graphs with spreadsheet programs.

5 FUTURE DEVELOPMENTS

A computer simulation model is never finished. When more experimental data become available and new scientific insights are obtained, a model has to be adapted and improved regularly. At this moment, the following two adaptions of FLOCR are foreseen:

- The possibility to use open water levels in ditches as bottom boundary condition. At present, model computations can only be conducted for soils with tile drains, or without any drainage system at all. Often, alluvial clay soils are drained by ditches.

- The introduction of rapid drain discharge caused by saturated water flow via shrinkage cracks to the drains. At present, FLOCR applies the following model concept: Part of the precipitation flows vertically via the cracks to the groundwater. As a result, the groundwater level rises rapidly, causing the cracks below the new water table to close instantenuously. Subsequently, groundwater flows horizontally to the drains. Because the cracks are considered to close rapidly, the saturated conductivity used to compute this horizontal saturated flow is relatively low.
  In reality, after precipitation causes the water level in the cracks to rise, it will take some time for the cracks to close. During this time, the horizontal saturated conductivity of this layer with open cracks will be very high, leading to a rapid drain discharge, untill the cracks are closed. This process will be incorporated in FLOCR because of its importance for solute transport through the soil to drains and surface waters.

REFERENCES

BAKEL, P.J.T. VAN, 1986. *A systematic approach to improve the planning, design and operation of regional surface water management systems. A case study.* Wageningen, The Netherlands. Institute for Land and Water Managent Research (ICW), Report 13.

BRONSWIJK, J.J.B., 1988. "Modeling of water balance, cracking and subsidence of clay soils". *J. Hydrol.* 97: 199-212

BRONSWIJK, J.J.B., 1989. "Prediction of actual cracking and subsidence in clay soils". *Soil Science,* 148: 87-93.

WIND, G.P. and W. VAN DOORNE, 1975. "A numerical model for the simulation of unsaturated vertical flow of moisture in soils". *J. Hydrol.* 24: 1-20.

UNPUBLISHED SOURCES

BUITENDIJK J., 1984. *FLOWEX: A numerical model for simulation of vertical flow of water through unsaturated layered soil.* Wageningen. ICW, Note 1494 (in Dutch).

APPENDIX 1 EXAMPLE OF THE CONTENTS OF AN INFO FILE

```
Header for simulation ------------------------------------------------------------------ 01
Simulation example report 47
-- Number of:      years,  drain depths, drain intensities ---------------------------- 02
                   1       1       1
-- Start.day,drain comp.,nr of prof.,nr of comp. per prof.,day parts ------------------ 03
   0.0     10     1     30     5
-- Comp._nr, Thickness, Vol. water perc. of sat. soil --------------------------------- 04
     1     10.0000    0.517
     2     10.0000    0.517
     3     10.0000    0.517
     4     10.0000    0.517
     5     10.0000    0.517
     6     10.0000    0.517
     7     10.0000    0.517
     8     10.0000    0.517
     9     10.0000    0.517
    10     10.0000    0.517
    11     10.0000    0.517
    12     10.0000    0.517
    13     10.0000    0.517
    14     10.0000    0.517
    15     10.0000    0.517
    16     10.0000    0.517
    17     10.0000    0.517
    18     10.0000    0.517
    19     10.0000    0.517
    20     10.0000    0.517
    21     10.0000    0.517
    22     10.0000    0.517
    23     10.0000    0.517
    24     10.0000    0.517
    25     10.0000    0.517
    26     10.0000    0.517
    27     10.0000    0.517
    28     10.0000    0.517
    29     10.0000    0.517
    30     10.0000    0.517
max. pool  pool  Bfactor (-1/h) ------------------------------------------------------- 05
  0.2      0.0   0.0000625
Drain depth.   intensity     Grwl.   Depth of deep aquifer  indicator ------------- 06
-95.0          0.0035        0.               -200.            0
vol.water content, pressure head, void ratio, moisture ratio, geometry factor -------- 07
  0.170          -16000.       0.493     0.255          3.
  0.180          -12200.       0.495     0.270          3.
  0.190          -9526.        0.498     0.285          3.
  0.200          -7485.        0.501     0.300          3.
  0.210          -5895.        0.504     0.315          3.
  0.220          -4663.        0.506     0.330          3.
  0.230          -3711.        0.509     0.345          3.
  0.240          -2972.        0.515     0.362          3.
  0.250          -2396.        0.522     0.379          3.
```

