



SVENSKA LANTBRUKSUNIVERSITET  
Institutionen för markvetenskap  
Föreläsning i Jordbruksmekanik  
730 07 - UPPSALA 7

BIBLIOTEKET

# Simulation of water flow in plant communities

## - SPAC model description, exercises and user's manual

2nd edition

**SPAC**  
version 5.0

Henrik Eckersten

---

Institutionen för markvetenskap  
Avdelningen för lantbrukets hydroteknik

Swedish University of Agricultural Sciences  
Department of Soil Sciences  
Division of Agricultural Hydrotechnics

Avdelningsmeddelande 97:5  
Communications

Uppsala 1997

ISSN 0282-6569

ISRN SLU-HY-AVDM--97/5--SE

---

Denna serie meddelanden utges av Avdelningen för lantbrukets hydroteknik, Sveriges Lantbruksuniversitet, Uppsala. Serien innehåller sådana forsknings- och försöksredogörelser samt andra uppsatser som bedöms vara av i första hand internt intresse. Uppsatser lämpade för en mer allmän spridning publiceras bl a i avdelningens rapportserie. Tidigare nummer i meddelandeserien kan i mån av tillgång levereras från avdelningen.

This series of Communications is produced by the Division of Agricultural Hydrotechnics, Swedish University of Agricultural Sciences, Uppsala. The series consists of reports on research and field trials and of other articles considered to be of interest mainly within the department. Articles of more general interest are published in, for example, the department's Report series. Earlier issues in the Communications series can be obtained from the Division of Agricultural Hydrotechnics (subject to availability).

---

Distribution:

Sveriges Lantbruksuniversitet  
Institutionen för markvetenskap  
Avdelningen för lantbrukets hydroteknik  
Box 7014  
750 07 UPPSALA

Tel. 018-67 11 85, 67 11 86

Swedish University of Agricultural Sciences  
Department of Soil Sciences  
Division of Agricultural Hydrotechnics  
P.O. Box 7014  
S-750 07 UPPSALA, SWEDEN

Tel. +46-(18) 67 11 85, +46-(18) 67 11 86

---



# Simulation of water flow in plant communities

- SPAC model description, exercises and user's manual

2nd edition



Henrik Eckersten

---

Institutionen för markvetenskap  
Avdelningen för lantbrukets hydroteknik

Swedish University of Agricultural Sciences  
Department of Soil Sciences  
Division of Agricultural Hydrotechnics

Avdelningsmeddelande 97:5  
Communications

Uppsala 1997

ISSN 0282-6569

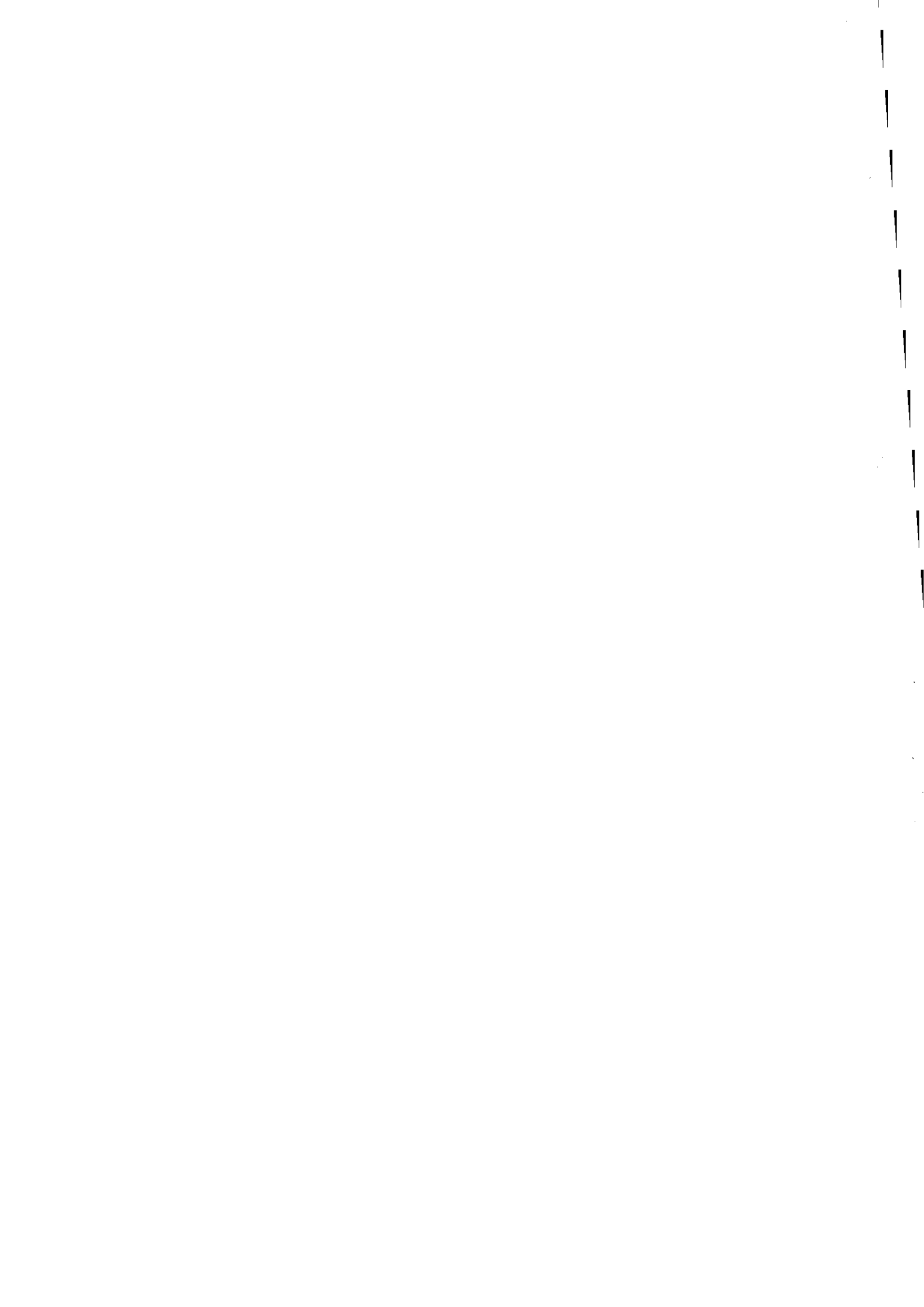
ISRN SLU-HY-AVDM--97/5--SE

---



## Table of Contents

1 PREFACE .....	5
SPAC MODEL DESCRIPTION .....	6
2.1 Plant water .....	7
2.2 Canopy energy balance .....	8
2.3 Resistances .....	9
2.4 Rain interception .....	11
2.5 Soil water .....	12
2.6 Special functions .....	13
SPAC SIMULATION EXERCISES .....	15
Exercise 1; Introduction to a simulation model (SPAC) .....	15
Exercise 2; Plant .....	20
Exercise 3; Effect of sun elevation on evaporation .....	23
Exercise 4; Effect of plant structure on evaporation and energy exchange .....	27
SPAC USER's MANUAL .....	31
4.1 Files .....	31
4.2 SWITCHES .....	32
4.3 PARAMETERS .....	35
4.4 OUTPUTS .....	41
SIMVB MANUAL .....	45
5.1 How to run SPAC .....	45
5.2 Alternative use of SIMvb .....	46
6 LIST OF SYMBOLS .....	49
7 REFERENCES .....	51



## 1 PREFACE

This is the second edition of this report. Compared to the first edition (Eckersten 1995) the sections on SPAC simulation exercises and SIMvb manual have been updated. The model description is only partly updated. The newest version of the model (version 5.1, dated February 1997) includes capillary rise of soil water, which is updated in the description of model outputs (chapter 4) but not described in the model equations (chapter 2).

This report is especially designed for courses in biogeophysics. Two previous published reports, SPAC-GROWTH model description (Eckersten, 1991a) and SPAC-GROWTH user's manual (Eckersten, 1991b), are shortened and put together. This report also describes a new subroutine for soil water dynamics added to the SPAC model version 5.0 (dated 951205). The main objective of introducing the soil module is to get the model more pedagogic in terms of representing a complete water balance of the site. The soil water module includes mainly two processes; estimation of soil water potential in the root zone and soil surface evaporation. Both processes are based on information taken from the SOIL model (Jansson 1991) which is a model representing soil in much more detail. Hence, the modifications of the original description of the SPAC model mainly concern: (i) including a soil water module (ii) taken away the description of the GROWTH submodel, (iii) renaming parameter and variable names used in the computer and (iv) adjust symbols to basically follow Rosenberg et al. (1983) and Eckersten et al. (1995). In addition some new parameters of the model are described. However, note that the parameter list is not complete in this report. A more popular description of SPAC ver 5.0 (written in Swedish) is included in Eckersten et al. (1995).

The report also includes a section for exercises specially designed for studying the dynamics of the SPAC model. These exercises have been used in courses in biogeophysics in 1993 and 1994 at the Swedish University of Agricultural Sciences, and have been developed in collaboration with teachers and students of the courses. Special acknowledgements are given to Elisabet Lewan, Anders Lindroth, Emil Cienciala, Karin Blombäck and Jennie Andersson at the Swedish University of Agricultural Sciences, Uppsala. These exercises are run with help of a WINDOWS based program named SIMvb, which is a further development of SOILNvb described by Eckersten et al (1994). How to use SIMVB is also described in this report.

This model description section serves as a tool when using the model and then should be used together with the User's manual describing variables used in the program etc which is also included in this report. The link between the model description and the manual is through the symbols (see List of symbols). As regards the validity of the model, the reader is referred to other publications (see list of references) in which tests of different parts of the model have been made. The software of the model is available from the author on request.

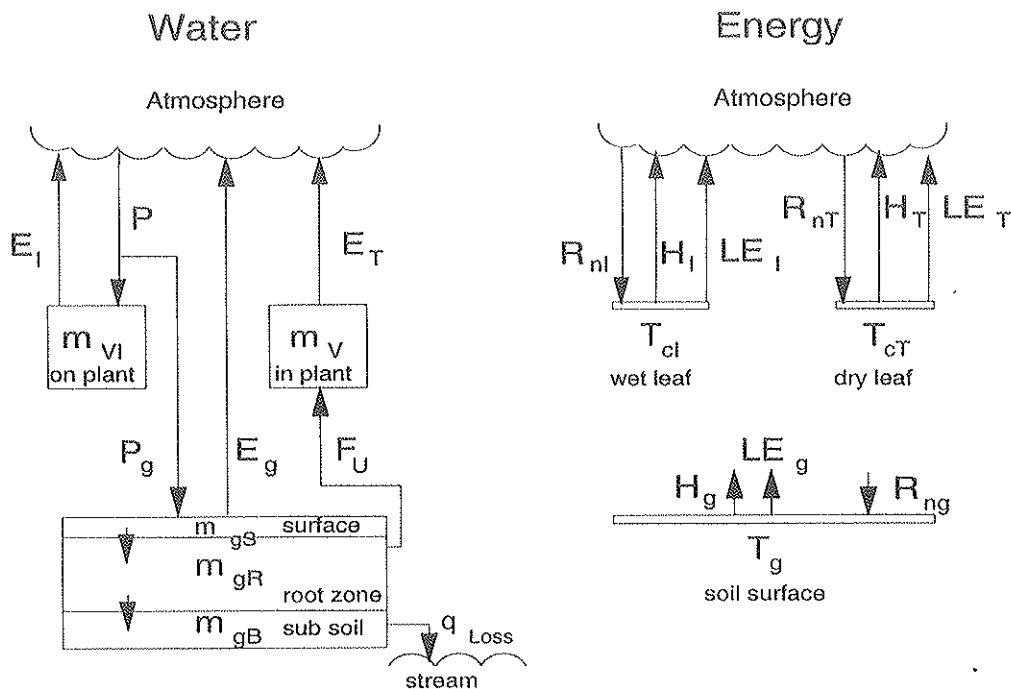
Since the model aims to be a research tool, although hopefully suitable for many practical purposes, it includes possibilities to choose among different hypotheses (see the section on special functions) and will be modified as research makes progress.

