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*G. v. Bahel*

## WATBAL

A simple water balance model for a unsaturated/saturated  
soil profile

J.T. Berghuijs - van Dijk

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## SUMMARY AND READING GUIDE

The model WATBAL simulates the water balance of a (cropped) soil in a simple and fast way, dividing the soil profile in two layers:

- the rootzone
- a layer below the rootzone as least as deep as the lowest occurring groundwater table.

The model calculates analytically per timestep:

- changes in moisture contents of these two layers
- changes in groundwater level

as influenced by

- precipitation
- evapotranspiration
- capillary rise from layer 2 to layer 1
- transport from layer 1 to layer 2
- drainage to possible different defined drainage systems.

Inputs concern:

- dimensions and most important soil characteristics of the two layers
- data on drainage systems
- soil cover characteristic of the crop
- precipitation and open-water evaporation data per timestep

The basic principles of the model are given in chapter 1.

In chapter 2 these are worked out for the chosen two-layer system.

Chapter 3 gives some results of a testrun.

For the user of WATBAL the necessary information is found in chapter 3 and in appendix A, which give directions for input, and explanation of output.

For the modeller who wants to change or further develop parts of the computer program appendix B, which contains a description of the program, is useful.

## PREFACE

Knowledge of the transport processes in a soil profile is essential for describing the behaviour of solutes in this soil profile.

Especially the transformation and transport processes of nitrogen species in soil is strongly influenced by moisture effects. Therefore a good watermanagement model is a prerequisite for a good nitrogen model.

The dutch Ministries of Agriculture and Fisheries and of Housing, Physical Planning and Environmental Hygiene have financed a project to develop a model which can predict nitrate leaching to groundwater as a result of agricultural activities on long-term scale. This project is carried out at the Institute for Land and Water Management Research (ICW) in Wageningen.

Because a number of processes in the nitrogen cycle is either not yet adequately known or dependent on local short-term weather conditions which are unpredictable, such a long term model will only be able to give global predictions. For describing the water management, existing models can be used, like the model SWATRE (Belmans e.a., 1983), developed at ICW. A disadvantage of this model is that rather detailed input is needed. The precision and the very small timestep ( $<0.1$  day) with which SWATRE describes the water management, are superfluous compared to the precision with which the nitrogen processes can be described. Therefore a model is developed which describes the water management of a soil profile in a more global way. The model should meet the following demands:

- Input of only the most important soil characteristics
- Good simulation of the water management of the root zone, in which the processes, resulting in nitrate leaching, take place
- Good simulation of the movement of the groundwater table, which is especially of importance for the process of denitrification
- Quantification of real evapotranspiration, capillary rise, drainage and deep percolation, which are important for crop production and N-content of the crop, and N disappearance from the soil-root system
- Not too expensive in computer time, because many long-term alternatives should be calculated easily.

Of course this model can also be used for other purposes than described above.

I would like to thank dr.ir. P.E. Rijtema and ir. C.W.J. Roest for their help and inspiration, and ing. H. Fonck for providing the necessary field data for the test run.

Joantine Berghuijs

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## 1. BASIC EQUATIONS

The water balance of the upper soil layer with plant cover can be written as:

$$\frac{dM}{dt} = PR - E_{re} - f_t - f_d - f_r + f_c$$

in which

- M = available amount of moisture for evapotranspiration (m)
- PR = precipitation (m d<sup>-1</sup>)
- E<sub>re</sub> = real evapotranspiration (m d<sup>-1</sup>)
- f<sub>t</sub> = transport to deeper layers (m d<sup>-1</sup>)
- f<sub>d</sub> = drainage (m d<sup>-1</sup>)
- f<sub>r</sub> = runoff (m d<sup>-1</sup>)
- f<sub>c</sub> = capillary rise from deeper layers (m d<sup>-1</sup>)

For the potential evapotranspiration of a cropped soil surface the equation

$$E_{max} = \alpha * E_0$$

can be used, in which

- E<sub>max</sub> = potential evapotranspiration (m d<sup>-1</sup>)
- α = crop reduction factor (-)
- E<sub>0</sub> = open-water evaporation (m d<sup>-1</sup>)

This relation holds for situations of complete soil cover and/or precipitation surplus, i.e.  $PR - E_0 \geq 0$ . When  $PR - E_0 < 0$  and the soil is not completely covered, potential soil evaporation will be limited because the top-layer of the soil dries out. Rijtema and Aboukhaled (1975) used an extra reduction factor for E<sub>0</sub> under dry circumstances:

$$E_{max} = R_f * \alpha * E_0$$

in which:

- R<sub>f</sub> = reduction factor for potential evapotranspiration under dry circumstances (-)

This reduction factor is dependent on the fraction soil cover (see table 1, from Rijtema and Aboukhaled, 1975).

Table 1.1. Reduction factor R<sub>f</sub> for evapotranspiration under dry circumstances (from Rijtema and Aboukhaled, 1975).

Fraction soil cover	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
R <sub>f</sub>	0.46	0.56	0.63	0.70	0.76	0.83	0.89	0.94	0.97	1.0	1.0

For all circumstances, we can use one equation, by splitting up the time in a dry and a wet part as follows:

$$E_{\max} = \left( \frac{PR}{\alpha * EO} \right) * \alpha * EO + \left( 1 - \frac{PR}{\alpha * EO} \right) * Rf * \alpha * EO$$

The real evapotranspiration,  $E_{re}$ , is dependent on the availability of moisture in the rootzone and the possibility of capillary rise from the subsoil. It is assumed that  $E_{re}$  is equal to  $E_{\max}$  as long as  $PR - \alpha * EO \geq 0$  or in case  $PR - \alpha * EO < 0$  and a certain level of desiccation of the rootzone has not been reached. At further desiccation  $E_{re}$  is a function of the evapotranspiration surplus and the moisture content of the rootzone (Rijtema and Roest, 1984):

$$E_{re} = \frac{M}{a * M_0} * E_{\max}$$

in which:

$E_{re}$  = Real evapotranspiration (m d<sup>-1</sup>)  
 $M_0$  = Amount of moisture available at field capacity in rootzone (m)  
 $a$  = fraction of  $M_0$  below which reduction in evapotranspiration takes place

From investigations by Rijtema and Aboukhaled (1975) it appeared that the factor  $a$  is virtually independent of soil type, but strongly influenced by the value of  $(E_{\max} - PR)$ . Following Rijtema and Roest (1984), the relation found by Rijtema and Aboukhaled (1975) for grass and cereals is used:

$$a = 0.7656 * (E_{\max} - PR)^{0.6413}$$

(N.B. parameters in this relation based on  $E_{\max}$  and  $PR$  in cm)  
 For the transport flux to deeper layers a simple relation is used (Rijtema and Roest, 1984):

$$f_t = \frac{(M - M_0)}{(M_s - M_0)} * k$$

in which:

$f_t$  = transport flux to deeper layers (m d<sup>-1</sup>)  
 $M_s$  = amount of moisture available at saturation  
 $k$  = saturated conductivity (m d<sup>-1</sup>)

It is assumed that transport to deeper layers will take place only when the moisture content is above field capacity, that is when  $M > M_0$

The flux to drainage systems can be described using a simplification of the theory of Ernst (1962):

$$f_d = \frac{h - h_d}{Y}$$

in which:

$f_d$  = drainage flux (m d<sup>-1</sup>)  
 $h$  = groundwater level (m) above a chosen  $h = 0$   
 $h_d$  = drainage level (m)

$Y$  = drainage resistance (d)

The drainage resistance can be calculated from:

$$Y = w * L + \frac{L^2}{8 * k * (D + h - h_d)}$$

in which:

$w$  = radial resistance (m-1 d)

$L$  = drain distance (m)

$D$  = distance from drain to drainage basis (m)

If no disturbing layers are present, one can use  $1/4 L$  instead of  $D$ , because 95% of the streamlines are within the layer with depth  $1/4 L$ .

For the deep drainage a fixed  $Y$  can be used.

If we define capillary rise as the flux from below the rootzone into the rootzone, this flux can be expressed as:

$$f_c = q_1 * q_2 * (E_{max} - PR)$$

in which:

$q_1$  = share of layer below root zone in total amount of available moisture for evapotranspiration

$q_2$  = relative depletion of available moisture in layer below root zone

It is assumed that capillary rise takes place only when the moisture content of the rootzone is below field capacity, that is when  $M < M_0$ .

## 2. DEVELOPMENT OF THE MODEL WATBAL

### 2.1. Geometry of the soil system

In the model WATBAL the soil is divided in two layers:

- layer 1: the root zone
- layer 2: the layer below the root zone to a depth below the lowest expected groundwater table.

For each of these layers different physical soil properties can be used.

In the rootzone the moisture is assumed uniformly distributed. In layer 2 the moisture fraction increases linearly with depth, until saturation at groundwater level.