0.260	-1948.	0.530	0.396	3.
0.270	-1600.	0.537	0.413	3.
0.280	-1329.	0.544	0.430	3.
0.290	-1119.	0.552	0.447	3.
0.300	-955.	0.559	0.464	3.
0.310	-821.	0.566	0.481	3.
0.320	-708.	0.578	0.501	3.
0.330	-612.	0.595	0.524	3.
0.340	-530.	0.611	0.547	3.
0.350	-459.	0.627	0.570	3.
0.360	-399.	0.644	0.593	3.
0.370	-348.	0.660	0.616	3.
0.380	-304.	0.678	0.639	3.
0.390	-265.	0.699	0.663	3.
0.400	-228.	0.721	0.687	3.
0.410	-188.	0.742	0.711	3.
0.420	-151.	0.767	0.739	3.
0.430	-118.	0.796	0.772	3.
0.440	-88.	0.824	0.804	3.
0.450	-55.	0.853	0.837	3.
0.460	-28.	0.881	0.869	3.
0.470	-12.	0.910	0.902	3.
0.480	-6.	0.939	0.934	3.
0.490	-3.	0.967	0.967	3.
0.500	-2.	1.020	1.010	3.
0.510	-1.	1.050	1.040	3.
0.517	0.	1.070393	1.070393	3.
-1	-1	-1	-1	-1

-- K0 values for three line segments-- 08
1.011141 0.058231 0.002419
-- Alfa values for three line segments-- 09
0.127260 0.021530 0.001522
-- Intersections -- 10
-26.9972 -158.9951
-- First input meteo file name -- 11
R72.DAT
-- Output identification --- 12
RP47
--Wat_bal, Wat_cnt, Pres_hd, Comp_thick, Cr_vol, Subs, Input (0=No,1=Yes) ------------- 13
1 1 1 1 1 1 1
-- Output frequency (1= per fifth of a day, 2= daily, 3= weekly ------------------------------ 14
2
-- Compute time step [Y/N] ? -- 15
Y
-- Time step -- 16
0.02 days

APPENDIX 2 INPUT FILE WITH THE METEOROLOGICAL DATA AND THE FLUX TO OR FROM THE AQUIFER PER ONE FIFTH OF A DAY

The first record contains the total number of day parts (1830) and an identifier. In the folowing records, the duaration of the precipiation must be given too when this identifier will be one.

```
1830   0
 0.0000 0.0000  0    1- 1-72
 0.0000 0.0000  0
 0.0000 0.0400  0
 0.0000 0.0000  0
 0.0000 0.0000  0
 0.0000 0.0000  0    2- 1-72
 0.0000 0.0000  0
 0.0000 0.0300  0
 0.0000 0.0000  0
 0.0000 0.0000  0
.        .
.        .
.        .
 0.0000 0.0000  0   30-12-72
 0.0000 0.0000  0
 0.0000 0.0500  0
 0.0000 0.0000  0
 0.0000 0.0000  0
 0.0000 0.0000  0   31-12-72
 0.0000 0.0000  0
 0.0000 0.0400  0
 0.0000 0.0000  0
 0.0000 0.0000  0
```

APPENDIX 3 SIMULATION OF THE WATERBALANCE USING THE INFO FILE AND THE METEO FILE FROM APPENDIX 1

The name of this file is WBRP47.DAT. The printed variables are in the folowing order: Day number, groundwater level (cm), actual evaporation (cm), potential evaporation (cm), bottom boundary flux (cm), flux to drains and ditches (cm), flux to deep aquifer (cm), matrix infiltration (cm), crack infiltration (cm), precipitation (cm), surface runoff (cm), thickness of the pool (cm) and change of water content (cm).

WATER BALANCE FILE

Simulation example report 47

1.0	-8.1	0.0	0.0	-0.2	-0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.3
2.0	-17.4	0.1	0.1	-0.5	-0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.5
3.0	-17.2	0.1	0.1	-0.7	-0.7	0.0	0.0	0.0	0.0	0.0	0.0	0.8
4.0	-20.7	0.1	0.1	-0.9	-0.9	0.0	0.0	0.0	0.0	0.0	0.0	1.0
5.0	-25.0	0.1	0.1	-1.1	-1.1	0.0	-0.1	0.0	-0.1	0.0	0.0	1.1
6.0	-26.7	0.2	0.2	-1.3	-1.3	0.0	-0.1	0.0	-0.1	0.0	0.0	1.4
7.0	-29.0	0.2	0.2	-1.5	-1.5	0.0	-0.1	0.0	-0.1	0.0	0.0	1.6
8.0	-36.1	0.2	0.2	-1.7	-1.7	0.0	-0.1	0.0	-0.1	0.0	0.0	1.8
9.0	-36.1	0.2	0.2	-1.8	-1.8	0.0	-0.1	0.0	-0.1	0.0	0.0	2.0
.	.	.	.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.	.	.	.
358.0	-66.5	51.9	53.8	-18.4	-18.4	0.0	-60.2	-5.4	-65.6	0.0	0.0	4.6
359.0	-67.7	51.9	53.8	-18.4	-18.4	0.0	-60.2	-5.4	-65.6	0.0	0.0	4.7
360.0	-69.4	51.9	53.8	-18.5	-18.5	0.0	-60.2	-5.4	-65.6	0.0	0.0	4.8
361.0	-71.6	52.0	53.9	-18.6	-18.6	0.0	-60.2	-5.4	-65.6	0.0	0.0	4.9
362.0	-73.4	52.0	53.9	-18.7	-18.7	0.0	-60.2	-5.4	-65.6	0.0	0.0	5.0
363.0	-73.9	52.0	53.9	-18.7	-18.7	0.0	-60.2	-5.4	-65.6	0.0	0.0	5.1
364.0	-74.4	52.1	54.0	-18.8	-18.8	0.0	-60.2	-5.4	-65.6	0.0	0.0	5.2
365.0	-74.8	52.1	54.0	-18.9	-18.9	0.0	-60.2	-5.4	-65.6	0.0	0.0	5.3
366.0	-75.2	52.1	54.0	-18.9	-18.9	0.0	-60.2	-5.4	-65.6	0.0	0.0	5.4