A section of the model description usually starts with a short general summary of its contents (written in italics) followed by a more detailed verbal (and graphic) description of the calculation procedure. The section ends with the mathematical expressions. The numbers given to equations, figures and tables are related to the number of the subsection concerned.

## SPAC MODEL DESCRIPTION

The model is a transpiration model based on the Soil-Plant-Atmosphere-Continuum (SPAC) concept simulating the flow of water from soil through the plant to the atmosphere. The model is developed for crops but can be applied on other species as well. The basic version of the model was described by Turner & Kowalik (1983) and Kowalik & Eckersten (1984).

The model (Fig. 300) consists of four compartments, one for easily available water located in the leaves, one for intercepted water on the canopy surface, one for soil water available for plant uptake and for soil water available for soil evaporation. The model simulates flows and states on a ground surface basis and assumes horizontally uniform stands (in terms of the model parameters). The time step of the water submodel is 1-4 minutes. Input data are minute values on global radiation, net radiation, air temperature, air relative humidity, wind speed and precipitation, registered above the canopy. Alternatively daily values on soil water potential can be used as input instead of being simulated. Also daily values of the weather driving variables can be used by choosing special functions generating minute values of temperature, air humidity etc.



**Figure 300.** Schematic description of the SPAC model. Solid lines are flows of water or energy. For explanation of symbols see text and list of symbols.



The leaves contain water which is easily available for transpiration. The transpiration occurs during day-time when stomata are open and the rate is determined by the radiation energy available, the drying "power" of the air and several factors regulating the flow of water from the plant to the atmosphere. The loss of plant water is compensated by the uptake of water from the soil which, however, for several reasons can be delayed or is too small to meet the transpiration demand. If, for instance, the soil water availability is small then the plant water reservoir decreases. The plant then closes its stomata and the transpiration decreases and the plant can stabilize its water status on a new lower level. During the night the stomata are closed and the plant loses water only very slowly through the cuticle. Then the plant can recover to a plant water status close to that of the soil. The flow of water is described in terms of water potentials and resistances.

## 2.1 Plant water

*The amount of easily available water is proportional to the leaf area. It is decreased by transpiration but increased through the root uptake created by the differences in water potentials of the plant and the soil. A closed canopy typically contains much less exchangeable water than is lost and gained daily through transpiration and uptake. Hence the water reservoir is replaced several times a day.*

There is a reservoir of easily available water in the plant ( $m_v$ ) from which water can be transpired ( $E_T$ ). The driving force for transpiration is the vapour pressure difference ( $e_{cs} - e_a$ ) between the air inside the stomata cavities and the ambient air. The flow is retarded by the resistances of stomata ( $r_c$ ) and the air outside the leaf ( $r_a$ ). As the plant loses water from its maximum value ( $m_{vMax}$ ) the canopy water potential ( $\psi_c$ ) drops below that of the soil ( $\psi_g$ ). This difference is the force for uptake of water ( $F_U$ ) against the resistances of the soil ( $r_g$ ) and the plant ( $r_p$ ). Each unit of leaf area can maximally contain  $m_{v0}$  amount of easily exchangeable water corresponding to a maximum water potential ( $\psi_{cMax}$ ). When the reservoir is emptied the canopy water potential is  $\psi_{cMin}$ . The difference in plant water content ( $\delta m_v$ ) during a time-step ( $\delta t$ ) is calculated with a procedure described by Kowalik & Eckersten (1984). (Eqs. 310-313).

$$\delta m_v = (F_U - E_T) \delta t \quad E_T \geq 0 \quad (310)$$

where:

$$F_U = (\psi_g - \psi_c) / (r_g + r_p) \quad (311)$$

$$\psi_c = \psi_{cMax} - (\psi_{cMax} - \psi_{cMin}) (1 - m_v / m_{vMax}) \quad m_{vMax} = m_{v0} LAI \quad (312)$$

$$E_T = \frac{\rho_a C_p}{\gamma L} \frac{e_{cs} - e_a}{r_c + r_a} \quad (313)$$

## 2.2 Canopy energy balance

The radiation energy absorbed by the canopy is used for the evaporation of water from the plant. The evaporation rate (latent heat flux) is also determined by other factors and often, during day-time, more radiation is absorbed than is needed to meet the energy demand by evaporation. Then the canopy surface becomes warmer than the ambient air. The excess heat is leaving the plant through the sensible heat flux. During night or at rainfall, normally the opposite occurs. We assume that the energy storage rate in leaf tissues is negligible in comparison with the other flows. This assumption is perhaps not so good when the other flows are small, as close to sunrise or sunset. The variables determining the partitioning of solar energy between the latent and sensible heat fluxes are for instance wind speed, air humidity and stomatal resistance.

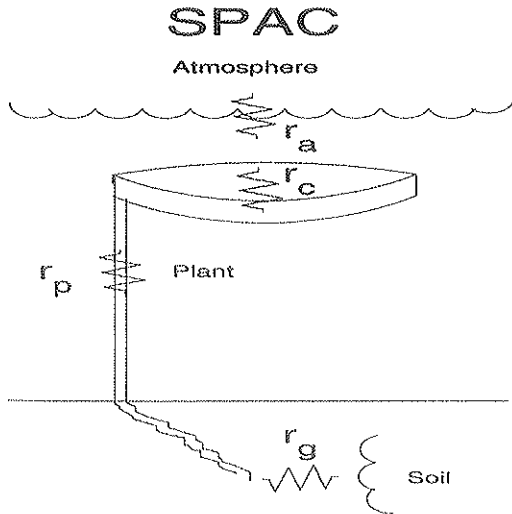
The surface temperature ( $T_c$ ) is adjusted so that the canopy energy balance is fulfilled. The radiation energy exchange between canopy and the surroundings is the net radiation intercepted by the canopy ( $R_{nc}$ ) which is the net radiation above canopy ( $R_n$ ) minus the corresponding value below canopy. The latter value is calculated according to Beers' law using the radiation extinction coefficient ( $\kappa$ ) and the leaf area index (LAI). The energy balance is, in addition to  $R_{nc}$ , also affected by the fluxes of sensible heat ( $H_T$ ) and latent heat ( $LE_T$ ) whereas storage of heat in plant tissues is neglected (Eqs. 320-322).

The sensible heat flux is proportional to the difference between the surface temperature and the air temperature ( $T_a$ ) divided by the resistance for flow of heat in the air which is assumed to be the same as for vapour ( $r_a$ ) (alternative exists, see section on special functions). The latent heat flux (which is proportional to transpiration) is created by the vapour pressure difference between the surface of the stomata cavities ( $e_{cs}$ ) and that of the surrounding air ( $e_a$ ) having a relative humidity equal to  $h_r$ . The air at the evaporating surfaces in stomata is assumed to be at saturation.  $T_c$  is determined by changing its value, using iteration, until the sum of all three fluxes is below a certain limit ( $\Delta_{Max}$ ) which is close to zero (Eqs. 320, 322-324).

$R_{nc} - H_T - LE_T \leq \Delta_{Max}$	$T_c$ is changed until this statement is fulfilled	(320)
<i>where:</i>		
$R_{nc} = R_n(1 - \exp(-\kappa LAI))$		(321)
$H_T = \rho_a C_p (T_c - T_a) / r_a$		(322)
$LE_T = \frac{\rho_a C_p}{\gamma L} \frac{e_{cs} - e_a}{r_c + r_a}$		(313)
$e_{cs} = a_c \exp((b_c T_c' - c_c) / (d_c T_c' - e_c))$	$T_c' = T_c + 273.15$	(323)
$e_a = h_a e_s$		(324a)
$e_s = a_a \exp((b_a T_a' - c_a) / (d_a T_a' - e_a))$	$T_a' = T_a + 273.15$	(324b)

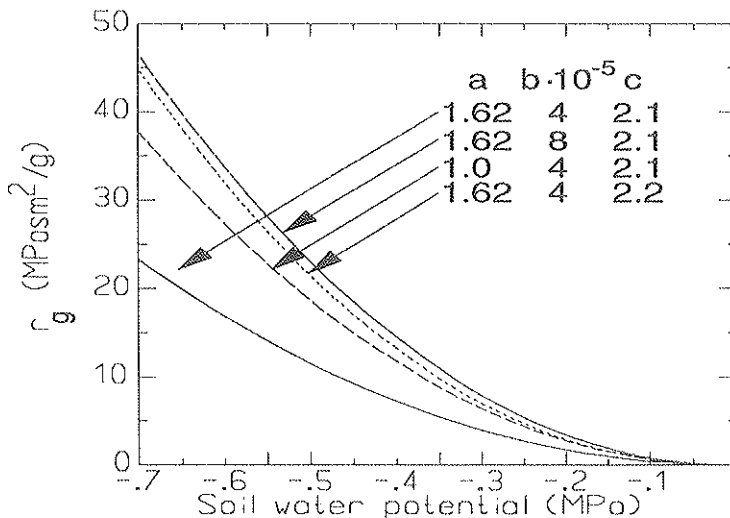
## 2.3 Resistances

The pathway for water flow from bulk soil to the atmosphere is represented by four resistances: the soil-root resistance ( $r_g$ ) from the soil, where the water potential is  $\psi_g$ , to the root surface, the plant resistance ( $r_p$ ) from the root surface to the mesophyll of leaves, the stomatal resistance ( $r_c$ ) from the leaf mesophyll to the air just outside the leaf surface and finally, the aerodynamic resistance ( $r_a$ ) from close to the leaf surface to the ambient air above canopy. The resistances vary with environmental conditions of the air and the soil as well as with the plant conditions. If, for instance, the wind speed or the radiation or the soil water potential increases then the resistance against water flow decreases (Fig. 330).



**Figure 330.** Schematic description of the pathway for water from soil through the plant to the atmosphere. For explanation of symbols, see text.