Important parameters in the model are (see fig.2.1):

- d1 = thickness of layer 1
- d2 = thickness of layer 2
- wp1 = volume fraction of moisture at wilting point for layer 1
- wp2 = volume fraction of moisture at wilting point for layer 2
- fc1 = volume fraction of moisture at field capacity for layer 1
- fc2 = volume fraction of moisture at field capacity for layer 2
- sat1 = volume fraction of moisture at saturation for layer 1
- sat2 = volume fraction of moisture at saturation for layer 2

Definitions of moisture contents and groundwater table, used in the model (see fig. 2.2) are:

- M1 = amount of moisture above wilting point present in layer 1 (m)
- M2 = amount of moisture present above the moisture content in the situation when the groundwater table is at the lower boundary of layer 2 (m)
- h = groundwater level (m) above lower boundary of layer 2
- LG = total depth of soil system described (m)

Fig.2.3 gives a schematical explanation of the following definitions of some special moisture contents:

- Ms1 = value of M1 at saturation (m)
- Ms2 = value of M2 at saturation(m)
- MO1 = value of M1 at field capacity(m)
- MO2 = amount of moisture available for evapotranspiration in layer 2 (m). This amount is defined as the moisture difference between situations with groundwater table at a defined level LGC (lowest groundwater table for capillary rise) and a groundwater table of 1m beneath the rootzone ('field capacity' of layer 2)
- z = distance from lower boundary of root zone to LGC
- Mr2 = moisture difference of layer 2 between situations with groundwater table at LGC and at LG.



Figure 2.1. Geometry of layers and moisture fractions.  
 For explanation of terms, see text.

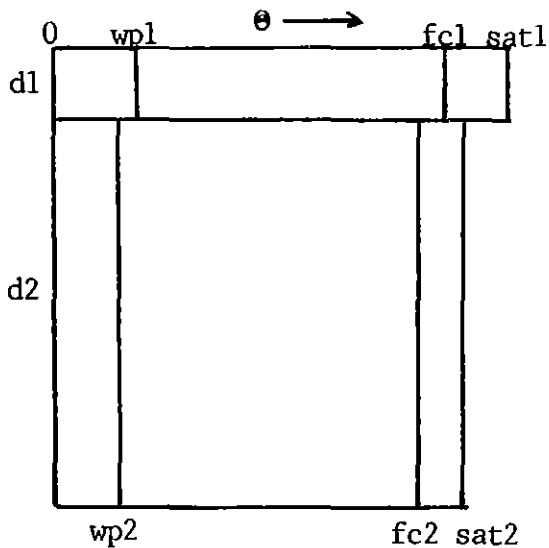


Figure 2.2. Definitions of moisture contents and groundwater table.  
 For explanation of terms, see text.

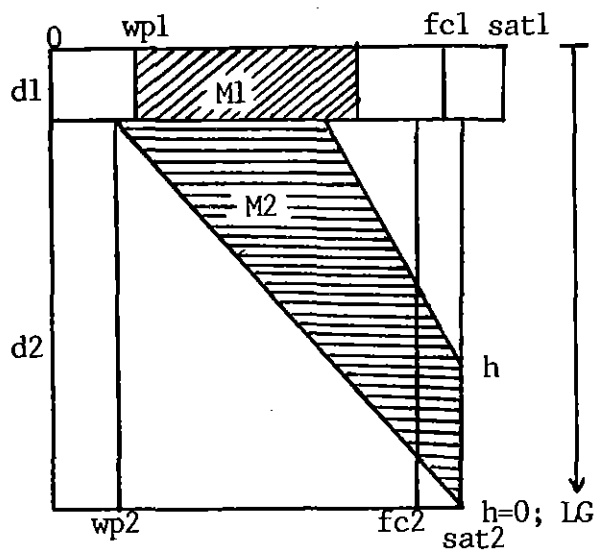
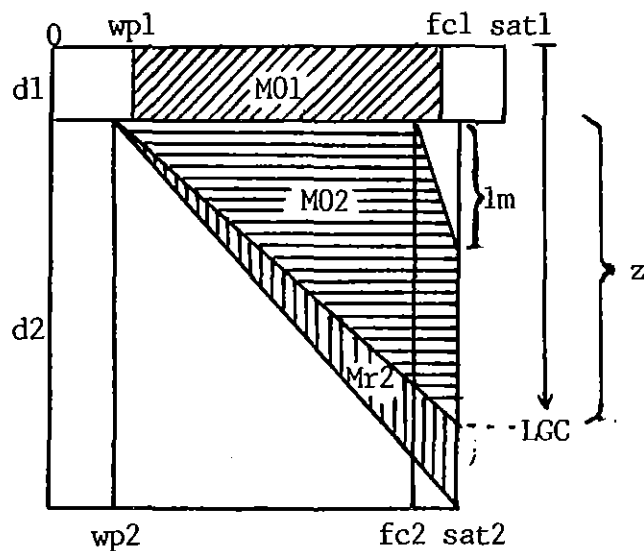


Figure 2.3. Definitions of special moisture contents.  
 For explanation of terms, see text.



In formulas:

$$Ms1 = d1*(sat1 - wp1)$$

$$Ms2 = 0.5*(sat2 - wp2)*d2$$

$$M01 = d1*(fc1 - wp1)$$

$$M02 = 0.5*z*(sat2 - wp2) - 0.5*(sat2 - fc2)$$

$$Mr2 = 0.5*d2*(sat2 - wp2) - 0.5*z*(sat2 - wp2) \\ = 0.5*(sat2 - wp2)*(d2 - z)$$

In coarse sandy soils where  $z < 1m$ , the relation

$$M02 = 0.5*z*(sat2 - fc2)$$

can be used.

## 2.2. Flux equations

The processes, as defined in chapter 2, can be specified for this soil system as follows:

- Potential evapotranspiration flux:

$$E_{max} = \left( \frac{PR}{\alpha * E0} \right) * \alpha * E0 + \left( 1 - \frac{PR}{\alpha * E0} \right) * Rf * \alpha * E0$$

The effective  $\alpha$  for the situation is then calculated from

$$\alpha = \frac{E_{max}}{E0}$$

- Real evapotranspiration flux:

$$E_{re} = \frac{M1(t)}{a * M01} * E_{max} \quad \text{for } PR < \alpha * E0 \text{ and } M1 < a * M01$$

$$E_{re} = E_{max} \quad \text{for all other situations}$$

- Transport from rootzone to deeper layers  
 (only if  $M1 > M01$ ):

$$f_t = \left( \frac{M1(t) - M01}{Ms1 - M01} \right) * k1$$

in which:

$$k1 = \text{saturated conductivity of layer 1 (m d}^{-1}\text{)}$$

- Drainage per drainage system i considered:

$$f_d(i) = \frac{h - h_d(i)}{Y(i)}$$

In principle, with the same equation, infiltration from a drainage system into the soil system can be described, if  $h < h_d(i)$

- Capillary rise flux  
 (only possible if  $M1 < M01$  and  $M2 > M_{r2}$ ):

$$f_c = q_1 * q_2 * (E_{max} - PR)$$

$$f_c = \frac{M02}{M01 + M02} * \frac{M2(t) - M_{r2}}{M02} * (E_{max} - PR)$$

### 2.3. Height of groundwater table

The groundwater level may be defined as a function of  $M2$  in case layer 2 is not saturated. In the model, we use a linear relation:

$$h(t) = r1 * M2(t) + r2 \quad (\text{solution H-1})$$

with  $r1$  and  $r2$  parameters dependent on soil characteristics. In this case, drainage fluxes can be written as a function of  $M2(t)$ :

$$f_d(i) = \frac{r1}{Y(i)} * M2(t) + \frac{r2 - h_d(i)}{Y(i)}$$

If layer 2 is saturated,  $h$  is a function of  $M1(t)$ :

$$h(t) = \frac{M1(t) - M01}{M_{s1} - M01} * d1 + d2 \quad (\text{solution H-2})$$

and the drainage fluxes are expressed as:

$$f_d(i) = \frac{d1}{Y(i) * (M_{s1} - M01)} * M1(t)$$

$$- \frac{1}{Y(i)} * \left( \frac{M01 * d1}{M_{s1} - M01} - d2 + h_d(i) \right)$$

If the total soil profile is saturated,  $h$  is a constant:

$$h(t) = d1 + d2 \quad (\text{solution H-3})$$

and the drainage fluxes are also constant:

$$f_d(i) = \frac{d_1 + d_2 - h_d(i)}{Y(i)}$$

#### 2.4. Calculation of moisture contents

For the rootzone, the moisture conservation equation reads (with between parentheses the moisture content of which the fluxes are dependent):

$$\frac{dM_1}{dt} = PR - E_{re} + f_c(M_2) - f_t(M_1) - f_d(M_1)$$

and for layer 2:

$$\frac{dM_2}{dt} = -f_c(M_2) + f_t(M_1) - f_d(M_2)$$

In both cases either  $f_c$  or  $f_t$  is zero and drainage terms may be absent.

Per situation, dependent on moisture contents and weather conditions, these two interrelated differential equations have different forms. In all cases, one of the equations is independent and must be solved first. If weather conditions are assumed constant during a timestep considered, the two equations can be solved analytically, resulting in new values for  $M_1$ ,  $M_2$  and  $h$ .

Eight different combinations of the two differential equations can be distinguished, according to the state of  $M_1$ ,  $M_2$ , and  $h$ :

1. $M_1 < a \cdot M_{O1}$	$h < d_2$	$M_2 > M_{r2}$ see note
2. ,,	,,	$M_2 < M_{r2}$ see note
3. $a \cdot M_{O1} < M_1 < M_{O1}$	,,	$M_2 > M_{r2}$
4. ,,	,,	$M_2 < M_{r2}$
5. $M_{O1} < M_1 < M_{s1}$	,,	$M_2 > M_{r2}$
6. ,,	,,	$M_2 < M_{s2}$
7. ,,	$d_2 < h < d_1 + d_2$	$M_2 = M_{s2}$
8. $M_1 = M_{s1}$	$h = d_1 + d_2$	$M_2 = M_{s2}$

Note: If, in case 1 or 2,  $PR - E_{MAX} \geq 0$ , the equations are equal to those of case 3 and 4, respectively.