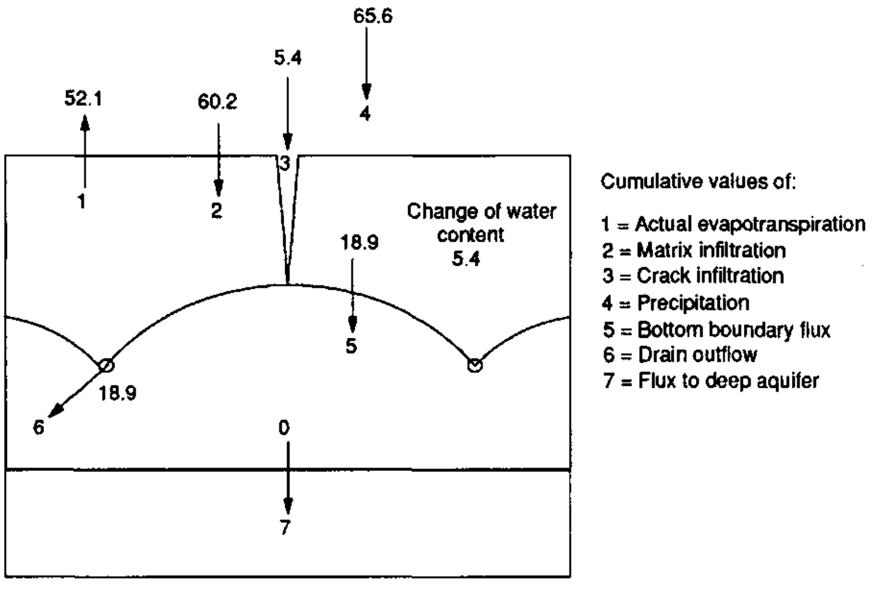

Fig. 7 Example of a schematic representation of a water balance

APPENDIX 4 SIMULATION OF THE VOLUMETRIC WATER CONTENTS PER COMPARTMENT USING THE INFO FILE FROM APPENDIX 1 AND THE METEO FILE FROM APPENDIX 2

The name of the output file is WCRP47.DAT. The printed variables are in the folowing order:

Day number, number of unsaturated compartments, groundwater level (cm), volumetric water content of each unsaturated compartment (%).

VOLUMETRIC WATER PERCENTAGES

Simulation example report 47

1.0	1	-8.1	49.3							
2.0	1	-17.4	47.2							
3.0	2	-17.2	47.1	49.8						
4.0	2	-20.7	46.9	48.3						
5.0	3	-25.0	46.7	47.5	51.3					
6.0	3	-26.7	46.3	47.1	50.0					
7.0	3	-29.0	46.3	46.9	48.5					
8.0	3	-36.1	46.1	46.6	47.2					
9.0	4	-36.1	46.0	46.3	47.1	50.4				
	.	.	.	.	.	.				
	.	.	.	.	.	.				
	.	.	.	.	.	.				
358.0	7	-66.5	44.1	44.9	45.4	45.9	46.4	47.0	49.2	
359.0	7	-67.7	44.1	44.8	45.4	45.8	46.3	46.9	48.6	
360.0	7	-69.4	43.8	44.8	45.3	45.8	46.3	46.8	48.1	
361.0	7	-71.6	43.8	44.7	45.3	45.7	46.2	46.7	47.7	
362.0	8	-73.4	43.8	44.6	45.2	45.7	46.1	46.6	47.4	51.6
363.0	8	-73.9	43.6	44.6	45.2	45.6	46.0	46.6	47.3	51.3
364.0	8	-74.4	43.4	44.5	45.1	45.6	46.0	46.5	47.2	50.9
365.0	8	-74.8	43.2	44.4	45.0	45.5	45.9	46.5	47.1	50.5
366.0	8	-75.2	43.0	44.4	45.0	45.5	45.9	46.4	47.1	50.1

APPENDIX 5 SIMULATION OF THE PRESSURE HEADS PER COMPARTMENT USING THE INFO FILE FROM APPENDIX 1 AND THE METEO FILE FROM APPENDIX 2

The name of the of the file is PHRP47.DAT. The printed variables are in the folowing order:

Day number, number of unsaturated compartments, groundwater level (cm), pressure head of each unsaturated compartment (cm).