The soil-root resistance ( $r_g$ ) is proportional to the root density factor ( $b_g$ ) which accounts for the geometry of the root system. The resistance increases with decreasing unsaturated hydraulic conductivity ( $a_g |\psi_g|^{-c_g}$ ) which in turn decreases faster with decreasing soil water potentials ( $\psi_g$ ) when the "soil pore size factor" ( $c_g$ ) is high, as for sandy soils for instance. (Eq. 330) (Fig. 331).



**Figure 331.** The soil-root resistance as function of the soil water potential.

The plant resistance ( $r_p$ ) is assumed to be constant (Eq. 331).

The stomatal resistance of the whole canopy, i.e. per unit ground surface ( $r_c$ ) is affected either by the incoming short-wave radiation ( $R_s$ ), the canopy water potential ( $\psi_c$ ) or the vapour pressure difference of the air ( $vpd=e_s-e_a$ ). Three separate mechanisms are assumed to regulate stomata, one represented by  $r_c(R_s)$ , one by  $r_c(\psi_c)$  and one by  $r_c(vpd)$ . The actual value of  $r_c$  is then the highest value given by the three functions. The User can choose which of the functions that should be active. If the User gives the resistances per unit leaf area the stomatal resistances are assumed to be coupled in parallel with each other, i.e. the stomatal resistance is inversely proportional to the leaf area index. (Note that in the program alternative ways of combining these functions are available, also more sub functions are available.) (Eqs. 332-337).

The aerodynamic resistance ( $r_a$ ) is inversely proportional to the wind speed ( $U$ ) measured at height ( $z_U$ ).  $r_a$  is expressed as a function of characteristic heights of the stand.  $r_a$  decreases with the roughness height ( $z_o$ ) and the displacement height ( $z_d$ ) at which the logarithmic wind profile (derived for the conditions above the canopy) yields a wind speed equal to zero (Eq. 338) (Fig. 334).

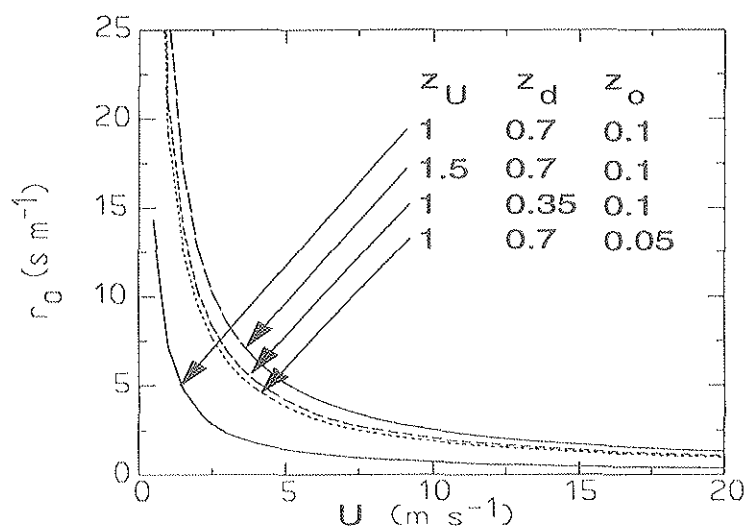


Figure 334. Aerodynamic resistance as function of wind speed.

$r_g = \frac{b_g}{a_g  \psi_g ^{c_g}}$	(330)
$r_p = \text{constant value}$	(331)
$r_c = \max (r_c(R_s(i)), r_c(\psi_c), r_c(vpd))$	(333)
<i>where:</i>	$r_{cMin} \leq r_c \leq r_{cMax}$
$r_c(\psi_c) = \text{different functions}$	<i>see par. RESCWAT</i> (334)
$r_c(R_s) = \text{different functions}$	<i>see par. RESCRAD</i> (335)
$r_c(vpd) = \text{different functions}$	<i>see par. RESCVPD</i> (336)
$r_c = r_s/LAI$	(337)
$r_a = \frac{\ln^2((z_U - z_d)/z_o)}{k^2 U}$	(338)

## 2.4 Rain interception

A fraction of the rain falling on the canopy ( $P$ ) is intercepted on the vegetative surfaces and thereafter evaporated to the air. The rest ( $P_g$ ) falls onto the ground and increases water content of soil. The rain is assumed to be intercepted by the canopy in a similar way as the radiation. This means that the fractional interception of the rain is the same for all sublayers of leaf area in the canopy. Hence Beers' law is used but, instead of the radiation extinction coefficient, we use the rain interception coefficient ( $\kappa_p$ ). The upper limit of water interception ( $m_{vIMax}$ ) is determined by the maximum amount of water possible to be retained by the unit leaf area ( $m_{vIo}$ ) (Eqs. 340-342).

The intercepted water evaporates ( $E_i$ ) in a way similar to that of the transpired water ( $E_T$ ) after it has passed through the stomata. Hence,  $E_i$  is calculated using the same equations as for  $E_T$  but with the stomatal resistance ( $r_c$ ) equal to zero. Since the evaporation takes place during the same time step as the interception, the reservoir for water on the canopy ( $m_{vI}$ ) often becomes zero already during the current time step (Eq. 345).

Normally, not the whole canopy is wet. The canopy has a dry part ( $LAI(1-m_{vI}/m_{vIMax})$ ) and a wet part ( $LAI m_{vI}/m_{vIMax}$ ). From the dry surfaces transpiration can continue whereas on the wet surfaces it stops. The dry and wet surfaces have different energy balances since transpiration is retarded by the stomata resistance, whereas the evaporation of intercepted water is not. The fraction of total net radiation energy ( $R_n$ ) available for transpiration is proportional to how large fraction of the canopy surface that is dry. Less number of stomata can transpire, therefore the stomatal resistance ( $r_c$ ) increases in the same proportion as the available net radiation decreases. The net radiation of the dry surfaces ( $R_{nT}$ ) and the increased  $r_c$  determines the temperature of the dry surfaces ( $T_{cT}$ ) (see Eq. 320). For the wet surfaces the temperature ( $T_{cI}$ ) is determined by the net radiation ( $R_{nI}$ ) and the fact that  $r_c=0$ . (Eqs. 343-348).

$$\delta m_{vI} = (P - P_g - E_i) \delta t \leq m_{vIMax} - m_{vI}(t-1) + P - P_g \quad (340)$$

where:

$$m_{vIMax} = m_{vIo} LAI \quad (341)$$

$$P_g = P \exp(-\kappa_p LAI) \quad (342)$$

wet surfaces:

$$R_{nI} - H_I - LE_i \leq \Delta_{Max} \quad T_{cI} \text{ is determined} \quad (343)$$

where:

$$R_{nI} = R_{nc} m_{vI} / m_{vIMax} \quad (344)$$

$$E_i = E_T \text{ in Eq. 313 but with: } \geq 0 ; \text{ if } m_{vI} + P - P_g > 0 \quad (345)$$

$$r_c = 0 \text{ and}$$

dry surfaces:

$$R_{nT} - H_T - LE_T \leq \Delta_{Max} \quad T_{cT} \text{ is determined} \quad (346)$$

where:

$$R_{nT} = R_{nc} - R_{nI} \quad (347)$$

$$E_T = E_T \text{ in Eq. 313 but with: } \text{if } m_{vI} + P - P_g > 0 \quad (348)$$

$$r_c = r_c + (r_{cMax} - r_c) (m_{vI} / m_{vIMax})$$

## 2.5 Soil water

The link of the soil water module to the plant part of the model is through the plant uptake as given by Eq. 311. The soil water potential is simulated as function of water content of the root zone (Eqs. 365-6). In turn, the plant affects the soil water content through input of water to soil (throughfall; Eqs. 342 and 351) and output of water (uptake, Eq 361 and soil evaporation, Eqs 354-356).

The soil is divided into three layers. The surface layer ( $m_{gS}$ ) receives water through rain (throughfall,  $P_g$ ) and lose water through soil evaporation ( $E_g$ ) to the atmosphere and percolation to the root zone ( $q_{S \rightarrow R}$ ). The root zone ( $m_{gR}$ ) receives water from the surface layer and lose water through root uptake ( $F_U$ ) and percolation to the layer below root zone ( $q_{R \rightarrow B}$ ). The layer below root zone ( $m_{gB}$ ) receives water by percolation from the root zone and lose water through percolation or run off to layers below ( $q_{Loss}$ ), which are not represented in the model. The amount of water in the root zone can also increase if the root depth increases ( $\Delta m_{gRDepth}$ , Eq. 362). Then water is taken from the layer below. If the thickness of the surface layer ( $z_{Surf}$ ) is larger (i.e. deeper) than the root depth ( $z_r$ ), no root uptake occurs. If no surface layer exists no soil evaporation occurs. The loss of water through percolation is the amount of water that is in excess of the amount of water at saturation ( $m_{gSMax}$ ,  $m_{gRMax}$  and  $m_{gBMax}$ , respectively), defined as the relative water content at saturation ( $\theta_s$ ) multiplied by the depth of the layer concerned and the density of water ( $\rho_w$ ).

Near saturation soil water potential in the root zone is a linear function of the relative water content ( $\theta$ ) which is related the bulk density of soil ( $\rho_g$ ) ((Eq 366). At all other occasions it is a non linear function given by Brooks & Corey relationship (Eq. 365).

Soil surface evaporation ( $E_g$ ) is determined by Penman-Monteith equation assuming the storage of heat in soil being neglectable in the energy balance. The aerodynamic resistance ( $r_{as}$ ) is increased in proportion to leaf area (Eq. 355) and the surface resistance ( $r_{ss}$ ) is inversely related to the relative water content of the surface layer ( $\theta_{gS}$ ) (Eq. 356).