No distinction has been made concerning the groundwater level with respect to depths of the different possible drainage systems. The drainage flux formula of each system is always included in the differential equation; at the beginning of each timestep it is decided which of the systems work, and by placing a parameter  $iwork(i)$  in front of the drainage formula this decision is made effective.

If  $h > h_d(i)$  then  $iwork(i) = 1$

If  $h < h_d(i)$  then  $iwork(i) = 0$ , unless the option of infiltration for the drainage system considered, is chosen.

The eight cases can be worked out as follows:

$$1. M1 < a*M01 \quad h < d2 \quad M2 > Mr2$$

$$\frac{dM1(t)}{dt} = PR - \frac{Em}{a*M01} * M1(t) + \frac{(Em - PR)}{(M01 + M02)} * M2(t) - \frac{(Em - PR)*Mr2}{(M01 + M02)}$$

$$\begin{aligned} \frac{dM2(t)}{dt} = & - \frac{(Em - PR)}{(M01 + M02)} * M2(t) + \frac{(Em - PR)*Mr2}{(M01 + M02)} \\ & - \sum_i \left\{ \frac{iwork(i)*r1}{Y(i)*Ms2} * M2(t) + \frac{iwork(i)*(r2 - hd(i))}{Y(i)} \right\} \end{aligned}$$

$$\begin{aligned} \frac{dM2(t)}{dt} + \left\{ \frac{(Em - PR)}{(M01 + M02)} + \sum_i \frac{iwork(i)*r1}{Y(i)*Ms2} \right\} * M2(t) = \\ - \sum_i \left\{ \frac{iwork(i)*(r2 - hd(i))}{Y(i)} \right\} + \frac{(Em - PR)*Mr2}{(M01 + M02)} \end{aligned}$$

with

$$p4 = \left\{ \frac{(Em - PR)}{(M01 + M02)} + \sum_i \frac{iwork(i)*r1}{Y(i)*Ms2} \right\}$$

and

$$p5 = - \sum_i \left\{ \frac{iwork(i)*(r2 - hd(i))}{Y(i)} \right\} + \frac{(Em - PR)*Mr2}{(M01 + M02)}$$

we get:

$$\frac{dM2(t)}{dt} + p4*M2(t) = p5$$

$$M2(t) = \frac{p5}{p4} - \left( \frac{p5}{p4} - M2(0) \right) * e^{-p4*t} \quad (\text{solution M2-1})$$

The equation for M1(t) can now be written as:

$$\begin{aligned} \frac{dM1(t)}{dt} + \frac{Em}{a*M01} * M1(t) = PR + \frac{(Em - PR)}{(M01 + M02)} * \left\{ \frac{p5}{p4} - \left( \frac{p5}{p4} - M2(0) \right) \right\} * e^{-p4*t} \\ - \frac{(Em - PR)*Mr2}{(M01 + M02)} \end{aligned}$$

with

$$p1 = \frac{Em}{a*M01}$$

$$p2 = PR + \frac{(Em - PR)}{(M01 + M02)} * \frac{p5}{p4} - \frac{(Em - PR)*Mr2}{(M01 + M02)}$$

$$p3 = - \frac{(p5/p4 - M2(0))*(Em - PR)}{(M01 + M02)}$$

we get:

$$\frac{dM1}{dt} + p1*M1(t) = p2 + p3*e^{-p4*t}$$

$$M1(t) = \frac{p2}{p1} + \frac{p3}{p1-p4} * e^{-p4*t} + (M1(0) - \frac{p2}{p1} - \frac{p3}{p1-p4}) * e^{-p1*t} \quad (\text{solution M1-1})$$

$$2. M1 < a*M01 \quad h < d2 \quad M2 < Mr2$$

$$\frac{dM1(t)}{dt} = PR - \frac{Em}{a*M01} * M1(t)$$

with

$$p1 = \frac{Em}{a*M01} \quad \text{and } p2 = PR \text{ this becomes}$$

$$\frac{dM1(t)}{dt} + p1*M1(t) = p2$$

$$M1(t) = \frac{p2}{p1} - \left\{ \frac{p2}{p1} - M1(0) \right\} * e^{-p1*t} \quad (\text{solution M1-2})$$

$$\frac{dM2(t)}{dt} + \sum_i \left\{ \frac{iwork(i)*r1}{Y(i)*Ms2} \right\} * M2(t) = - \sum_i \left\{ \frac{iwork(i)*(r2 - hd(i))}{Y(i)} \right\}$$

with

$$p4 = \sum_i \left\{ \frac{iwork(i)*r1}{Y(i)*Ms2} \right\}$$

and

$$p5 = - \sum_i \left\{ \frac{iwork(i)*(r2 - hd(i))}{Y(i)} \right\}$$

we can use solution M2-1

$$3. \quad a \cdot M01 < M1 < M01 \quad h < d2 \quad M2 > Mr2$$

$$\begin{aligned} \frac{dM1(t)}{dt} &= PR - Em + \frac{(Em - PR)}{(M01 + M02)} \cdot M2(t) - \frac{(Em - PR) \cdot Mr2}{(M01 + M02)} \\ \frac{dM2(t)}{dt} &= - \sum_i \left\{ \frac{iwork(i) \cdot r1}{Y(i) \cdot Ms2} \cdot M2(t) + \frac{iwork(i) \cdot (r2 - hd(i))}{Y(i)} \right\} \\ &\quad - \frac{(Em - PR)}{(M01 + M02)} \cdot M2(t) + \frac{(Em - PR) \cdot Mr2}{(M01 + M02)} \end{aligned}$$

with

$$p4 = \sum_i \left\{ \frac{iwork(i) \cdot r1}{Y(i) \cdot Ms2} + \frac{(Em - PR)}{(M01 + M02)} \right\}$$

and

$$p5 = - \sum_i \left\{ \frac{iwork(i) \cdot (r2 - hd(i))}{Y(i)} \right\} + \frac{(Em - PR) \cdot Mr2}{(M01 + M02)}$$

we can use solution M2-1

The equation for M1(t) can be written as:

$$\begin{aligned} \frac{dM1(t)}{dt} &= PR - Em + \frac{(Em - PR)}{(M01 + M02)} \cdot \left\{ \frac{p5}{p4} - \left( \frac{p5}{p4} - M2(0) \right) \cdot e^{-p4 \cdot t} \right\} \\ &\quad - \frac{(Em - PR) \cdot Mr2}{(M01 + M02)} \end{aligned}$$

with

$$\begin{aligned} p1 &= PR - Em + \frac{(Em - PR)}{(M01 + M02)} \cdot \frac{p5}{p4} - \frac{(Em - PR) \cdot Mr2}{(M01 + M02)} \\ p2 &= - \left\{ \frac{(Em - PR) \cdot (p5/p4 - M2(0))}{(M01 + M02)} \right\} \end{aligned}$$

we get:

$$\frac{dM1(t)}{dt} = p1 + p2 \cdot e^{-p4 \cdot t}$$

for which the solution is:

$$M1(t) = p1*t - \frac{p2}{p4} * e^{-p4*t} + M1(0) + \frac{p2}{p4} \quad (\text{solution M1-3})$$

$$4. \quad a*M01 < M1 < M01 \quad h < d2 \quad M2 < Mr2$$

$$\frac{dM1(t)}{dt} = PR - Em$$

$$M1(t) = M1(0) + (PR - Em)*t \quad (\text{solution M1-4})$$

For M2(t) see case 2 (solution M2-1)

$$5. \quad M01 < M1 < Ms1 \quad h < d2 \quad M2 > Mr2$$

$$\frac{dM1(t)}{dt} = PR - Em - \frac{(M1(t) - M01)}{(Ms1 - M01)} * k1$$

with

$$p1 = \frac{k1}{Ms1 - M01} \quad \text{and} \quad p2 = PR - Em + \frac{M01}{Ms1 - M01} * k1$$

we get:

$$\frac{dM1(t)}{dt} + p1*M1(t) = p2$$

and we can use solution M1-2

$$\begin{aligned} \frac{dM2(t)}{dt} &= \frac{(M1(t) - M01)}{(Ms1 - M01)} * k1 \\ &- \sum_i \left\{ \frac{iwork(i)*r1*M2(t)}{Y(i)*Ms2} + \frac{iwork(i)*(r2 - hd(i))}{Y(i)} \right\} \\ \frac{dM2(t)}{dt} + \sum_i \left\{ \frac{iwork(i)*r1}{Y(i)*Ms2} \right\} * M2(t) &= - \sum_i \left\{ \frac{iwork(i)*(r2 - hd(i))}{Y(i)} \right\} \\ &+ \frac{(p2/p1 - M01)}{(Ms1 - M01)} * k1 - \frac{(p2/p1 - M1(0))}{(Ms1 - M01)} * k1 * e^{-p1*t} \end{aligned}$$

with

$$p4 = \sum_i \left\{ \frac{iwork(i)*r1}{Y(i)*Ms2} \right\}$$



$$p5 = - \sum_i \left\{ \frac{iwork(i) * (r2 - hd(i))}{Y(i)} \right\} + \frac{(p2/p1 - M1(0))}{(Ms1 - M01)} * k1$$

$$p6 = - \frac{(p2/p1 - M1(0))}{(Ms1 - M01)} * k1$$

we get:

$$\frac{dM2(t)}{dt} + p4 * M2(t) = p5 + p6 * e^{-p1 * t}$$

for which the solution is:

$$M2(t) = \frac{p5}{p4} + \frac{p6}{p4 - p1} * e^{-p1 * t} + (M2(0) - \frac{p5}{p4} - \frac{p6}{p4 - p1}) * e^{-p4 * t}$$