PRESSURE HEADS

Simulation example report 47

1.0	1	-8.1	2							
2.0	1	-17.4	9							
3.0	2	-17.2	11	2						
4.0	2	-20.7	13	4						
5.0	3	-25.0	16	9	0					
6.0	3	-26.7	23	11	2					
7.0	3	-29.0	24	13	3					
8.0	3	-36.1	25	20	9					
9.0	4	-36.1	30	23	10	1				
	.	.	.	.						
	.	.	.	.						
	.	.	.	.						
358.0	7	-66.5	84	60	43	31	21	12	3	
359.0	7	-67.7	85	61	45	32	22	13	4	
360.0	7	-69.4	94	63	46	34	23	15	5	
361.0	7	-71.6	96	65	47	35	25	16	7	
362.0	8	-73.4	96	67	49	36	26	18	10	0
363.0	8	-73.9	101	69	51	38	28	19	10	1
364.0	8	-74.4	106	71	52	39	29	20	11	1
365.0	8	-74.8	114	73	54	40	30	20	11	1
366.0	8	-75.2	118	76	56	42	31	21	11	2

APPENDIX 6 SIMULATION OF THE COMPARTMENT THICKNESSES USING THE INFO FILE FROM APPENDIX 1 AND THE METEO FILE FROM APPENDIX 2

The name of the of the file is LTRP47.DAT. The printed variables are in the following order:

Day number, number of unsaturated compartments, thickness of each unsaturated compartment (cm).

COMPARTMENT THICKNESSES

Simulation example report 47

1.0	1	9.92							
2.0	1	9.82							
3.0	2	9.82	9.94						
4.0	2	9.81	9.87						
5.0	3	9.81	9.83	9.99					
6.0	3	9.79	9.82	9.95					
7.0	3	9.79	9.81	9.88					
8.0	3	9.78	9.80	9.82					
9.0	4	9.78	9.79	9.82	9.97				
	.	.	.						
	.	.	.						
	.	.	.						
358.0	7	9.71	9.74	9.76	9.78	9.79	9.81	9.92	
359.0	7	9.71	9.74	9.76	9.77	9.79	9.81	9.89	
360.0	7	9.70	9.73	9.76	9.77	9.79	9.81	9.86	
361.0	7	9.70	9.73	9.75	9.77	9.79	9.80	9.84	
362.0	8	9.70	9.73	9.75	9.77	9.78	9.80	9.83	10.00
363.0	8	9.69	9.73	9.75	9.77	9.78	9.80	9.82	9.99
364.0	8	9.69	9.73	9.75	9.76	9.78	9.80	9.82	9.98
365.0	8	9.68	9.72	9.74	9.76	9.78	9.80	9.82	9.97
366.0	8	9.67	9.72	9.74	9.76	9.78	9.79	9.82	9.95

APPENDIX 7 SIMULATION OF THE CRACK VOLUMES PER COMPARTMENT USING THE INFO FILE FROM APPENDIX 1 AND THE METEO FILE FROM APPENDIX 2

The name of the file is CVRP47.DAT. The printed variables are in the folowing order:

Day number, number of unsaturated compartments, crack volume of each unsaturated compartment (cm).

CRACK VOLUMES

Simulation example report 47

1.0	1	0.15							
2.0	1	0.35							
3.0	2	0.36	0.11						
4.0	2	0.37	0.26						
5.0	3	0.38	0.33	0.02					
6.0	3	0.40	0.36	0.09					
7.0	3	0.41	0.37	0.23					
8.0	3	0.42	0.39	0.35					
9.0	4	0.43	0.40	0.35	0.07				
	.	.	.						
	.	.	.						
	.	.	.						
358.0	7	0.55	0.50	0.46	0.43	0.40	0.36	0.16	
359.0	7	0.55	0.51	0.47	0.44	0.40	0.37	0.22	
360.0	7	0.57	0.51	0.47	0.44	0.41	0.37	0.27	
361.0	7	0.57	0.51	0.48	0.44	0.41	0.38	0.31	
362.0	8	0.57	0.52	0.48	0.45	0.42	0.39	0.34	0.00
363.0	8	0.58	0.52	0.48	0.45	0.42	0.39	0.34	0.02
364.0	8	0.59	0.53	0.49	0.45	0.43	0.39	0.35	0.04
365.0	8	0.61	0.53	0.49	0.46	0.43	0.40	0.35	0.06
366.0	8	0.62	0.54	0.49	0.46	0.43	0.40	0.36	0.09

APPENDIX 8 SIMULATION OF WATER CONTENT AND VOLUME CHANGES OF THE WHOLE SOIL PROFILE USING THE INFO FILE FROM APPENDIX 1 AND THE METEO FILE FROM APPENDIX 2

The name of the file is SCRP47.DAT. The printed variables are in the following order:
Day number, change of water content (cm), volume change (cm), subsidence (cm) and change in crack volume (cm).