*Soil surface water balance:*

$$\delta m_{gS} = (P_g - q_{S \rightarrow R} - E_g) \delta t \quad (351)$$

where:

$$q_{S \rightarrow R} = m_{gS}(t-1) - m_{gSMax} > 0 \quad (352)$$

where:

$$m_{gSMax} = \rho_w \theta_s z_{Surf} \quad (353)$$

*Soil evaporation:*

$$E_g = \frac{\Delta R_{ng} + \rho_a C_p vpd / r_{as}}{\Delta + \gamma(1 + r_{ss} / r_{as})} \quad (354)$$

where:

$$r_{as} = r_a + a_{ras} LAI \quad (355)$$

$$r_{ss} = a_{rss} / (\theta_{gS} + \theta_{rss})^{brss} \quad (356)$$

where:

$$\theta_{gS} = m_{gS} / (z_{Surf} \rho_g) \quad (357)$$

*Root zone water balance:*

$$\delta m_{gR} = (q_{S \rightarrow R} + \Delta m_{gRDepth} - q_{R \rightarrow B} - F_U) \delta t \quad (361)$$

where:

$$\Delta m_{gRDepth} = m_{gB}(z_r(t) - z_r(t-1)) / (z_g - z_r) \quad (362)$$

$$q_{R \rightarrow B} = m_{gR}(t-1) - m_{gRMax} > 0 \quad (363)$$

where:

$$m_{gRMax} = \rho_w \theta_s (z_r - z_{Surf}) \quad (364)$$

*Root zone water potential:*

$$\psi_g = \psi_a ((\theta - \theta_r) / (\theta_s - \theta_r))^{-c_{BC}} - 0.01 (z_s + z_g / 2) \quad \text{if } \theta < \theta_s - \theta_m \quad (365)$$

$$\psi_g = \psi_m (1 - (\theta + \theta_m - \theta_s) / \theta_m) - 0.01 (z_s + z_g / 2) \quad \text{if } \theta > \theta_s - \theta_m \quad (366)$$

where:

$$\theta = m_{gR} / ((z_r - z_{Surf}) \rho_g) \quad (367)$$

$$\psi_m = \psi_g (\theta_s - \theta_m) \quad (368)$$

*Layer below root zone water balance:*

$$\delta m_{gB} = (q_{R \rightarrow B} - \Delta m_{gRDepth} - q_{Loss}) \delta t \quad (371)$$

where:

$$q_{Loss} = m_{gB}(t-1) - m_{gBMax} > 0 \quad (372)$$

where:

$$m_{gBMax} = \rho_w \theta_s (z_g - z_r) \quad (373)$$

## 2.6 Special functions

In this section alternative or complementary calculations are presented. These are available in the model and normally activated using the switch named Special.

The stomatal resistance ( $r_c$ ) can, in addition to the subfunctions given in chapter 3 also be a combined function ( $r_c(R_s, vpd)$ ) of radiation and vapour pressure deficit ( $vpd$ ). Different functions can be chosen. The function is included among the other subfunctions. (Eqs. 411-413).

The aerodynamic resistance ( $r_a$ ) is modified by a factor named the Richardson number ( $Ri$ ) which accounts for the effect of thermal convection on the transport of heat and vapour in the air. This factor is proportional to the gravitation force ( $g$ ), the distance from the canopy top to the roughness height ( $z_U - z_o$ ) and the temperature difference between the surface and the air ( $T_c(t_1) - T_a$ ;  $t_1$  means that the input value of the time step is used). Normally it is very small (Eqs. 414-415).

The displacement height ( $z_d$ ) and the roughness length ( $z_o$ ) used for calculating the aerodynamic resistance could be set proportional to the height where the wind speed is measured ( $z_U$ ). (Eq. 418-419)

In the original version of the model the aerodynamic resistances for heat and vapour are given equal values. The resistance for heat ( $r_{aH}$ ) could, however, be divided by a factor ( $a_{rH}$ ) as compared to that for vapour ( $r_a$ ) (Eq. 419a).

The net radiation above canopy ( $R_n$ ) should be an input variable. However, this variable is often lacking and then it can be estimated from the global radiation above canopy ( $R_g$ ) (Eq. 420).

$$r_c(R_s, vpd) = \text{different functions} \quad \text{see par. RESCLOHA} \quad (412)$$

$$r_a = r_a / (1 + 10Ri) \quad (414)$$

where:

$$Ri = g(z_U - z_o)(T_c(t_1) - T_a) / ((T_a + 273.15)U^2) \quad (415)$$

$$z_d = a_d z_U \quad (418)$$

$$z_o = a_o z_U \quad (419)$$

$$r_{aH} = r_a / a_{ra} \quad (419a)$$

$$R_n = a_R R_s - b_R \quad (420)$$



# SPAC SIMULATION EXERCISES

## Exercise 1; Introduction to a simulation model (SPAC)

### Objective

The aim of this exercise is to give you some answers to the following questions:

- What is a simulation model?
- How is it used technically?
- What is the structure of the SPAC model?
- How does the most essential water dynamics of a plant work?

*A simulation model, what is that?*

I will try to answer that question shortly by describing some used terms.

A basic problem that we will try to solve is: What is the effect of weather on plant water dynamics? To answer this question we must have an idea of how the plant interacts with its environment.

In this case the plant and its surrounding is our system. The system is limited in space; it has a boundary. The boundary conditions is here the situation in the atmosphere (weather). These conditions vary with time and are input to the model given by driving variables.

We have some ideas of how weather influences soil and plant. These ideas are our conceptual model which often is clear in structure and theory but normally not possible to evaluate in detail or comparable with measurements in a systematic way.

The formalised model is based on the conceptual model. The theory of the conceptual model is formalised in terms that can be evaluated quantitatively. A theory expressed in words, for instance "when the atmosphere is dry the evaporation from the wet leaves is high", should be expressed in precise terms. How dry is the air? How wet are the leaves? How is vapour transported from the wet leaves to the dry air? All these things must be expressed in quantitative terms. The formalised model we call a mathematical model or here only model. The model represents a system including several processes going on simultaneously. The processes are represented by equations, for instance how the stomata of the leaves open when light fall on the leaves. The reason for the opening is that light causes chemical reactions in the guard cells. This is a rather general rule for plants and can be represented by one type of equation. However, the degree of opening differs between species, given a certain amount of light. In the model the degree of light dependency is represented by parameters. Hence, parameter values represent plant properties and normally differ between plant types. A parameter value is normally independent of time. If it is not, its variations is an indication that the model is not general in some way.

The result of the model concerns a certain time interval. If the time step is one minute, as it is in the SPAC model, the calculations of for instance the transpiration, concerns the evaporation from leaves to the atmosphere during the last minute. Similarly the uptake calculations concerns the amount of water taken up by roots during the last minute. These two variables are called flow variables and transport water from the plant and to the plant, respectively. In this way they determine the amount of water stored in plant, which is called a state variable and is the base for the calculations of flows during the next minute. The model calculates the flows to and from the state variable which then changes minute by minute. We could say that the model imitate the plant development. This type of model we call simulation model. The state variable is hence the amount of water that exists at a certain occasion. The unit is independent of time and is the mass divided by a reference area ( $\text{gH}_2\text{O}/\text{m}^2$ ). The flows which change the state over time are expressed in  $\text{gH}_2\text{O}/\text{m}^2/\text{s}$ . At the start of a simulation state variables are given by initial values which are input to the model.

In case a flow variable depends on the state variable that it changes, there is a feedback in the system. It is a positive feedback if an increase in the state variable increases the flow into it. There is an unstable situation between state and flow. In the opposite case we have a negative feedback and a self-regulating situation (increased state decreases inflow).

All these calculations can theoretically be made by hand. However, for practical reasons we make use of a computer since there is an enormous amount of calculations to be made.

#### Summary:

- The system is represented by the model.
- The model has a boundary. The conditions at the boundary change with time and are model input represented by driving variables.
- The structure of the model is built up of state and flow variables.
- At start of simulation the state variables are given by initial values.
- The flow variable changes the state variables.
- The flows are determined by the processes of the system.
- Processes are represented by equations and parameters.
- Properties of the system are represented by parameter values

**The objective** of using a simulation model differs:

- As a research tool it is used to evaluate hypotheses about interactions in nature and to get ideas for setting up new hypotheses.
- As an education tool it is used to illustrate dynamics in nature which of practical reasons otherwise are not possible to study (because the resources are limited). Both already known processes and purely theoretical processes can be studied this way.
- As a forecast tool it is used to evaluate the effect of known or possible changes of the system properties or of changes in the boundary conditions on a certain variable, for instance the transpiration.

---

#### *How to run the model*

- Start the SIMvb-program:

From WINDOWS you start the model by making a double-click on the icon for SIMvb (if there is an icon, otherwise you use the "run" option under "Archive" by starting `c:\simvb\exe\simvb3.exe`). Note that within the SIMvb-program only single-clicks are used.

- Select exercise:

Start by pressing:

"Start here"

then select model:

"SPAC"

then select application:

"BGF-course"

then select exercise:

"Ex1" f.i.

- A typical procedure to make a simulation:

Select first initial loading of the application:

"GIVE INPUT", "Initial prep"

Select input data to the simulation:

"GIVE INPUT", "Normal",

"Soil", f.i. "Clay"

"Plant", f.i. "Brassica"

"Weather", f.i. "Sunny day"

"Management", f.i. "No irrigation"

View input data:

"SHOW INPUT"

"View parameters", "Select file", f.i.

"PARAMET.txt"

"Weather", f.i. "Air temperature"

Make a normal simulation:

"SIMULATE", "Normal"

View the results of the simulation:

"SHOW OUTPUT"

an example:

"Select file", "No comparison"

"Plant water flow", "Et(transp)"

Store the simulation results in a file that is not overwritten "Store Files"

by new simulations:

"Current to Store..", f.i. "Store\_0"

After going through this procedure once you can select any option at any time. In many cases you come to a sub-menu, when choosing an option. You go back to the main menu by closing the sub-menu (x in upper right corner).

If you for some reason happen to leave the SIMvb program you can enter the program without repeating all preparations etc.

- Restart the program and select model, application and exercise concerned.

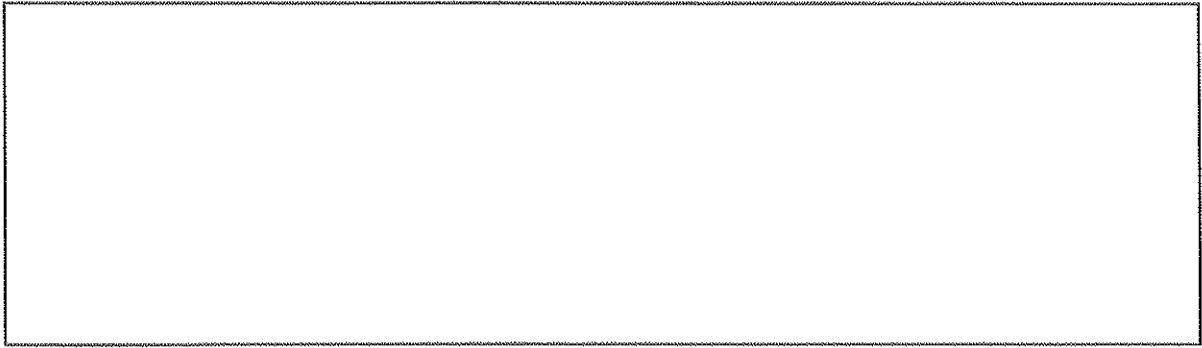
- After that, choose "Check off". Then you have access to earlier made preparations, and current, previous and stored simulations. For further information see the SIMvb description below.