(solution M2-2)

$$6. M01 < M1 < Ms1 \quad h < d2 \quad M2 < Mr$$

For M1(t) see case 5; solution M1-2

For M2(t) see case 2; solution M2-1

$$7. M01 < M1 < Ms1 \quad d2 < h < d1 + d2 \quad M2 = Ms2$$

$$\frac{dM1(t)}{dt} + \sum_i \left\{ \frac{iwork(i) * d1}{Y(i) * (Ms1 - M01)} \right\} * M1(t) =$$

$$PR - Em + \sum_i \left\{ \frac{iwork(i)}{Y(i)} * \left( \frac{M01 * d1}{Ms1 - M01} - d2 + hd(i) \right) \right\}$$

with

$$p1 = \sum_i \left\{ \frac{iwork(i) * d1}{Y(i) * (Ms1 - M01)} \right\}$$

$$p2 = PR - Em + \sum_i \left\{ \frac{iwork(i)}{Y(i)} * \left( \frac{M01 * d1}{Ms1 - M01} - d2 + hd(i) \right) \right\}$$

we get:

$$\frac{dM1(t)}{dt} + p1 * M1(t) = p2$$

and we can use solution M1-2

$$M2(t) = Ms2 \quad \text{(solution M2-3)}$$

$$8. M1 = Ms1$$

$$h = d1 + d2$$

$$M2 = Ms2$$

$$M1 + Ms1$$

(solution M1-5)

$$M2 = Ms2$$

(solution M2-3)

In this case, the soil is saturated, and in case the precipitation surplus is greater than the drainage, surface runoff will take place.

Summarized, the combinations of solutions for the 8 cases are:

M1	h	M2	solutions		
			M1	M2	h
1. $M1 < a \cdot M01$	$h < d2$	$M2 > Mr2$	1	1	1
2. ,,	,,	$M2 < Mr2$	2	1	1
3. $a \cdot M01 < M1 < M01$	,,	$M2 > Mr2$	3	1	1
4. ,,	,,	$M2 < Mr2$	4	1	1
5. $M01 < M1 < Ms1$	,,	$M2 > Mr2$	2	2	1
6. ,,	,,	$M2 < Ms2$	2	1	1
7. ,,	$d2 < h < d1+d2$	$M2 = Ms2$	2	3	2
8. $M1 = Ms1$	$h = d1 + d2$	$M2 = Ms2$	5	3	3

## 2.5. Validity of chosen solutions

If, within a timestep, M1 or M2 or h reach a boundary value for the validity of their solutions, another combination of solutions must be chosen for the remaining part of the timestep. The point of time when the boundary is reached,  $t_{lim}$ , has to be calculated. In some cases this can be done analytically, in others not. For simplicity of modelling, WATBAL calculates  $t_{lim}$  in a numerical way for all cases. It should be mentioned here that in spite of the direct dependence of h from M1 or M2, the validity of a set of solutions can be further limited by h because each  $h_d(i)$  represents a limit from which, although the same types of solutions are used, other parameter values have to be used.

## 2.6. Mass balance

At the end of each (part of a) timestep with a certain set of solutions, the mass balance for the profile as a total can be written as:

$$M1(0) + M2(0) + \int_0^t \{PR - Ere - fr - fd\}dt - M1(t) - M2(t) = 0$$

Integration of the different fluxes in time yields:

- for precipitation:

$$\int_0^t PR \, dt = PR * t$$

- for evapotranspiration:

if  $PR \geq E_{max}$  or  $M1 > a * M01$  :

$$\int_0^t E_{re} \, dt = E_{max} * t$$

in other cases:

$$\int_0^t E_{re} \, dt = \int_0^t \frac{E_{max}}{a * M01} * M1(t) \, dt$$

for solution M1-1 this becomes:

$$\begin{aligned} \int_0^t E_{re} \, dt &= \int_0^t \left\{ \frac{E_{max}}{a * M01} * \left( \frac{p2}{p1} + \frac{p3}{p1-p4} * e^{-p4*t} \right) \right. \\ &\quad \left. + \left( M1(0) - \frac{p2}{p1} - \frac{p3}{p1-p4} \right) * e^{-p1*t} \right\} dt \\ &= \frac{E_{max}}{a * M01} * \left\{ \frac{p2}{p1} * t - \frac{p3}{p4 * (p1-p4)} * (e^{-p4*t} - 1) \right. \\ &\quad \left. - \frac{1}{p1} * \left( M1(0) - \frac{p2}{p1} - \frac{p3}{p1-p4} \right) * (e^{-p1*t} - 1) \right\} \end{aligned}$$

and for solution M1-2:

$$\begin{aligned} \int_0^t E_{re} \, dt &= \int_0^t \left\{ \frac{E_{max}}{a * M01} * \left( \frac{p2}{p1} - \left( \frac{p2}{p1} - M1(0) \right) * e^{-p1*t} \right) \right\} dt \\ &= \frac{E_{max}}{a * M01} * \left\{ \frac{p2}{p1} * t + \frac{1}{p1} * \left( \frac{p2}{p1} - M1(0) \right) * (e^{-p1*t} - 1) \right\} \end{aligned}$$

- for runoff:

$$\begin{aligned} \int_0^t fr \, dt &= fr * t \\ &= (PR - E_m) * t - \sum_i \left\{ \frac{(d1 + d2 - hd(i))}{Y(i)} \right\} * t \end{aligned}$$

- for drainage:

if  $h < d_2$  (h in layer 2):

$$\int_0^t f_d dt = \int_0^t \sum_i \left\{ \frac{iwork(i)*r1}{Y(i)} * M_2(t) + \frac{iwork(i)*(r_2 - hd(i))}{Y(i)} \right\} dt$$

in case of solution M2-1 this becomes:

$$\int_0^t f_d dt = \int_0^t \sum_i \left\{ \frac{iwork(i)*r1}{Y(i)} * \left( \frac{p_5}{p_4} - \left( \frac{p_5}{p_4} - M_2(0) \right) * e^{-p_4*t} \right) + \frac{iwork(i)*(r_2 - hd(i))}{Y(i)} \right\} dt$$

$$= \sum_i \left\{ \frac{iwork(i)*r1}{Y(i)} * \frac{p_5}{p_4} * t + \frac{iwork(i)*(r_2 - hd(i))}{Y(i)} * t + \frac{iwork(i)*r1}{p_4*Y(i)} * \left( \frac{p_5}{p_4} - M_2(0) \right) * (e^{-p_4*t} - 1) \right\}$$

and in case of solution M2-2:

$$\int_0^t f_d dt = \int_0^t \sum_i \left\{ \frac{iwork(i)*r1}{Y(i)} * \left( \frac{p_5}{p_4} + \frac{p_6}{p_4 - p_1} * e^{-p_1*t} + \left( M_2(0) - \frac{p_5}{p_4} - \frac{p_6}{p_4 - p_1} \right) * e^{-p_4*t} + \frac{iwork(i)*(r_2 - hd(i))}{Y(i)} \right) \right\} dt$$

$$= \sum_i \left\{ \frac{iwork(i)*r1}{Y(i)} * \frac{p_5}{p_4} * t \right\} + \sum_i \left\{ \frac{iwork(i)*(r_2 - hd(i))}{Y(i)} * t \right\} + \sum_i \left\{ \frac{iwork(i)*r1}{Y(i)} * \left( \frac{p_6}{p_1*(p_4 - p_1)} * (1 - e^{-p_4*t}) + \frac{1}{p_4} * \left( M_2(0) - \frac{p_5}{p_4} - \frac{p_6}{p_4 - p_1} \right) * (1 - e^{-p_4*t}) \right) \right\}$$

for  $h > d_2$  (h in layer 1):

$$\int_0^t f_d dt = \int_0^t \sum_i \left\{ \frac{d_1}{Y(i)*(M_{s1} - M_{O1})} * M_1(t) - \frac{1}{Y(i)} * \left( \frac{M_{O1}*d_1}{M_{s1} - M_{O1}} - d_2 + hd(i) \right) \right\} dt$$

In this case, only solution M1-2 occurs, and we get:

$$\begin{aligned} \int_0^t f_d dt &= \int_0^t \sum_i \left\{ \frac{d1}{Y(i) * (Ms1 - M01)} * \left( \frac{p2}{p1} - \left( \frac{p2}{p1} - M1(0) \right) * e^{-p1*t} \right) \right. \\ &\quad \left. - \frac{1}{Y(i)} * \left( \frac{M01*d1}{Ms1 - M01} - d2 + hd(i) \right) \right\} dt \\ &= \sum_i \left\{ \frac{d1*t}{Y(i) * (Ms1 - M01)} * \frac{p2}{p1} - \frac{t}{Y(i)} * \left( \frac{M01*d1}{Ms1 - M01} - d2 + hd(i) \right) \right. \\ &\quad \left. + \frac{d1}{p1 * Y(i) * (Ms1 - M01)} * \left( \frac{p2}{p1} - M1(0) \right) * (e^{-p1*t} - 1) \right\} \end{aligned}$$