WATER CONTENT AND VOLUME CHANGES OF THE WHOLE SOIL PROFILE.
Simulation example report 47

1.0	0.28	0.23	0.08	0.15
2.0	0.53	0.53	0.18	0.35
3.0	0.76	0.70	0.24	0.47
4.0	0.98	0.95	0.32	0.63
5.0	1.14	1.11	0.38	0.73
6.0	1.37	1.30	0.44	0.86
7.0	1.58	1.52	0.52	1.00
8.0	1.79	1.75	0.59	1.15
9.0	2.00	1.90	0.65	1.26
.	.	.	.	
.	.	.	.	
.	.	.	.	
358.0	4.58	4.36	1.49	2.87
359.0	4.68	4.48	1.53	2.95
360.0	4.81	4.61	1.57	3.04
361.0	4.92	4.72	1.61	3.11
362.0	5.00	4.80	1.64	3.16
363.0	5.11	4.89	1.67	3.22
364.0	5.21	4.97	1.70	3.27
365.0	5.32	5.06	1.73	3.33
366.0	5.42	5.15	1.76	3.39

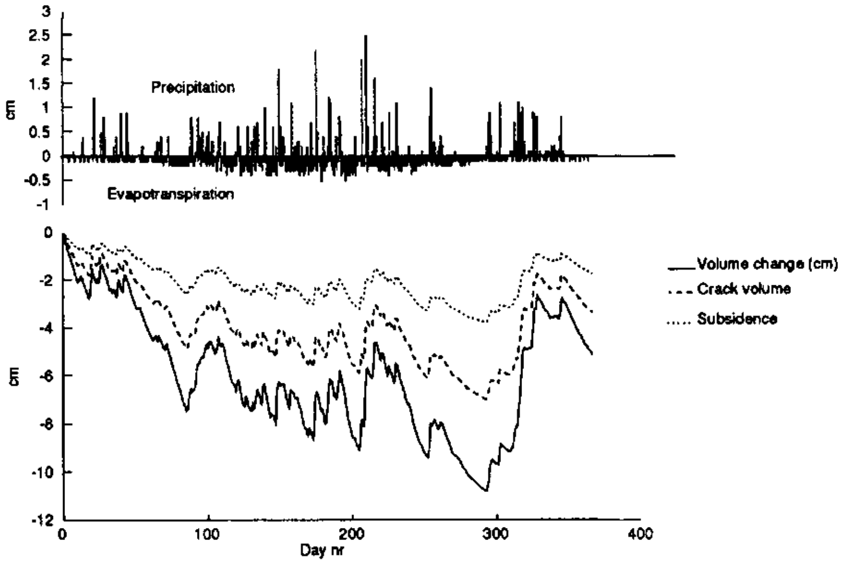

Fig. 8 ***Example of a graphical representation of total volume change, subsidence and crack volume in relation to precipitation and evapotranspiration***