---

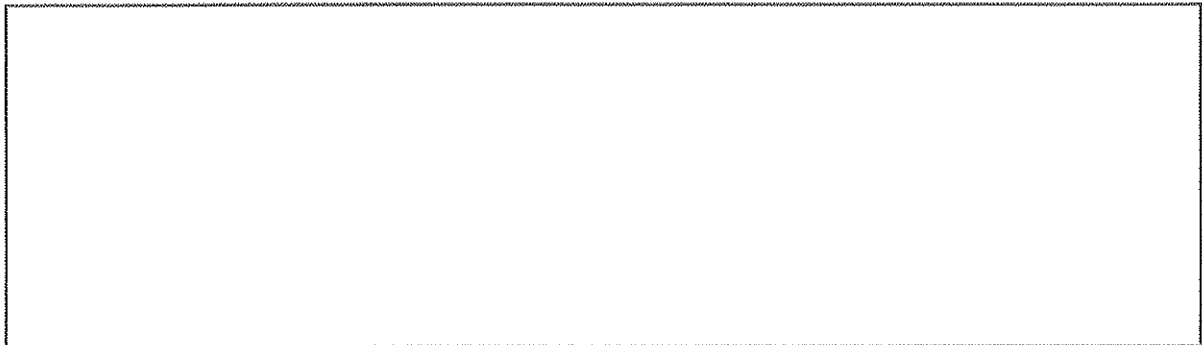
### *Simulation exercise*

Run the program according to the instructions given above. Select a "Sunny day" and answer the following questions:

-1- Which parameter groups exist in the model?



-2- Which are the driving variables?

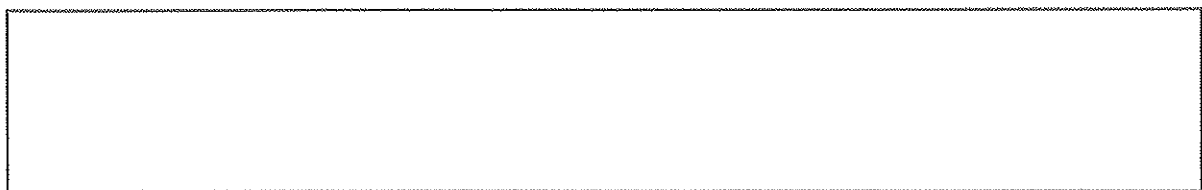


-3- Make the simulation

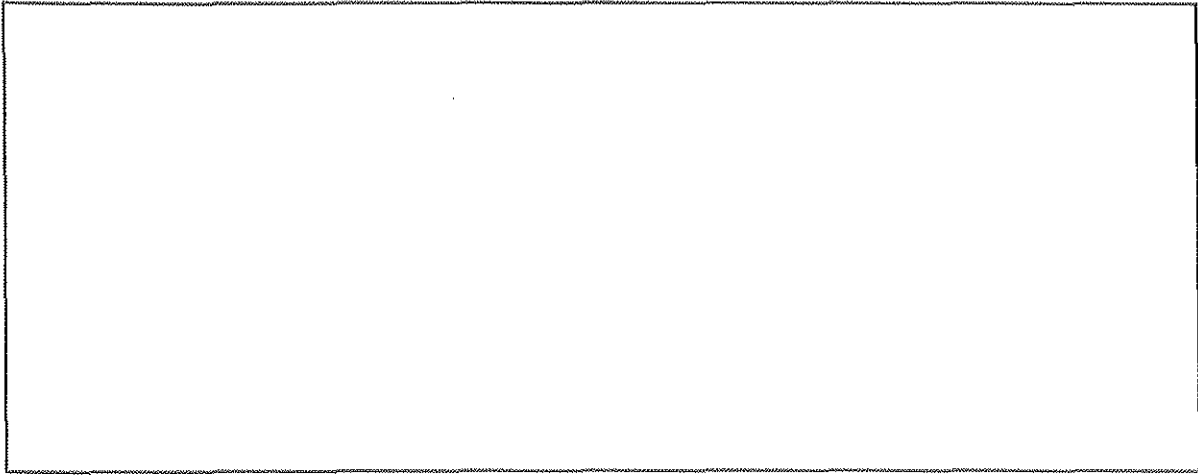
-4- Which are the state variables that describes the storage of water?



-5- Which are the flows of water to the state variables, and from them?



-6- Make a picture of how the state and flow variables are connected.



-7- Store the simulation

## Exercise 2; Plant

### Objective

To illustrate the effects of plant properties on water and energy dynamics in the soil-plant-atmosphere system.

### Background

During night when it is dark stomata are closed and the plant does not transpire. As the sun rises in the morning the solar radiation is absorbed by the leaves and stomata open. The plant starts to transpire. If the stomata of some reason do not open, there will be less transpiration and leaf temperature will increase. Monitoring this plant community, by for instance remote sensing, this increase in surface temperature could be observed. It is far more difficult to measure how much the stomata resistance has increased. However, by using the SPAC model you could estimate how much it should have increased to give the observed temperature increase. In the examples below you will be trained to derive properties of the plant (like stomata opening) from simulated output variables like leaf temperature, transpiration etc.

#### 1) Make a reference simulation

Start the SIMvb-program. Choose model "SPAC", application "BGF-course" and exercise "Ex2". Give inputs to the simulation. Make the simulation. Store the simulation. Make use of the instructions in Exercise 1 above. In the plant preparation option, select "Brassica". Store the reference simulation so that you can compare it with later simulations (f. i. as "Store\_0").

#### 2) Simulation with a plant with other properties

You have another plant community which basically is of the same type as the one you stored as reference above. However, there is one property that differs from the reference plant. The aim of this exercise is to examine which property this is by analysing differences in transpiration, water uptake, plant water status, radiation absorption, sensible and latent heat fluxes and leaf surface temperature, compare to the reference plant. Note that there is one precise answer in terms of which property (parameter value) that differs. Try to find this answer and explain how you could derive it from the analysis of differences in transpiration, uptake etc (i.e from differences in output variables).

Simulation with a plant with other properties:

- Give new inputs to the simulation. Only one modification is needed compare to 1) above: In the plant preparation option choose "Plant\_A".
- Make a new simulation.
- View output and compare the results with the reference simulation. "SHOW OUTPUT", "Select file", f.i. "Store\_0", "Plant water flow", f.i. "FU(uptake)"
- Make notations of differences in output variables.
- Analyse, with help of the model description, what could be the reason for the differences.
- Which parameter could be the reason for the difference?

Make a simulation with changed parameter values:

Make a change of the value of the parameter you expect to be the reason for the differences you found above. Make the change so as to give the same result as the reference simulation, i.e. try to eliminate the differences compared to the reference simulation. Do it this way:

- Change parameter value:

"GIVE INPUT", "Changes",  
"Parameters etc"  
"Select file", "ain\_plan.par", Change  
parameter value  
Press Enter  
"Save"

- Make simulation

- View output and compare the results with the reference simulation. Did the differences decrease?

- Repeat this, making new simulations with modified parameter values, until no differences remain. Note that the changes you introduce in ain\_plan.par remains until you choose "Plant\_A" in the normal preparation again.

### 3) Document the results

Answer the following questions:

- Which parameter was changed?

- Which value was achieved?

- Explain how the differences between the simulated values of Plant\_A and the reference plant could be explained by the differences in the parameter value.

### 4) Plant\_B

Examine differences between Plant\_B and the reference simulation. Follow the instructions of 2) and 3) above.

### 5) Plant\_C

Examine differences between Plant\_C and the reference simulation. Follow the instructions of 2) and 3) above.

Plant\_A:

Plant\_B:

Plant\_C:



## Exercise 3; Effect of sun elevation on evaporation

### Objectives

- To estimate how global radiation and net radiation change when the latitude change
- To estimate how the radiation change influence the evaporation and energy balance of a crop.

### Background

Solar radiation is the most important factor influencing processes on earth. It varies a lot between different latitudes. For instance, how much more solar radiation do surface receive on latitude 40° (for instance Italy) compare to here in Uppsala (60°)? Why is the radiation higher in Italy? Is it because the sun beams reach the soil surface at a different angle or is it because the sun beams have a shorter pathway through the atmosphere? If the plants in Sweden would receive as much radiation as in Italy, just for a day, how would that influence transpiration? But, of course, if we consider longer time periods than one day, the climate should change due to the high radiation level. Which other weather variables would also change? And what would then be the effect on transpiration?

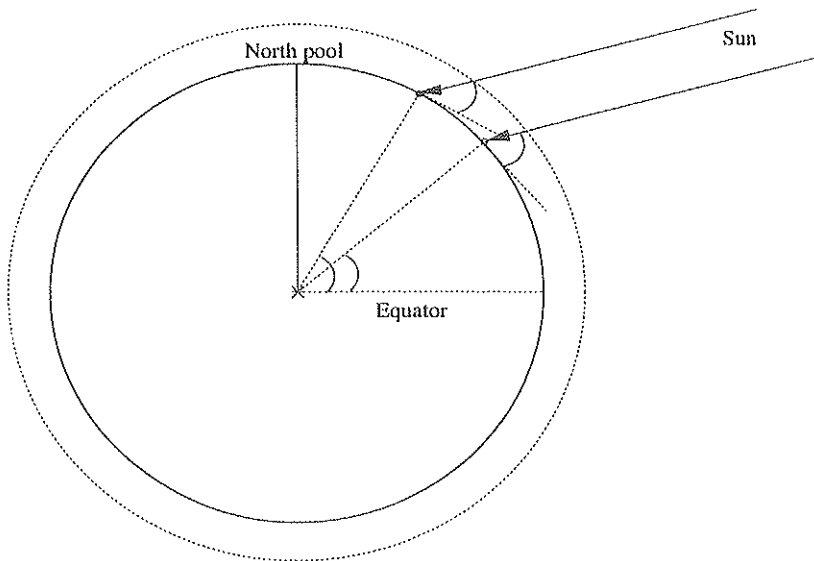
The exercise is divided into four parts:

- (1) estimate the change in radiation conditions in Uppsala (60 °N) if the sun elevation would be the same as for latitude 40 °N (corresponds to Italy).
  - (2) estimate the plant water and temperature conditions during a sunny day in August in Uppsala.
  - (3 and 4) estimate the change in plant water and temperature conditions due to the changed radiation climate.
- 

#### 1) Estimate the change in radiation due to latitude change

Estimate the difference in global radiation between the latitudes by estimating how it differs under clear sky conditions at noon.

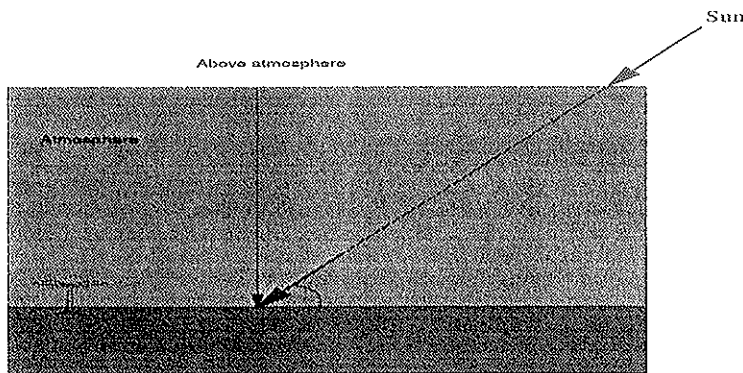
First you have to know the sun elevation at 40 °N. Estimate this by making use of the fact that the difference in sun elevation between latitudes, at noon, is related to the difference in latitude. A suggestion is that you start by calculating the sun declination. Make use of the Figure below. At noon the sun elevation is at maximum, and for August 13 in Uppsala it is 45°.