If  $h = d1 + d2$  (profile saturated; runoff)

$$\int_0^t f_d dt = \int_0^t \sum_i \left\{ \frac{d1 + d2 - hd(i)}{Y(i)} \right\} dt = \sum_i \frac{(d1 + d2 - hd(i)) * t}{Y(i)}$$

- for capillary rise:

This integral is not needed for the mass balance of the soil profile as a whole, because it concerns only a redistribution of moisture. It is, however, useful for calculating the flux towards the root zone, which can be used in a water quality model.

$$\int_0^t f_c dt = \int_0^t \left\{ \frac{Em - PR}{M01 + M02} * M2(t) - \frac{(Em - PR) * Mr2}{M01 + M02} \right\} dt$$

for solution M2-1, the only one occurring when capillary rise takes place, this becomes:

$$\begin{aligned} \int_0^t f_c dt &= \int_0^t \left\{ \frac{Em - PR}{M01 + M02} * \left( \frac{p5}{p4} - \left( \frac{p5}{p4} - M2(0) \right) * e^{-p4*t} \right) \right\} dt \\ &\quad - \frac{(Em - PR) * Mr2}{M01 + M02} * t \\ &= \frac{Em - PR}{M01 + M02} * \left( \frac{p5}{p4} * t + \frac{1}{p4} * \left( \frac{p5}{p4} - M2(0) \right) * (e^{-p4*t} - 1) - Mr2 * t \right) \end{aligned}$$

- for transport from the rootzone:

The same remark as for capillary rise applies: this integral is useful for water quality calculations.

$$\int_0^t f_t dt = \int_0^t \left\{ \frac{k1}{Ms1 - M01} * (M1(t) - M01) \right\} dt$$

$$= \frac{k_1}{M_{s1} - M_{O1}} * (M_1(t)dt - M_{O1} * t)$$

for case 6 this becomes:

$$\int_0^t f_t dt = \frac{k_1}{M_{s1} - M_{O1}} * \left\{ \frac{p_2}{p_1} * t + \frac{1}{p_1} * \left( \frac{p_2}{p_1} - M_1(0) \right) * (e^{-p_1 * t} - 1) - M_{O1} * t \right\}$$

and for case 8:

In this case the drainage fluxes also go through layer 1 first, and we have to make a distinction between the part of the drainage that is flowing out of layer 1 directly and the part that is flowing out of layer 2. If the flux intensity towards the drainage systems is the same throughout the whole soil profile, the transport to layer 2 is:

$$\begin{aligned} \int_0^t f_t dt &= \int_0^t f_d dt - \int_0^t \sum_i \frac{i_{work}(i) * d_1}{LG - h_d(i)} * f_d(i) dt \\ &= \int_0^t \sum_i \left( 1 - \frac{i_{work}(i) * d_1}{LG - h_d(i)} \right) * f_d(i) dt \\ &= \sum_i \left\{ \left( 1 - \frac{i_{work}(i) * d_1}{LG - h_d(i)} \right) * \left( \frac{d_1 + d_2 - h_d(i)}{Y(i)} \right) * t \right\} \end{aligned}$$

and for case 7:

In this case the watertable is variable and the drainage integral is more complicated. We can use the same formulation as above taking the average value of h during the timestep:

$$\begin{aligned} h' &= 0.5 * (h(0) - h(t)) \\ \int_0^t f_t dt &= \sum_i \left\{ \left( 1 - \frac{i_{work}(i) * (h' - d_2)}{LG - h_d(i)} \right) * \left( \frac{h' - h_d(i)}{Y(i)} \right) * t \right\} \end{aligned}$$

(Formulated like this, it is assumed that the saturated conductivity of layer 1 is always greater than the drainage capacity at full saturation of the profile!).

### 3. TEST OF THE MODEL USING FIELD DATA

To test the model WATBAL data of a permanent grassland field on sandy soil for the year 1981 at Ruurlo are used (Fonck, 1982a, 1982b, 1984).

The results will be compared to those obtained with the model SWATRE (Belmans e.a., 1983) for the same situation.

#### 3.1. Input data

In table 3.1 a survey is given of the input data for WATBAL and a global indication of the data needed for SWATRE. It is obvious that WATBAL is much more simple to use; as a consequence, the results of WATBAL cannot be as detailed as those of SWATRE.

Table 3.1 can be used as an example for the order in which the input data for WATBAL are needed. These data should be present in a file with the name WATBAL.IN.

#### 3.2. Results and comparison with SWATRE

The results of a run with WATBAL can be found in the output files WATBAL.OUT (terms of the water balance) and WATBAL.DAT (specification of the different fluxes needed for a water quality model).

The cumulative values given in WATBAL.OUT of time, evapotranspiration, and  $E_{re}/E_{max}$  quotient are put at zero at termination of each calendar year. The cumulative values of drainage and runoff are put at zero in the middle of each calendar year.

Before starting to evaluate the obtained results, it should be stressed that, when a comparison is made with SWATRE, WATBAL has never been meant as a model competitive to SWATRE. SWATRE is a much more refined model and can provide much more detailed information than WATBAL. Moisture content output values of different layers of SWATRE had to be added up to be comparable to the output of WATBAL. The comparison is only made to evaluate the results of WATBAL referring to a generally accepted good watermanagement model.

Figure 3.1 shows the measured moisture contents and those simulated by WATBAL and SWATRE. It should be mentioned that for the top 1-5 cm no measurements were available, and as "measured" moisture content of the 30 cm rootzone was taken  $6/5 \times$  moisture content of 5-25 cm.

Results of SWATRE give a more regular impression than those of WATBAL. This is caused by the fact that SWATRE can provide output for exactly those days when measurements are made, whereas WATBAL gives standard output for each time-step, but not at intermediate points of time. In spite of this irregularity, the results of WATBAL as a whole give a good simulation of reality, while in SWATRE the rootzone is systematically too dry and layer 2 systematically too wet. Figure 3.2 gives the measured groundwater table changes and those simulated by the two models. Both models tend to give