APPENDIX 9 PRESENTATION OF THE INPUT FILE

```
-- Header for simulation ------------------------------------------------------------------------ 01
Simulation example report 47
-- Number of:      years,  drain depths, drain intensities ------------------------------------- 02
        1       1       1
-- Start.day,drain1_comp.,nr of prof.,nr of comp. per prof.,day parts --------------------------- 03
 0.0000000E+00     10      1      30      5
-- Comp._nr., Thickness, Vol. water perc. of sat. soil ----------------------------------------- 04
 1 10.0   0.5
 2 10.0   0.5
 3 10.0   0.5
 4 10.0   0.5
 5 10.0   0.5
 6 10.0   0.5
 7 10.0   0.5
 8 10.0   0.5
 9 10.0   0.5
10 10.0   0.5
11 10.0   0.5
12 10.0   0.5
13 10.0   0.5
14 10.0   0.5
15 10.0   0.5
16 10.0   0.5
17 10.0   0.5
18 10.0   0.5
19 10.0   0.5
20 10.0   0.5
21 10.0   0.5
22 10.0   0.5
23 10.0   0.5
24 10.0   0.5
25 10.0   0.5
26 10.0   0.5
27 10.0   0.5
28 10.0   0.5
29 10.0   0.5
30 10.0   0.5
Poolmx          PoolBfactor (-1/h) ------------------------------------------------------------- 05
-0.2000000      0.0000000E+00  6.2500003E-05
Drain depth      intensity     Grwl.          Depth of aquifer   Indicator------------- 06
 -95.00000      3.5000001E-03  0.0000000E+00   -200.  0
ol.water content,pressure head,void ratio,moisture ratio,geometry  factor ---------------------- 07
 0.1700000     -16000.00     0.4930000     0.2550000     3.000000
 0.1800000     -12200.00     0.4950000     0.2700000     3.000000
 0.1900000     -9526.000     0.4980000     0.2850000     3.000000
 0.2000000     -7485.000     0.5010000     0.3000000     3.000000
 0.2100000     -5895.000     0.5040000     0.3150000     3.000000
 0.2200000     -4663.000     0.5060000     0.3300000     3.000000
 0.2300000     -3711.000     0.5090000     0.3450000     3.000000
 0.2400000     -2972.000     0.5150000     0.3620000     3.000000
 0.2500000     -2396.000     0.5220000     0.3790000     3.000000
```

```
 0.2600000    -1948.000    0.5300000    0.3960000    3.000000
 0.2700000    -1600.000    0.5370000    0.4130000    3.000000
 0.2800000    -1329.000    0.5440000    0.4300000    3.000000
 0.2900000    -1119.000    0.5520000    0.4470000    3.000000
 0.3000000    -955.0000    0.5590000    0.4640000    3.000000
 0.3100000    -821.0000    0.5660000    0.4810000    3.000000
 0.3200000    -708.0000    0.5780000    0.5010000    3.000000
 0.3300000    -612.0000    0.5950000    0.5240000    3.000000
 0.3400000    -530.0000    0.6110000    0.5470000    3.000000
 0.3500000    -459.0000    0.6270000    0.5700000    3.000000
 0.3600000    -399.0000    0.6440000    0.5930000    3.000000
 0.3700000    -348.0000    0.6600000    0.6160000    3.000000
 0.3800000    -304.0000    0.6780000    0.6390000    3.000000
 0.3900000    -265.0000    0.6990000    0.6630000    3.000000
 0.4000000    -228.0000    0.7210000    0.6870000    3.000000
 0.4100000    -188.0000    0.7420000    0.7110000    3.000000
 0.4200000    -151.0000    0.7670000    0.7390000    3.000000
 0.4300000    -118.0000    0.7960000    0.7720000    3.000000
 0.4400000    -88.00000    0.8240000    0.8040000    3.000000
 0.4500000    -55.00000    0.8530000    0.8370000    3.000000
 0.4600000    -28.00000    0.8810000    0.8690000    3.000000
 0.4700000    -12.00000    0.9100000    0.9020000    3.000000
 0.4800000    -6.000000    0.9390000    0.9340000    3.000000
 0.4900000    -3.000000    0.9670000    0.9670000    3.000000
 0.5000000    -2.000000     1.020000     1.010000    3.000000
 0.5100000    -1.000000     1.050000     1.040000    3.000000
 0.5170000    0.0000000E+00  1.070393    1.070393    3.000000
 -1.000000    -1.000000    -1.000000    -1.000000   -1.000000
-- K0 values for three line segments ------------------------------------------ 08
 1.011141     5.8231000E-02  2.4190000E-03
-- Alfa values for three line segments ---------------------------------------- 09
 0.1272600    2.1530000E-02  1.5219999E-03
-- Intersections -------------------------------------------------------------- 10
 -26.99720    -158.9951
-- First input meteo file name ------------------------------------------------ 11
R72.dat
-- Output identification ------------------------------------------------------ 12
RP47
--Wat_bal,Wat_cnt,Pres_hd,Comp_thick,Cr_vol,Subs,Input (0=No,1=Yes) ---------- 13
     1     1     1      1     1    1    1
-- Output frequency (1= per fifth of a day, 2= daily, 3= weekly) -------------- 14
      2
-- Compute time step [Y/N] ? -------------------------------------------------- 15
Y
-- Time step ------------------------------------------------------------------ 16
 0.2000

===============================================================================

 SOIL PROFILE AT T = T0:

   PSI     THETA      K     VSCH    LAAGD
  (CM)    (CM3/CM3) (CM/DAG) (CM/LG)  (CM)
```

0.00	0.517	1.011	0.0000	10.0000
0.00	0.517	1.011	0.0000	10.0000
0.00	0.517	1.011	0.0000	10.0000
0.00	0.517	1.011	0.0000	10.0000
0.00	0.517	1.011	0.0000	10.0000
0.00	0.517	1.011	0.0000	10.0000
0.00	0.517	1.011	0.0000	10.0000
0.00	0.517	1.011	0.0000	10.0000
0.00	0.517	1.011	0.0000	10.0000
0.00	0.517	1.011	0.0000	10.0000
0.00	0.517	1.011	0.0000	10.0000
0.00	0.517	1.011	0.0000	10.0000
0.00	0.517	1.011	0.0000	10.0000
0.00	0.517	1.011	0.0000	10.0000
0.00	0.517	1.011	0.0000	10.0000
0.00	0.517	1.011	0.0000	10.0000
0.00	0.517	1.011	0.0000	10.0000
0.00	0.517	1.011	0.0000	10.0000
0.00	0.517	1.011	0.0000	10.0000
0.00	0.517	1.011	0.0000	10.0000
0.00	0.517	1.011	0.0000	10.0000
0.00	0.517	1.011	0.0000	10.0000
0.00	0.517	1.011	0.0000	10.0000
0.00	0.517	1.011	0.0000	10.0000
0.00	0.517	1.011	0.0000	10.0000
0.00	0.517	1.011	0.0000	10.0000
0.00	0.517	1.011	0.0000	10.0000
0.00	0.517	1.011	0.0000	10.0000
0.00	0.517	1.011	0.0000	10.0000
0.00	0.517	1.011	0.0000	10.0000