Sun declination:


Sun elevation at noon, August 13 at 40 °N:

Estimate, with help of Beer's law and Lambert's cosine law, the global radiation at Uppsala and then the corresponding value for 40 °N assuming the same turbidity as in the air above Uppsala.



$R_{sc}$  = Solar constant

$R_s$  = Solar radiation at ground surface but perpendicular against the sun arrays.

$R_g$  = Global radiation

$\beta$  = Sun elevation

$x_0 = 10^5$  m (100 km) = shortest distance between soil surface and the upper boundary of the atmosphere.

$x$  = length of the pathway of the sun arrays through the atmosphere.

$\kappa_a = 0.22 \cdot 10^{-5} \text{ m}^{-1}$  = extinction coefficient, related to  $x$ .

What is the relative change in global radiation?


What is the relative change in global radiation, only caused by a decreased pathway for sun arrays through the atmosphere?

2) Reference simulation for Uppsala

Make a reference simulation and store the results so that you can compare future simulations with this one (see Exercise 1).

3) Effect of changed incoming radiation on the energy balance, transpiration and plant water storage.

Make a new simulation including the estimated change in radiation ("GIVE INPUT", "Changes", "Variables"). Remember to change both global and net radiation.

3a) First, examine the changes in energy exchange in more detail. Give the changes between the new simulation and the previous one (choose the way to compare yourself):

Variable	Change approx.	Equation	Factor(s) mainly responsible for the change. Refer to the equation and explain why.
net radiation			
sensible heat flux			
latent heat flux			
leaf temperature			
On a daily basis, are the canopies warmed or cooled?			

3b) Sum up using your own words, the important changes in both energy exchange and water conditions, and give an explanation to them.

---

4) *Effect of changed climate on plant water and energy conditions.*

For latitude 40 °N not only the global radiation changes. As a consequence of the different global radiation also other weather variables will differ (we continue to assume optimum soil water conditions).

First you change the weather factor you want to change ("*GIVE INPUT*", "*Changes*"), then you make new simulations and compare the results with other simulations to answer the following questions:

Which weather factor(s) have you changed? How? Give an explanation of why this (these) variables) should be changed? Describe and give an explanation of the important changes of water and energy conditions. Compare with the case when you only changed the radiation.

## Exercise 4; Effect of plant structure on evaporation and energy exchange

### Objectives

- Estimate how wind speed above the canopy differs between an agricultural crop and a forest.
- Estimate how the difference in plant aerodynamic properties influence evaporation and energy balance of the plant.
- Estimate how large the influences due to the aerodynamic properties are in comparison with other differences between an agricultural crop and a forest.
- Estimate properties that can explain differences in uptake rates of a crop and a spruce stand.

### Background

The transport of heat and vapour in the air is related to the wind. Close to the canopy, wind is disturbed by the roughness of the surface. Turbulence occur which is very effective in transporting vapour and heat. The degree of turbulence depends on how "rough" the surface is. Is the forest more rough than an ordinary agricultural crop? Is there some measure for this difference? How will this difference in surface structure influence the plant energy and water conditions? This exercise will try to answer this later questions. It will also ask you for other differences between a crop and a forest in terms of properties that determine the water dynamics. By considering the most important differences, you might predict the water uptake by spruce. You can check how well you succeed by comparing your simulated results with measured data on sap flow in spruce.

The exercise is divided into six parts:

(1) Estimate the parameters for plant structure that determine wind speed above the canopy. (2) Compare simulated evaporation and energy exchange between the plant and the atmosphere for two plants: one with aerodynamic properties of an agricultural crop and one with those of a forest. (3) Evaluate the relative importance of differences in aerodynamic properties compare to other differences between crops and forest. (4) Compare the simulated water uptake with measured sap flows. (4) Calibration of the SPAC model. (5) Validation of the SPAC model.

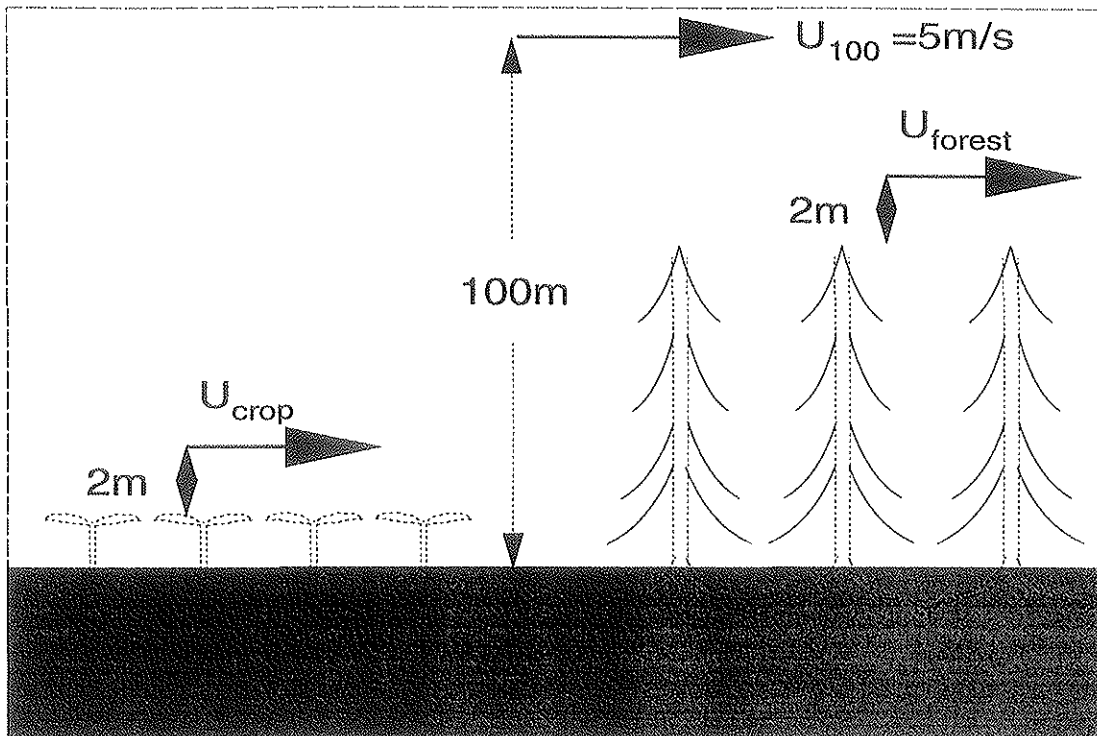
#### *1) Estimate plant properties and wind speed.*

1a) Describe the surface properties of the different plant types. Do this by estimating the parameters in the logarithmic wind profile equation. Assume the crop to be 1 m high and the forest to be 20 m high.

Under which circumstances can the logarithmic wind profile law be used to determine the wind speed above the canopy?

Surface properties of the crop:

Surface properties of the forest:

$U$  = wind speed ( $\text{m s}^{-1}$ )

1b) Estimate the wind speed 2 m above the canopies if the wind speed at 100 m is  $5 \text{ m s}^{-1}$ .

Equation:

Wind speed 2 m above the crop:

Wind speed 2 m above the forest:

Ratio between wind speed above forest and crop ( $U_{forest}/U_{crop}$ ):


2) Make simulations with the estimated values.

- Start SIMvb, select model "SPAC", application "BGF-course" and exercise "Ex4", and make initial preparation "GIVE INPUT", "Initial prep."
- Select input for the simulation: "GIVE INPUT", "Normal", "Soil", "Clay", "Plant", "Brassica", "Weather", "Sunny day", "Management", "No irrigation"
- Change parameter values to those you estimated above ("GIVE INPUT", "Changes", "Parameters etc", "Select file", "ain\_plan.par", Change parameter values (RESAIRH, RESAIRD, RESAIRZ), Press Enter, "Save")
- Make a simulation for the crop
- Store the results.

- Change parameter values again, now to those of the forest.
- Change the wind speed according to the ratio between forest and crop, which you estimated above ("*GIVE INPUT*", "*Changes*", "*Variables*", "*Wind speed*", Give the relative difference). Note that this change remains until you make a new normal preparation of Weather.
- Make a simulation for the forest.
- Compare the results between forest and crop and describe the important differences and the reason for them:

3) *Sensitivity test. Other differences between crop and forest.*

Evaluate the effects of other differences between agricultural crops and forest. Crops and forest differ in more aspects than the aerodynamic properties like for instance leaf area index etc. What are the effects of a change in such a property compared to the differences in roughness length and displacement height? Are there other properties that differs and what are the effects of them?

- First, store the results from the forest simulation in 2) above.
- Change parameter values ("*GIVE INPUT*", "*Changes*", "*Parameters etc*", "*Select file*", "*ain\_plan.par*", Change parameter value, *Press Enter*, "*Save*")
- Make a simulation
- Compare the results with previous simulations for the forest and the crop. Which were the effects of the introduced parameter changes. Were they larger or smaller than in 2) above? What are the reasons for the effects? Give answers to these questions below:

4) Compare the simulated uptake with measured values for sap flow in spruce.

First you have to get access to the measured sap flow data. Choose "GIVE INPUT", "Validation", "Sap flow".

Then you can compare the simulated values with the measured ones by choosing "SHOW OUTPUT", "Validation".

Give a description of how well your simulation fitted measured data. Both in your own words and in terms of statistical values:

	Tree 1 & Tree 2 <u>A0, A1, R2, n</u>
--	---

5) Calibration

Above, when simulating the forest, you changed only the plant structure. However, other properties will also differ compared to a crop. Which ones do you think? Select those properties that you think will improve your plant uptake predictions. Express the properties in terms of parameters of the model. Change the parameter value(s) (as in 2 above) and make a new simulation. Repeat this until you are not able to get a better agreement between simulated uptake and measured sap flow. Note that changes of parameter values should be realistic. Consider first of all that leaf area index of a spruce stand of this type is about 8 or even more.

Changed parameters. How and why?	Best simulation Tree 1 & Tree 2 <u>A0, A1, R2, n</u>
----------------------------------	--

6) Validation

Select a new period and make a new simulation with the parameter values derived for spruce with help of the calibration above.

Describe the performance of the model:	Tree 1 & Tree 2 <u>A0, A1, R2, n</u>
--	---



# SPAC USER's MANUAL

This manual describes the SPAC model version 5.0 (dated 951210). It is a shortened and revised version of the original SPAC User's manual (Eckersten, 1991b).

## 4.1 Files

### ■ Input files

**XXXX.BIN:** The driving variable file is a PG-file. The variables in the PG-file can be organized in different ways depending on how different parameters are specified. An ASCII file should be converted to PG-file before it can be used by the model (use the PG-program).