Figure 3.1. Simulation of moisture data at Ruurlo, 1981

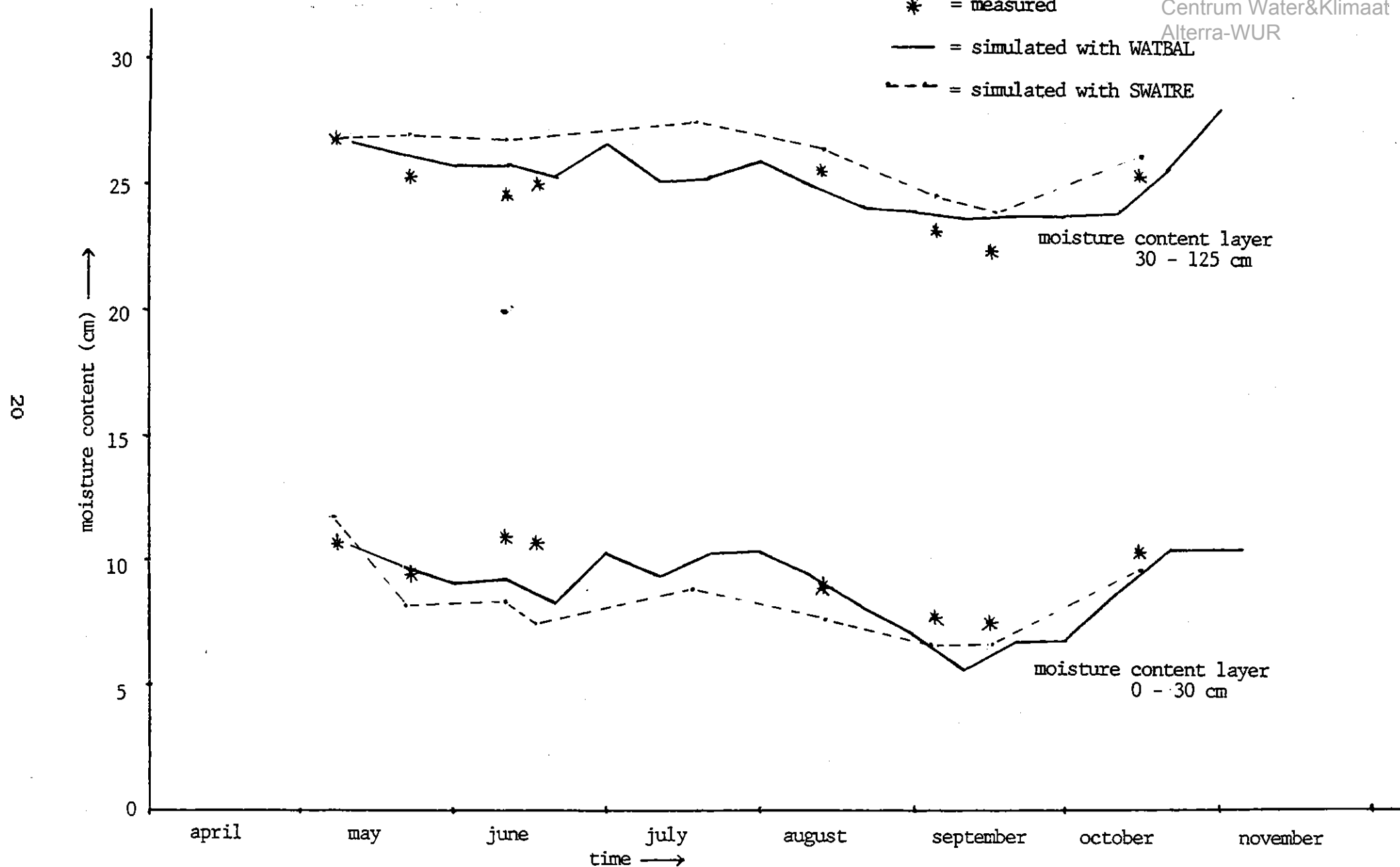
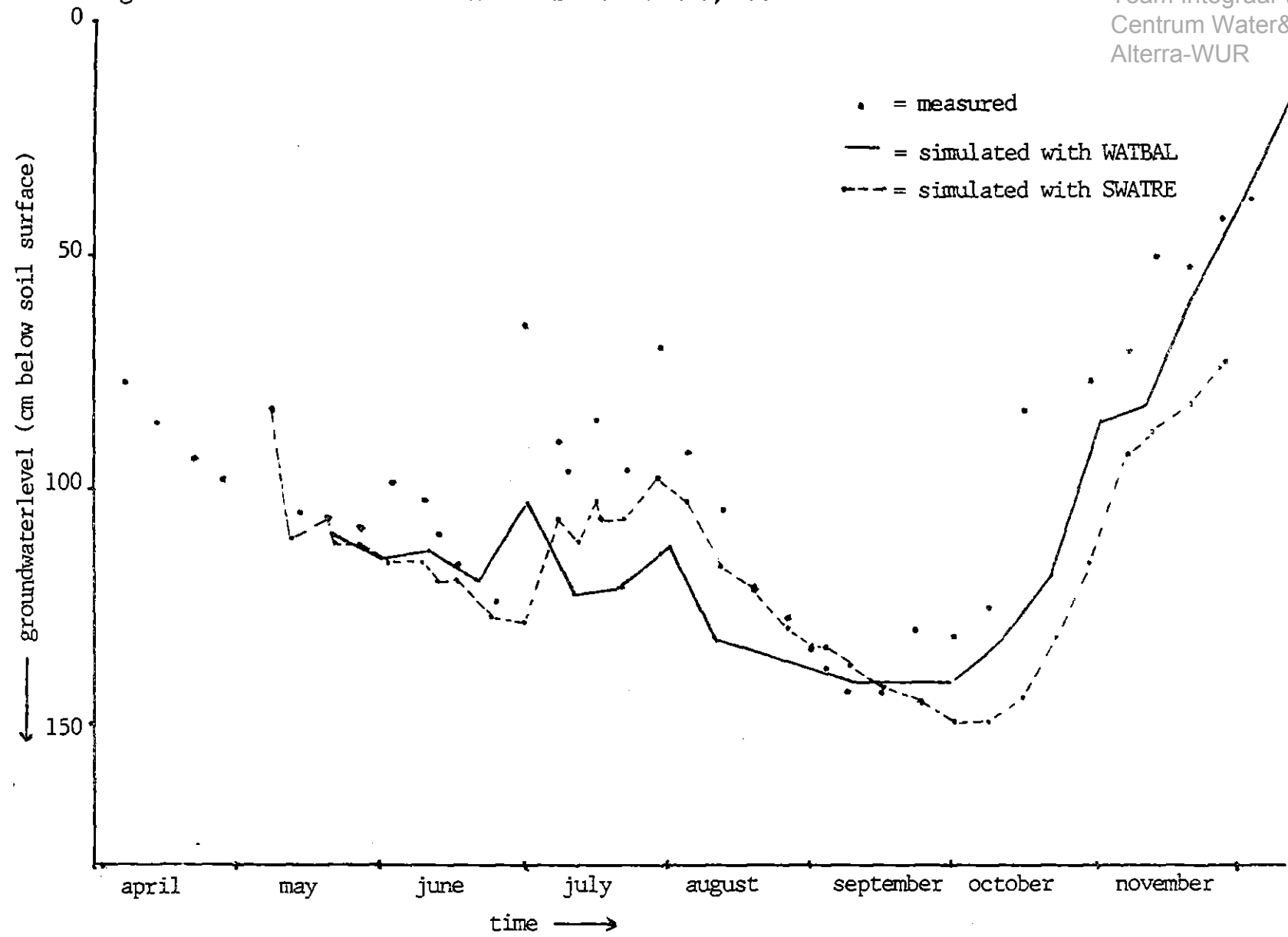




Figure 3.2. Groundwater level simulation at Ruurlo, 1981



a retardation in watertable rise and generally give a too low watertable. SWATRE gives the best results here. This is a result of the strong schematization of the moisture fraction change in layer 2 (linear increase with depth) in WATBAL. The retardation in watertable rise is probably caused by the fact that both models do not take account of irregularities in the soil system like exceptionally big pores or cracks through which the water can move downwards faster. Also, both models do not describe the effect of hysteresis. The computer time needed for WATBAL is about 5 seconds on a VAX 750 computer per year simulated when timesteps of a decade are used.

### 3.3. Sensitivity analysis

For a few input parameters a rough sensitivity analysis was made, by changing that parameter a little compared to the value of table 3.1.

In this context, the input parameter Z (maximal depth from lower boundary of rootzone from which capillary rise can reach the rootzone) is of importance, because Z has to be calibrated. If a value for z would be taken, according to the soil characteristics given by Rijtema (1969), as the depth from which a capillary flux of 0.02 cm d<sup>-1</sup> can reach the rootzone, the model gives a much too great watertable fall in summer resulting from this capillary rise.

A increase or decrease of 7% in z resulted in watertable differences of 5 cm during some periods. M1 was hardly affected, and M2 changed with maximal 2%.

Decreasing ALPHA (still taking the same value for winter and summer for grass) with 12.5% resulted in increased M1 and M2-values of maximal 20 and 3%, respectively, and in watertable increases up to 28 cm.

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Table 3.1. Input data for the model WATBAL

Parameter	description	dimen- sion	value in WATBAL	comparable data SWATRE
initial data:				
ALPHAS	crop reduction factor for summer period	-	0.8	Daily potential evapotranspiration of grass, calculated from detailed meteorological data; parameters for relation suction rootzone-reduction evapotranspiration
ALPHAH	crop reduction factor for winter period	-	0.8	-
TIYR(1-8)	days of the year for which soil cover data are given	-	0. 50. 100. 150. 200. 250. 300. 365.	not relevant because Emax-data are given
SOCOYR(1-8)	soil cover data at corresponding TIYR	-	1. 1. 1. 1. 1. 1. 1. 1.	
SOCO(1-11)	Fraction soil cover for which RF is given	-	see table 1.1	
RF(1-11)	Reduction factor for evapotranspiration in dry periods	-	see table 1.1	
WP1	moisture fraction at wilting point for layer 1	-	0.092	detailed pF-curves for 4 distinct layers
WP2	moisture fraction at wilting point for layer 2	-	0.066	
FC1	moisture fraction at field capacity for layer 1	-	0.345	
FC2	moisture fraction at field capacity for layer 2	-	0.232	
SAT1	moisture fraction at saturation for layer 1	-	0.410	
SAT2	moisture fraction at saturation for layer 2	-	0.340	
D1	thickness layer 1	m	0.30	30 layers of 0.1 m
LG	Lower boundary of layer 2 from soil surface	m	3.00	
TFIX	Length of timestep for which input data are given	d	10.1458	1 day
EXIS(1-4)	existence of drainage systems 0 = non existent 1 = existent	-	1 1 0 0	fd-groundwater level relation including all systems
HD(1-4)	drainage levels			

	from lower boundary of layer 2	m	-1.0 2.3 1. 1.	
INF(2-4)	option for infil- tration	-	0 0 0	
	0 = no inf.possible 1 = inf. if h < hd			
OME(2-4)	radial resistance drainage system	m-1 d-1	0.3 1.0 1.0	
L(2-4)	drain distance per system	m	80. 1. 1.	
D(2-4)	distance from drain to drainage basis	m	25.0 1. 1.	
K(2-4)	saturated conducti- vity near drain	m d-1	0.4 1. 1.	
RES(1)	drainage resistance of system 1	d	45600.	
K1	saturated conduc- tivity of layer 1	m d-1	0.8	
STEPSTART	stepnr. from begin- ning of year when simulation starts	-	10	analogous
YST	year in which simu- lation starts	-	1980	
STEPEND	stepnr. for end of simulation	-	36	
YEND	year in which simu- lation ends	-	1982	
VOL1	moisture content of layer 1	m	0.0995	moisture fraction per layer for the 30 layers
DVOL2	height of layer below rootzone for which VOL2 is given	m	0.95	
VOL2	moisture content of layer below rootzone	m	0.2744	
VOL2D	moisture content of layer below root zone when groundwater table is at lower boundary of this layer	m	0.250	
Z	max. depth ground- water table for capillary rise from lower boundary root- zone	m	0.70	
CO1 and CO2	coefficients for relation calculating evapotranspiration stress (factor a)	-	0.7656 0.6413	
per timestep:				
PR and EO	Precipitation and Open-water evaporation	mm step-1		PR and Emax per day!