APPENDIX 10 EXPLANATORY LIST OF VARIABLES

Variable	Explanation	Dimension
A	Exponent in the integrated flow equation	
AHDZ	Exponential part of the transport equation used to calculate the flux between different horizons	
AGEM	Exponential part of the transport equation (see variable A)	
AG	Average ALFA, for calculating the flux between two adjacent compartments when the pressure heads of these compartments are not on the same section of the k(h) relation	
ALFA	Alfa values of the three line segments which describe partly the exponantial relation between pressure head and hydraulic conductivity	
ASTER	Drainage resistance	d
BFACT	Reduction factor for calculating the actual evapotranspiration	cm^{-1}
BVAL	Part of the vertical resistance (for soils with several horizons only)	
DAQ	Depth of deep aquifer	cm
DD	Drain depth	cm
DELLD1	Change in compartment thickness of the soil matrix	cm
DELTAT	Time step	d
DELTAZ	Distances between the nodal points of the successive compartments	cm
DELVM	Water available for infiltration through cracks within the present time step	cm
DELW	Change in water content of the whole soil profile	cm
DELZ	Change of the vertical thickness of a compartment	cm
DRINT	Drain intensity	d^{-1}
ET	Evapotranspiration	$cm.d^{-1}$
EVAP	Evapotranspiration for one day part	cm
GRENS	The two intersections of the three lines segments which together describe the exponential relation between the pressure head and the hydraulic conduct	cm
GRWST	Groundwater level	cm
HA	Hydraulic head of deep aquifer	cm
HG	Groundwater level above draindepth	cm
ID	Pointer to one of the three sections of the K(h) relation	cm
IDENT	Indicator	
ILUN	Logical unit number	
INFO	Name of the file containing the hydrological parameters and the soil physical data	
INPUT	Name of the file containing the meteorological data	
IPSIAL	Pressure head	cm
ITRANS	Compartment numbers at which a new horizon starts	

Variable	Explanation	Dimension
J	Number of the first saturated compartment	
K	Hydraulic conductivity of each compartment	$cm.d^{-1}$
K0	Values of the saturated hydraulic conductivity of the three line segments which together describe the relation between the pressure head and the hydraulic conductivity	$cm.d^{-1}$
KOVER	Hydraulic conductivity at transition of horizons	$cm.d^{-1}$
LAAGD	Thickness of each compartment	cm
LAAGDM	Maximum compartment thickness	cm
LAAGNR	Compartment number	
MAXT	Number of points of the water retention curve for each horizon	
NDPART	Number of day parts within one day (default = 5)	
NDRAIN	Number of drain depths	
NDRINT	Number of drain intensities	
NJAAR	Number of years to be simulated	
NLAAG	Number of compartment containing the drain	
NLAYER	Compartment containing groundwater level	
NPARTS	Number of day parts within a meteorological year	
NPG	Number of horizons until drainage level	
NPROFL	Number of horizons	
NSTEPS	Number of time steps within one day part	
NTRANS	Number of compartments per horizon	
OUTPUT	Identifier for the output filename	
POOL	Thickness of pool (the total amount of water available for infiltration, within one time step)	cm
POOLMX	Maximum thickness of the pool	cm
PSI	Pressure head of each compartment	cm
PSIT	Table of pressure heads which is related to THETAT	cm
PSITER	Pressure head at the boundary of two horizons	cm
RAIN	Precipitation during one day part	cm
REGEN	Precipitation intensity	$cm.d^{-1}$
RMRATIO	Moisture ratio	
RUNOFF	Runoff	cm
SRPLUS	Surplus amount of water, positive when an overflow of the maximum soil water content occurs. Then it is added to the compartment above or, in case it is the first compartment, added to the pool	cm
SUMEA	Cumulative actual evapotranspiration	cm
SUMEP	Cumulative potential evapotranspiration	cm
SUMP	Cumulative precipitation	cm
SUMRNF	Cumulative runoff	cm
SUMVCR	Cumulative water infiltrated into cracks (bypass flow)	cm
SUMVDR	Cumulative drain outflow	cm