Two type of input files can be given. Normally minute (or about 10-minute) values are given and then they should be given in the order shown in the table below. In case daily values are given then the switch DRIVANA should be 2 and variables should be given in the following order (see further Eckersten 1991b): 1) Daily maximum temperature 2) daily minimum temperature 3) Air humidity at time  $t_1$  4) Air humidity at time  $t_2$  5) Air humidity at time  $t_3$  6) Global radiation 7) Wind speed 8) Precipitation 9) Soil water potential 10) Net radiation.

[ ]: the variable should be given in this position in the input file.

Variable	Symbol ; Explanation	(Unit)
<i>DNETRAD</i>	[7] $R_n$ ; Net radiation above the canopy (see parameter STNETRAD).	(W m <sup>-2</sup> )
<i>DPREC</i>	[5] Precipitation or leaf wetness. (i) Precipitation (P). To prevent interpolation between values of DPREC the values of the adjacent minutes must be zero. (mm min <sup>-1</sup> ) (ii) If INTERCEPT-switch = 10 or 20: Leaf Wetness (<0.9 is wet ; >=0.9 is dry). (-)	(differs)
<i>DRHUMAIR</i>	[2] $h_a$ ; Relative humidity of the ambient air.	(%)
<i>DSOLRAD</i>	[3] $R_s$ ; Global radiation at the canopy top.	(W m <sup>-2</sup> )
<i>DTEMPAIR</i>	[1] $T_a$ ; Temperature of the ambient air.	(°C)
<i>DWATPOTG</i>	[6] $\psi_g$ ; Soil water potential (see SOILWPOT-switch).	(MPa)
<i>DWINDSP</i>	[4] U ; Wind speed in the ambient air.	(m s <sup>-1</sup> )

**XXXX.PAR:** The parameter file is an ordinary DOS-file with ASCII-characters. All parameters and their actual numerical values should be included in the file. If any parameter is missing in the file a message is displayed on the screen and a default value is selected from the SPAC.DEF file. New parameter files may be created prior the execution of the model using the EXECUTION-WRITE command.

**SPAC.INI:** Initial values of state variables should be given here. (Else they are zero).

## ■ Output files

SPAC.FIN: Final values of state variables.

SPAC\_NNN.bin: Output variables are stored in a PG-structured where NNN is the current number of simulation. The file is a binary file to be used by the PGraph program for plotting results from the simulation. The file can be converted to ASCII format by using the PG-program.

SPAC\_NNN.SUM: Contains a summary of all inputs used by the simulation and a summary of simulated results. The first part of this file (until the sign ;) corresponds to a parameter file. This means that you can repeat the simulation by renaming this file to a file with extension .PAR.

## 4.2 SWITCHES

The purpose of switches is to chose the simulation mode. Most switches could either be OFF or ON. Others can achieve different values.

### ■ Technical

#### *CHAPAR*

OFF <i>Default</i>	Parameter values are constant during the whole simulation period.
ON	Parameter values may be changed at different times during the simulation period. If editing directly into parameter files: the time of change and the new parameter values should be specified after the other parameter values (valid from the start of the simulation). A maximum of 20 time points can be specified.

#### *INSTATE*

OFF <i>Default</i>	The plant water is set initially so that the leaf water potential equals the soil water potential. All other state variables are initially zero.
ON	Initial values of state variables will be read from a file. The name of the file is specified by the user, the format should be similar as in the file for final values of state variables, created by the model when the OUTSTATE switch is on.

#### *OUTSTATE*

OFF <i>Default</i>	no action.
ON	final values of state variables will be written on a file at the end of a simulation. The name of the file is specified by the user and the format is the same as used in the file for initial state variables (see the INSTATE switch).

■ Model Specific

*DRIVANA*

0 <i>Default</i>	Driving variables are minute values
1-2	Some of the minute driving variables in the input file are not available, or wanted to be modified. This option allow you then to make simple modifications of the following driving variables: Soil water potential (DWATPOTG; parameters WSPSR and WSPSD) and Net radiation (DNETRAD; parameter STNETRAD). Only used if SPECIAL-switch is ON. For net radiation also when DRIVANA-switch = 2.
2	Weather driving variables are daily synoptic values. Those are used to calculate analytical minute values.

*DRIVPREC*

1 <i>Default</i>	The driving variable DPREC is the registration of precipitation rate (see further DPREC).
2	The the driving variable DPREC is the registration of wet or dry canopy (see further DPREC).

*INTERCEPT*

0	No simulations of evaporation of intercepted water on leaf surfaces. Precipitation is assumed to be zero.
1 <i>Default</i>	Evaporation of intercepted water ( $E_I$ ) and transpiration ( $E_T$ ) are NOT going on simultaneously. First the intercepted water is evaporated until the canopy is dry (no transpiration occurs). Then the transpiration starts.
2	Evaporation of intercepted water ( $E_I$ ) and transpiration ( $E_T$ ) are going on simultaneously. The total canopy net radiation ( $R_{nc}$ ) is shared between the two processes in proportion to area of the two surfaces. The intercepted water receives $m_{VI}/m_{VIMAX}$ fractions of $R_{nT}$ and the water for transpiration the rest. The stomatal resistance is increased linearly towards $r_{cMAX}$ when the fraction of dry surface decreases.

*IRRIGAUT*

0 <i>Default</i>	No irrigation
1	Automatic irrigation starts when soil water potential becomes lower than a critical value (IRRIGPSI). (The concept is taken from the SOIL model (Jansson 1991))

## *PENMANM*

1 <i>Default</i>	Evaporation simulations are made using an iteration method for solving the canopy energy balance.
2	Evaporation simulations are made using the Penman-Monteith equation for calculating the latent heat flux and the energy balance. The simulation time decreases.

## *RESCANOP*

0 <i>Default</i>	Different stomata resistance sub functions are combined by selecting the one with highest value.
1	Different stomata resistance sub functions are combined by adding them. Only used if SPECIAL-switch=1.
2	Different stomata resistance sub functions are combined by multiplication. Only used if SPECIAL-switch=1.

## *SOILWPOT*

0 <i>Default</i>	Soil water potential is input given in the driving variable file
1	Soil water potential is simulated (Note that still the variable nr 6 in driving variable must exist although not used)

## *SPECIAL*

OFF <i>Default</i>	Parameters in the group Special are NOT available.
ON	Parameters in the group Special are available. These parameters enables modifications or introduction of special functions normally kept fixed or not used.

## *TRANSP*

0	No water flow simulations are made.
1 <i>Default</i>	Actual canopy evaporation ( $E_T$ and/or $E_i$ ) simulations are made.

## TRANSPPOT

0	No calculations of the potential transpiration ( $E_{Tp}$ ).
1 <i>Default</i>	The potential transpiration ( $E_{Tp}$ ), defined as the transpiration being independent of the plants internal water status (i.e. $m_v = m_{vMax}$ ), is simulated using the iteration method for solving the canopy energy balance.
2	The potential transpiration ( $E_{Tp}$ ) is defined as: the water content is non limiting and located on the leaf surface (i.e. surface resistance $r_c = 0$ )

### 4.3 PARAMETERS

Note that the units sometimes are multiples of the basic SI-system.

Variable	Symbol ; Explanation	(Unit)
----------	----------------------	--------

#### ■ Plant\_water

<b>PLANWATX</b>	$m_{v0}$ ; Maximum available plant water per unit of leaf surface.	(g m <sup>-2</sup> )
<b>WATPOTGP</b>	$\Psi_{gp}$ ; $\Psi_g$ for the potential transpiration. Only used if TRANSPPOT-switch > 0.	(MPa)
<b>WATPOTN</b>	$\Psi_{cMin}$ ; Canopy water potential when the plant is out of water easily available for transpiration.	(MPa)
<b>WATPOTX</b>	$\Psi_{cMax}$ ; Canopy water potential when plant water content is at maximum.	(MPa)

#### ■ Aerodynamic resistance

<b>RESAIRD</b>	$z_d$ ; Displacement height. (parameters should be set: SWRESAIR = 1 and RESAIRD0 = 0).	(m)
<b>RESAIRH</b>	$z_U$ ; Height for measurements of wind speed. (parameters should be set: SWRESAIR = 1 and RESAIRH0 = 0).	(m)
<b>RESAIRZ</b>	$z_0$ ; Roughness length. (parameters should be set: SWRESAIR = 1 and RESAIRZ0 = 0).	(m)
<b>SWRESAIR</b>	Switch [1] ; Switch for choosing between two functions for the aerodynamic resistance ( $r_a$ ). =1: $r_a = f(h, d, z_0) / U$ =0: $r_a = f(LAI) / U$ .	(-)

#### ■ Resistance\_stomata

Parameters related to the resistance for vapour flow through stomata. Special care should be taken as regards the units of parameters. The units of the given functions refer to the leaf surface or the ground surface depending on the specification given by the User. The stomatal resistance function is taken the highest value of those proposed by the different "sub functions". For selection of sub functions see parameter SWRESCAN.

<b>RADRESR</b>	$R_{sMin}$ ; $R_s < R_{sMin} \rightarrow r_s(R_s) = r_{sMax}$ . This parameter is the radiation level below which the stomatal resistance $r_s(R_s)$ is constant equal to its maximum value. Only used if SWRESCAN(2) > 0.	(W m <sup>-2</sup> )
----------------	--	----------------------