In appendix A the meaning of some of the input parameters is explained in more detail for the user of WATBAL.

## APPENDIX A. FURTHER DIRECTIONS FOR THE USER

### A.1 Input data

For the user of WATBAL, some of the input data need a further explanation, which will be given here.

#### ALPHAS and ALPHAW:

Distinction between summer and winter in the values of ALPHAS and ALPHAW can be useful when soil cover functions are not specified and still a global distinction between cropped and uncropped periods should be made.

#### TFIX:

For timesteps of weeks or decades information on weather conditions is usually easy obtainable. In the example of chapter 3, the average length of a decade,  $365/36 = 10.1458$  days, was taken.

EXIS, HD, INF, OME, L, D, K: The drainage parameters.

A maximum of 4 drainage systems can be specified, numbered 1 to 4, according to the following rules:

Numbering of the systems is from bottom to top: nr. 1 is deep drainage or upward seepage, number 2 and 3 are channels or ditches with  $HD(2) < HD(3)$  both in layer 2, number 1 is a ditch or trench with  $HD(4)$  in layer 1.

Existence of one of these systems  $i$  is defined by  $EXIS(i) = 1$ , non-existence by  $EXIS(i) = 0$ .

For the systems 2 to 4 values of EXIS, INF, HD, OME, L, D and K must be given; if a system is non-existent, the value 0 for EXIS and INF and the value 1. for HD, OME, L, D, and K must be given.

System 1 is considered as always present, and the parameter use is a little different from the other systems. Such values of the parameters RES(1) and HD(1) must be given that the desired direction of flux takes place. When deep drainage is desired, HD(1) must be below layer 2 and is negative, when upward seepage is desired, HD(1) must be taken greater than  $d1 + d2$ . Accompanying values of RES(1) are not necessarily realistic, but only have the function of providing the desired seepage or drainage rate.

System 4, if not present in reality, may be used to provide for extra runoff, when the profile is not totally saturated. When timesteps of a week or longer are used, runoff is highly improbable to occur according to the model, because the precipitation is averaged over the timestep.

For system 4, INF must always be 0. The differential equations do not allow infiltration through the system in the rootzone. This may be a subject to be built in in the future.

#### VOL1:

This is the total moisture content of layer 1, including the moisture present at wilting point. Not to be confused with M1 as used in the model.

DVOL2 is a practical parameter only used for input of ini-

tial data, and is the depth over which the initial moisture content of layer 2 is given. Often moisture .op contents are measured to a depth of only 1.5 or 1 m or less, whereas for the model a deeper lower boundary is considered. The model calculates the moisture content of the whole layer 2, assuming the rest of the layer saturated. So DVOL2 is the upper part of D2, and must contain the groundwater table.

**VOL2:**

This is the moisture content of the layer DVOL2.  
(N.B. In the output VOL2 is the moisture content of the whole layer 2).

**VOL2D:**

The moisture content of the layer DVOL2 when the groundwater table is at the lower boundary of this layer. From this value together with DVOL2, the linear relation  $h = r1*M2 + r2$  between moisture content of layer 2 and groundwater table, used in the model, is calculated. The initial height of the groundwater table is not asked as input, but calculated from this relation.

**Z:**

This is the maximal distance from the lower boundary of the root zone from which capillary rise towards the root zone can occur. This parameter has to be calibrated.

N.B. The input data must be given as reals or integers according to the given example.

## A.2 Error detection

If the model, written in Fortran, is compiled with the option /D\_lines, extra output information will be written to a file called WATCON.OUT.

The model itself does not control correctness of input data. In the file WATCON.OUT information is given on intermediate results of calculations.

Most failures are the result of incorrect input.

On some occasions this results in interruption of execution, on others in looping. The extra information is written using the parameter names of the fortran program, which can be found in the dictionary WATBAL.MEM.

For understanding this extra information knowledge of the computer program (as given in appendix B) is necessary.

For normal executions, use of the /D\_lines option is not advisable, because the file WATBAL.CON becomes very large and the calculations require more computer time.

## APPENDIX B.

### Description of the computer program for the modeller

The program consists of 6 main parts:

1. Input initial data and initial calculations
  - 1.1. Input initial data
  - 1.2. Initial calculations
2. Input per timestep; initial calculations per timestep
  - 2.1. Input per timestep
  - 2.2. Calculations once per timestep
3. Choice of solution
  - 3.1. Decide which drainage systems work and calculate drainage resistances
  - 3.2. Type of solution and limits of validity
  - 3.3. Calculation of constants for solution formulas
4. Reduce length of timestep if necessary
  - 4.1. Reduction of timestep if M1 reaches limit of validity
  - 4.2. Reduction of timestep if M2 reaches limit of validity
  - 4.3. Reduction of timestep if H reaches limit of validity
5. Mass balance
6. Time control

and a number of functions and subroutines:

- AFL
- FM1
- FM2
- FH
- SUM1
- SUM2
- TLIM
- OUTPUT

Part 1 is used once in a run, parts 2-6 are used each timestep, parts 3-6 are used more than once per timestep if a limit of validity is reached. The functions and subroutines are often used during one timestep.

The external file COMMON.FOR includes declarations of all variables used, in the main program as well as in the functions and subroutines (except the dummy arguments of the functions and subroutines). It also contains all COMMON-statements used (except the dummy arguments and one COMMON-block used in OUTPUT). In the main program as well as in all the functions and subroutines, the whole WATCOM.FOR is included for convenience of programming, although not always all the variables need to be transferred to all the functions and subroutines.

The calculations performed by each of the program parts will be explained now, in the order given above.



## 1. Input initial data and initial calculations

### 1.1. Input initial data

Declaration of input- and output files:

WATBAL.IN = input file

WATBAL.OUT = output file containing terms of the water balance

WATCON.OUT = file containing extra information on intermediate results of calculations. See appendix A.2.

Only used when the program is compiled with the /D\_lines option.

Reading the input data from WATBAL.IN:

See table 3.1 and Appendix A for explanation.

### 1.2. Initial calculations

Moisture contents at defined points:

For D1, M01, M02, MS1, MS2, and MR2 see chapter 2.1.

Starting with M2D, the parameters R1 and R2 in the linear relationship between M2 and H, which has the form

$$H = R1 \cdot M2 + R2$$

are calculated. Two (M2,H) pairs are needed.

One is the pair (H = D2, M2 = MS2)

The other is (H = D2 - DVOL2, M2 = M2D). This is the situation when the groundwater table is at the lower boundary of the part DVOL2 of layer 2 for which the moisture content is given. This moisture content is VOL2D. First VOL2D is converted in terms of M2 by adding the saturated moisture content of the rest of layer 2 and then subtracting the not-available moisture of layer 2 (see ch. 2.1):

$$\begin{aligned} M2D &= VOL2D \\ &+ SAT2 \cdot (D2 - WP2) \\ &- WP2 \cdot D2 - 0.5 \cdot (SAT2 - WP2) \cdot D2 \end{aligned}$$

The R1 and R2 calculation continues under the heading "groundwater level". First the available moisture contents at start of simulation, M1 and M2 are calculated. The given starting moisture content VOL2 is corrected by adding up the rest of the moisture present in layer 2:

$$VOL2 = VOL2 + (D2 - DVOL2) \cdot SAT2$$

Then the not-available moisture per layer (see ch. 2.1) is subtracted, giving M1 and M2, respectively.

The linear relationship between M2 and h can be written in terms of the two (h,M2) points:

$$h = (D2 - DVOL2) - \frac{DVOL2}{MS2 - M2D} \cdot (M2 - M2D)$$

or:

$$h = (D2 - DVOL2) - \frac{DVOL2}{MS2 - M2D} * M2D + \frac{DVOL2}{MS2 - M2D} * M2$$

so the desired parameters are:

$$r1 = \frac{DVOL2}{MS2 - M2D} \quad \text{and} \quad R2 = (D2 - DVOL2) - \frac{DVOL2}{MS2 - M2D} * M2D$$

and H can be calculated. If layer 2 is saturated and the groundwater table is in layer 1, another relationship is used:

$$H = \frac{M1 - M01}{MS1 - M01}$$

The groundwater level GRWALE is expressed as depth beneath soil surface.

Time variables:

STEP = STEPSTART - 1 is done because the input is expected to be given in the form of: "we start with the 10th decade of the first year, and the input for this 10th decade is: ..."

In reality the starting point in time then is the end of the 9th decade.

TIME is the variable that represents the time during a year, expressed in days.

T is current timestep length. At the beginning of each timestep it is given the value TFIX. During execution, it can be temporarily decreased.

CALL OUTPUT(1): at the end of each part of the main program specific output concerning that part is written to the output-file(s).

## 2. Input per timestep; initial calculations per timestep

### 2.1 Input per timestep

Precipitation and open-water-evaporation can be given in the form in which they are normally given: mm per timestep (week, decade, day).

### 2.2. Calculations once per timestep

The model performs its calculations in m and d: it converts the given weather input data to these units.

Next the precipitation surplus (m) of the timestep and the precipitation flux (m d<sup>-1</sup>) are calculated.

ALPHA is given the value ALPHAS or ALPHAW, according to the time of year.

The fraction soil cover SOC is interpolated from the given 8 data pairs (TIYR, SOCQYR) by the function AFL.

EMAX; see ch. 2.2.