Variable	Explanation	Dimension
SUMVINF	Cumulative infiltration into soil matrix	cm
SVA	Flux to aquifer	$cm.d^{-1}$
TETA	Volumetric water content of each compartment	
TETMAX	Maximum volumetric water content for each compartment	
THETAT	Table of volumetric water content which is related to PSIT	
THICK	Thickness of the profile	cm
THICKN	Distance between the drain and the top of the horizon containing the drain	cm
TIMCAL	Variable to decide if the time step has to be calculated	
TSTEP	Time step	d
TYD	Time	d
V	Darcy-fluxes between compartments	$cm.d^{-1}$
VA	Fluxes to aquifer or hydraulic head of aquifer	$cm.d^{-1}$/cm
VB	Total flux through bottom boundary	$cm.d^{-1}$
VCR	Water available for infiltration within the present time step	cm
VCRACK	Total flux into cracks (bypass flow) within one time step	$cm.d^{-1}$
VCRACK1	Part of rain that falls directly in the cracks, within one time step	$cm.d^{-1}$
VCRACK2	Part of rainfall that flows into cracks because Imax of the soil matrix is exceeded within one time step	$cm.d^{-1}$
VD	Flux to drains or ditches	$cm.d^{-1}$
VIN	Max. infiltration rate into soil matrix	$cm.d^{-1}$
VOUT	Actual evapotranspiration within one time step	cm
VRATIO	Void ratio	
VSCH	Volume of the cracks per compartment	cm
VSCHT	Total crack volume of the whole soil	cm

APPENDIX 11 REFENCE MAP OF VARIABLES

Fl Main program FLOCR
Ag ALGEM
Ai ALGEMI
Ca CRACKING
Ci CRINFIL * - Referenced
De DELTIM = - Defined/Referenced
Fu FLUX
G2 GWS2
Gt GWST
If INFIL
Ii INIFLW
It ITERA
Kp KPSI
Te TETPSI
Th THETA
Va Variable name

Va	Fl	Ag	Ai	Ca	Ci	De	Fu	G2	Gt	If	Ii	It	Kp		Te	Th
A				=			*			*	=					
AG		=	=									=				
AGEM		=			*		=									
AHDZ				=							=	*				
ALFA		*	*	*		*					=	*	*			
ASTER									*		=					
BFACT										*	=					
BVAL									*		=					
DAQ								*	*		=					
DD									*		=					
DELLD1	=															
DELTAT	=				*	=				*					*	
DELTAZ				=				*	*		=					
DELVM					=											
DELVM1	=															
DELW	=															
DELZ				=												
DRINT											=					
ET	*									*	=					
EVAP										=	=					
GRENS			*	*			*					=	*	*		
GRWST	*							=	=		=					
HA								*	*		=					
HG									=							

VA	Fl	Ag	Ai	Ca	Ci	De	Fu	G2	Gt	If	Ii	It	Kp		Te	Th
ID		*	*				*					*	=			
IDENT								*	*		=					
ILUN						=										
INFO	=										*					
INPUT	=										=					
IPSIAL	=															
ITRANS	*			*		*	*		*		=			*		
J	*				*			*	*		=		=	*		
K							*		=	*	=	*	=			
K0						*			*	*	=	*	*			
KOVER												=				
LAAGD	*	*		=	=	*					=	*		=	=	
LAAGDM	*				*						=			*	*	
LAAGNR											=					
MAXT	*					*					=			*		
NDPART	*										=					
NDRAIN	=										=					
NDRINT	=										=					
NJAAR	=										=					
NLAAG	*								*		=				*	
NLAYER	=			=	=	*					=		*			
NPARTS	*										=					
NPG									*		=					
NPROFL				*		*	*				=					
NSTEPS	=															
NTRANS											=					
OUTPUT											=					
POOL	*								*	=	=					
POOLMX										*	=					
PSI	*	*						*	*	*	=	*	*	=		
PSIT			*			*					=			*		
PSITER												=				
RAIN										=	=					
REGEN	*									*	=					
RLAAGD0				=												
RMRATIO				=												
RUNOFF										=						
SRPLUS	*									=	=				=	
SVA	*							=	=							
SUMEA	=															
SUMEP	=															
SUMP	=															
SUMRNF	*									=						

Va	Fl	Ag	Ai	Ca	Ci	De	Fu	G2	Gt	If	Ii	It	Kp	Te	Th
SUMVCR	*				=										
SUMVDR	=														
SUMVINF	=														
TETA	*			=	=						=		*	=	
TETMAX				*	*						=			*	
THETAT	*					*					=		*		
THICK											=				
THICKN											=				
TIMCAL						*					=				
TSTEP	=														
TYD	=										=				
V	=						=		=	=	=	=		*	
VA								*	*		=				
VB	*							=	=						
VCR	=				*					=					
VCRACK	*									=					
VCRACK1										=					
VCRACK2										=					
VD	*							=	=						
VIN	*									=				=	
VOUT										=					
VPOR				=											
VRATIO				=											
VSCH	*			=	=					*	=		=	=	
VSCH0				=											
VSCHT		=													
VVOCHT				=											