Moisture stress factor A: see ch. 2.2. To prevent divisions

by zero, a very small  $EMAX$  A is assumed when  $EMAX = 0$  and a very small A if no stress is present.

### 3. Choice of solution

#### 3.1. Decide which drainage systems work and calculate drainage resistances

System 1 always works, the other systems I work (if they exist, which is seen from  $EXIS(I) = 1$  or  $0$ ), if  $H > HD(I)$  or  $H < HD(I)$  and infiltration is possible ( $INF(I) = 1$ ). Drainage resistances  $RES(I)$  are calculated according to the formula in ch. 1.

#### 3.2. Type of solution and limits of validity

A set of solutions is chosen according to the scheme given at the end of ch. 2.4., based on the state of M1, M2 and H at the current point of time. The array  $SO(1-3)$  is filled with the numbers of their respective solutions. Limits of validity to both sides (L and R) are given to M1 and M2 according to the same scheme. Limits of validity for H, which are not implicitly given together with limits of M1 or M2, from one of which H is always dependent, can exist of  $HD(I)$  values. At saturation of the profile, when H is a constant, dummy limit values have to be used. Because of the special character of system 1, the deep drainage system, its  $HD(I)$ , which is not beforehand known as situated above or beneath all the others, is separately evaluated.

#### 3.3. Calculation of constants for solution formulas

This is done according to the solutions and solution parameters worked out in ch. 2.4.

### 4. Reduce length of timestep if necessary

4.1. Reduction of timestep if M1 reaches limit of validity

4.2. Reduction of timestep if M2 reaches limit of validity

4.3. Reduction of timestep if H reaches limit of validity

T1, T2 and T3, if they get a value  $> 0$  in one of these parts, represent the reduced length of timestep in which the chosen solutions for M1, M1 and M2, and M1, M2 and H, respectively, are valid.

The procedure in each of these parts is as follows:

1. Exclude certain solutions that will certainly not reach limits.

2. Calculate the expected value of the variable under consideration at the end of the current timestep.

This is done using the function FM1, FM2 or FH.

3. Compare the outcome with the limit values.

4. If one of the limits should be exceeded, calculate the time when this happens, using the function TLIM. That time will be the new timestep length.

## 5. Mass balance

Calculations according to chapter 2.6.

Drainage:

DR(I) is the drainage (m) realized during the timestep for system I.

DRTO(I) is the cumulative drainage (m) realized by system I.

DRTOO(I) is the cumulative drainage realized by system I at the end of the last total timestep.

DRTOT is the drainage realized during the timestep by all systems.

CUMDR is the cumulative drainage realized by all the systems.

Values needed for ANIMO:

ANIMO is the name of the water quality model to which the outputfile WATBAL.DAT will be connected, and for which also the capillary rise and transport (percolation) fluxes are calculated.

## 6. Time control

When the mass balance is correct, the values of M1, M2 and H are given their definitive new values calculated with the functions FM1, FM2 and FH using the timestep T which may be smaller or equal to TFIX.

The part of the total timestep with length TFIX that is over, is represented by TT. As long as  $TT < TFIX$ , a new partial timestep  $T = TFIX - TT$  is taken, for which new solutions have to be determined (back to 300).

If the total timestep is over, the time variables TIME and STEP are given their new values and TT is set at zero.

The output parameters VOL1 and VOL2 and GRWALE are calculated, and T is put at TFIX again.

(Variables needed in ANIMO: output of all separate fluxes (m d<sup>-1</sup>))

If the end of a calendar year is reached, certain cumulations start at new. Drainage and runoff cumulations start at new in the middle of a calendar year.

If the end of the simulation time is not reached, execution continues at 210 by reading new input data for the next timestep.

## Description of functions and subroutines:

- Function AFL(X,Y,N,X1)

This function interpolates between N given (X,Y) pairs on basis of a certain X1. The (X,Y) pairs are given in the arguments with which the function is called, as two arrays X(N) and Y(N) of length N. The X-value for which the interpolated Y-value is needed, is given as the argument X1. X1 Should fall within the range of X(1-N); if not program execution is stopped with the information "extrapolation". At normal executions this never occurs.

- Function FM1(SO,P,T)

This function calculates the value of M1 at time t, using the chosen solution set given by the array SO and the parameter values given by the array P in the argument.

The function uses one of the solutions M1-1 through M1-5

(indicated by the value of  $SO(1)$ ), as worked out in chapter 2.4.

- Function  $FM2(SO,P,T)$

Analogous to function  $FM1$ ; one of the solutions  $M2-1$  through  $M2-3$  is used.

- Function  $FH(SO,P,T)$

Analogous to function  $FM1$ ; one of the solutions  $H-1$  through  $H-3$  is used; because  $H$  is dependent of either  $M1$  or  $M2$ , one of the functions  $FM1$  or  $FM2$  is called with the  $T$  used in the argument of function  $FH$ .

- Function  $SUM1(SO,IDR)$

This function is used when the parameter values  $P(1-6)$  for the solution formulas are calculated.  $SUM1$  is the sum over the  $I$  drainage systems present, occurring in the coefficient  $P(1$  or  $4)$  in the differential equation before  $M1(t)$  or  $M2(t)$ , when the equation is written in the form

$\frac{dM(t)}{dt}$

$----- + P(1 \text{ or } 4)*M = P(2 \text{ or } 5)*f(t) + P(3 \text{ or } 6)$

The argument  $IDR$  gives the number of drainage systems that is possibly working.

The different forms of the sums calculated can be found in ch. 2.4, where the parameter values are derived.

- Function  $SUM2(SO,IDR)$

Analogous to function  $SUM1$ .  $SUM2$  is the sum occurring in  $P(2)$  or  $P(5)$ , behind the equal sign (see above).

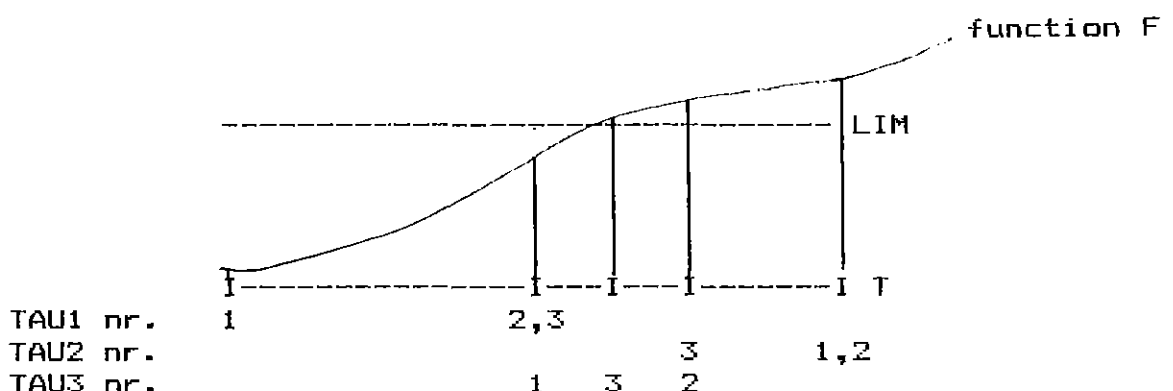
- Function  $TLIM(F,LIM,FO,SO,P,T)$

This function calculates the time when a given limit of validity  $LIM$  in a function  $F$  ( $FM1$ ,  $FM2$  or  $FH$ ), using solution formula  $SO(1$  or  $2$  or  $3$  respectively) with parameter values indicated by the array  $P$  is reached, when the starting value is  $FO$  ( $M1$ ,  $M2$  or  $H$ ) and the original timestep length is  $T$ .

As pointed out in chapter 2.5, this calculation is done in a numerical way, so that one calculation scheme is applicable to all solution types.

The scheme is quite simple (see fig. B.1):

Fig. B.1. Calculation scheme of function  $TLIM$



For  $LIM > F0$  (upper limit will be reached):

1.  $TAU1 = 0$  and  $TAU2 = T$
2.  $TAU3 = 0.5 * (TAU1 + TAU2)$
3. Calculate  $FTRY = F(TAU3)$
4. If  $F(TAU3) > LIM$  the difference with  $LIM$  is evaluated; if not continue with step 7.
5. If  $F(TAU3) - LIM < 0.001 * LIM$  then  $TLIM$  is found and is equal to  $TAU3$ . If not, continue with next step.
6. If  $F(TAU3) > LIM$ ,  $TAU2$  gets the value of  $TAU3$  and go to step 2.
7. If  $F(TAU3) < LIM$ ,  $TAU1$  gets the value of  $TAU3$  and go to step 2.

In this way a  $F(TAU3)$  is found, that is always just a little above  $LIM$ . This is done deliberately, so that no choice problems will occur when new solution sets are subsequently determined in the main program.

For  $LIM < F0$  (lower limit will be reached) the procedure is the same, except that now a value of  $F(TAU3)$  just smaller than  $LIM$  is desired. This is reached by putting  $Q = -1$  in this case, and  $Q = 1$  in the former. Step 4 for both cases can then be put as:

4. If  $Q * (F(TAU3) - LIM) > 0$  etc.

- Subroutine  $OUTPUT(NROUT)$

Each time this subroutine is called, only a part of it is used. The argument  $NROUT$  gives the number of the main part of the program from which the subroutine is called. With this number a jump to a certain part of the subroutine is calculated, where the output for that specific part of the main program is formulated. After termination of the output of that part a return to the main program is made.