<b>RESCGROU</b>	In analogy with RESCTEMP but SWRESCAN(4) replaced by SWRESCAN(5).	( )
<b>RESCLOHA</b>	Coefficients used for alternative stomatal functions. Be aware of the units. Note: If SWRESCAN(3) greater or equal to 100 or GROWTH-switch = 0, than $r_s$ should be given per units of ground surface.  Only used if IF SWRESCAN(3)=1 or 100: $f(\psi_c)$ *Lohammar eq: $f(\psi_c) = d_L * \exp(-e_L(f_L + \psi_c) + g_L)$  RESCLOHA(1): $d_L(-)$ RESCLOHA(2): $e_L(\text{MPa}^{-1})$ RESCLOHA(3): $f_L(\text{MPa})$ RESCLOHA(4): $g_L(-)$	( )
<b>RESCMAX</b>	$r_{s\text{Max}}$ ; Maximum value of stomatal resistance. It equals the resistance per unit of leaf surface through cuticular. Note: If all separate stomatal functions used are given per units of ground surface (i.e. all SWRESCAN(1-3), not equal to zero, are greater or equal to 100, or GROWTH-switch = 0), then $r_{s\text{Max}}$ should be given per units of ground surface ( $r_{c\text{Max}}$ ).	(s m <sup>-1</sup> )
<b>RESCMIN</b>	$r_{s\text{Min}}$ ; Minimum value of stomatal resistance per unit of leaf surface. Note: If all separate stomatal functions used are given per units of ground surface (i.e. all SWRESCAN(1-3), not equal to zero, are greater or equal to 100, or GROWTH-switch = 0) $r_{s\text{Min}}$ should be given per units of ground surface ( $r_{c\text{Min}}$ ).	(s m <sup>-1</sup> )
<b>RESCRAD</b>	Coefficients for determining the stomatal resistance per unit of leaf surface as a function of incident shortwave radiation. Note: If SWRESCAN(2) greater or equal to 100 or GROWTH-switch = 0, then stomatal resistance should be given per units of ground surface ( $r_c$ ).  If SWRESCAN(2)= 1,10,100: Conductance is a polynomial function and: $r_c(R_s) = 1 / (a_1 + b_2 R_s + c_1 R_s^2)$ If SWRESCAN(2)= 2,20,200: Resistance is an exponential function: $r_s(R_s) = a_c * \exp(-b_c R_s) + c_c$  RESCRAD(1): $a_1$ (m s <sup>-1</sup> ) or $a_c$ (s m <sup>-1</sup> ) RESCRAD(2): $b_2$ or $b_c$ RESCRAD(3): $c_1$ or $c_c$ (s m <sup>-1</sup> )	
<b>RESCTEMP</b>	Coefficients for determining the stomatal resistance per unit leaf surface as a function of canopy temperature. Note: If SWRESCAN(4) greater or equal to 100 or GROWTH-switch = 0, than $r_s$ should be given per units of ground surface ( $r_c$ ).  If SWRESCAN(4)= 1,100: Conductance is a polynomial function and: $r_s(T_c) = a_T + b_T T_c + c_T T_c^2$ If SWRESCAN(4)= 2,200: Resistance is an exponential function: $r_s(T_c) = a_T * \exp(b_T(T_c + c_T)) + d_T$ If SWRESCAN(4)= 3,300: Resistance is a logarithmic function: $r_s(T_c) = a_T * \ln(b_T(T_c + c_T)) + d_T$	( )
<b>RESCVPD</b>	Coefficients used for alternative stomatal functions. Be aware of the units. Note: If SWRESCAN(3) greater or equal to 100 or GROWTH-switch = 0, than stomatal resistance should be given per units of ground surface ( $r_c$ ).	( )

IF SWRESCAN(3)=1 or 100:  
 $f(\psi_c)$ \*Lohammar eq:  
 $r_s(vpd, R_s) = c_L(R_s + a_L)(b_L vpd + 1)/R_s$   
 (Note! for  $f(\psi_c)$  see RESCVDPD)  
 IF SWRESCAN(3)=2 or 200:  
 $r_s(vpd, R_s) = a_v + b_v vpd + c_v(R_s/100)^2$   
 IF SWRESCAN(3)=3 or 300:  
 $r_s(vpd) a_e \exp(b_e(vpd - c_e)) + d_e$   
 IF SWRESCAN(3)=4 or 400:  
 Lohammar eq (Cienciala vers.):  
 $r_s(vpd, R_s) = 1/g_s$  where:  
 $g_s = (d_c + c_c R_s / (R_s + a_c)) / (b_c vpd + 1)$

RESCVPD(1):  $a_L$  ( $W m^{-2}$ ) or  $a_v$  ( $s cm^{-1}$ ) or  $a_e$  ( $s m^{-1}$ ) or  $a_c$  ( $W m^{-2}$ )  
 RESCVPD(2):  $b_L$  ( $hPa^{-1}$ ) or  $b_v$  ( $s cm^{-1} hPa^{-1}$ ) or  $b_e$  ( $hPa^{-1}$ ) or  $b_c$  ( $hPa^{-1}$ )  
 RESCVPD(3):  $c_L$  ( $s m^{-1}$ ) or  $c_v$  ( $cm s^{-1} (m^2/0.01W)^2$ ) or  $c_e$  ( $hPa$ ) or  $c_c$  ( $m s^{-1}$ )  
 RESCVPD(4):  $d_c$  ( $s m^{-1}$ ) or  $d_e$  ( $m s^{-1}$ )

### RESCWAT

Coefficients for determining the stomatal resistance per unit leaf surface as a function of canopy water potential. ( )

Note: If SWRESCAN(1) greater or equal to 100 or GROWTH-switch = 0, than  $r_s$  should be given per units of ground surface ( $r_c$ ).

If SWRESCAN(1)= 1,100: Conductance is a polynomial function and:  
 $r_s(\psi_c) = 1/(a_c + b_c \psi_c + c_c \psi_c^2 + d_c \psi_c^3 + e_c \psi_c^4)$ ; (OBS!  $\psi_c$  is in units of 0.1MPa).

If SWRESCAN(1)= 2,200: Resistance is an exponential function:  
 $r_s(\psi_c) = a_e \exp(-b_e(\psi_c + c_e)) + d_e$ ; (OBS!  $\psi_c$  is in units of MPa).

RESCWAT(1):  $a_c$  ( $m s^{-1}$ ) or  $a_e$  ( $s m^{-1}$ )  
 RESCWAT(2):  $b_c$  or  $b_e$  ( $MPa^{-1}$ )  
 RESCWAT(3):  $c_c$  or  $c_e$  ( $MPa$ )  
 RESCWAT(4):  $d_c$  or  $d_e$  ( $s m^{-1}$ )  
 RESCWAT(5):  $e_c$

### SWRESCAN

switches for choosing arbitrarily among different stomatal resistance functions. ( - )  
 $r_s = f(R_s \text{ or/and } \psi_c \text{ or/and } vpd, R_s \text{ or/and } T_c \text{ or/and } \psi_g)$ . (Polyn=polynomial function for conductances; Exp=exponential function for resistances; Loham=Lohammar equation; Layers=canopy is divided into layers of unity leaf area, in each layer the resistance is the maximum value given by all resistance functions used, if not Layers function is used then canopy resistance is the stomatal resistance divided by the leaf area index). If SWRESCAN is multiplied by 100 i.e. equal to 100, 200, 300, 400 etc. than the input functions on stomatal resistance are assumed to be expressed per units of ground surface ( $r_c$ ). (see RESCWAT, RESCRAD, RESCVDPD)

for  $r_s = f(\psi_c)$ :  
 SWRESCAN(1): [1] ; (0/1/2 = No/Polyn/Exp)  
 for  $r_s = f(R_s)$ :  
 SWRESCAN(2): [1] ; (0/1/2/10/20 = No/Polyn/Exp/Polyn(layers)/Exp(layers))  
 for  $r_s = f(R_s \text{ and/or } vpd)$ :  
 SWRESCAN(3): [0] ;  
 (0/1/2/3/4 = No/Loham./f( $R_s, vpd$ )/f( $vpd$ )/Loham.(Cienciala v.))  
 for  $r_s = f(T_c)$ :  
 SWRESCAN(4): [0] ; (0/1/2/3 = No/Polyn/Exp/ln)  
 for  $r_s = f(\psi_g)$ :  
 SWRESCAN(5): [0] ; (0/1/2/3 = No/Polyn/Exp/ln)

## ■ Plant resistance

**RESPLANT**  $r_p$ ; Plant resistance from root surface to the mesophyll of leaves. (MPa s m<sup>2</sup> g<sup>-1</sup>)

## ■ Soil-root resistance

**RESGROA**  $a_g$ ; Hydraulic conductivity of saturated soil (g m<sup>-2</sup> s<sup>-1</sup>)

**RESGROB**  $b_g$ ; Factor related to the root density. (MPa)

**RESGROC**  $c_g$ ; Coefficient related to soil pore size distribution. (-)

## ■ Interception

**INTERCK**  $\kappa_p$ ; Rain interception coefficient related to leaf area. (-)

**PLANINTX**  $m_{v10}$ ; Maximum amount of water intercepted per unit of leaf area index. (g m<sup>-2</sup>)

## ■ Growth

**EXTCRAD**  $\kappa$ ; Radiation (300-3000 nm) extinction coefficient related to leaf area. (-)

**LAI** LAI; Leaf area index. (-)

## ■ Soil water

These parameters are used only if the SOILWPOT-switch = 1.

**BROOKPOR**  $a_{por}$ ; Pore size distribution coefficient (Brooks & Coreys equation) (-)

**BROOKPSIA**  $\psi_a$ ; Air entry pressure (Brooks & Coreys equation) (MPa)

**BROOKPSIX**  $\psi_x$ ; Lower limit of water potential for use of Brooks & Coreys equation (MPa)

**BROOKRES**  $\theta$ ; Relative water content, lower limit for use of Brooks & Corey eq. (-)

**BULKDENS**  $\rho_g$ ; Dry weight of soil per unit bulk volume. (g m<sup>-3</sup>)

**IRRIGPSI**; Soil water potential in root zone at which automatic irrigation should start (MPa)

**IRRIGWAT**; Water supplied through irrigation (g m<sup>-2</sup> s<sup>-1</sup>)

**IRRIGSUR**; Fraction of irrigated water supplied below canopy directly to soil surface (-)

**RALAI**  $a_{ras}$ ; Coefficient for determining the aerodynamic resistance as function of leaf area index (s m<sup>-1</sup>)

**RESGROBG**  $b_{gg}$ ; Factor related to resistance against water flow in bulk soil. Similar to RESGROB, however, without influence of root density. (MPa)

**ROOTDEP**  $z_r$ ; Rootdepth (should be positive) (m)

**RSSCOEF**  $a_{rss}$ ; Coefficient for soil surface resistance; proportional against the inverse of relative water content (s m<sup>-1</sup>)

**RSSEXP**  $b_{rss}$ ; Coefficient for determining soil surface resistance; exponential for the relative water content (-)

**RSSTHETA**  $\theta_{rss}$ ; Coefficient for determining soil surface resistance; (-)

**SOILDEP**  $z_g$ ; Depth of whole soil volume (should be positive) (m)

**SURDEP**  $z_{surf}$ ; Depth of surface layer from which soil evaporation takes place (should be positive) (m)

**THETADM**  $\theta_m$ ; Difference between soil water content at saturation and at the situation when soil water potential equals air entry pressure. (-)



**THETAS**  $\theta_s$ ; Soil relative water content at saturation (-)

### ■ Plotting\_on\_line

Variables can be plotted on screen during the simulation by selecting appropriate values on XTGD and PMAX. Using this option version of model is written on screen.

**PMAX** plot maximum [1000]; The expected maximum value among the variables selected by XTGD. (differs)

**XTGD** variables plotted on screen [4000]; Numbers of output variables to be presented on the screen during the simulation (e.g. 4200 means 4 X-, 2 T-, zero G- and zero D variables). <=0 implies no plotting. (numbers)

### ■ Special

These parameters are activating special options. It includes sensitivity parameters (names starting with S). The value for no test is given in brackets. The subscript <sub>o</sub> denotes the original value. Where both the relative and the absolute values are possible to change a constant value of the variable concerned can be chosen by setting the relative change to 0.

[ ] is the value normally used.

**RESAIRHV**  $a_{ra}$  [1]; = $r_{aff}/r_a$ ; The ratio between the aerodynamic resistance for heat and vapour. (-)

**RESAIRRI**  $Ri-Ri_o$  [0]; Relative change of the Richardson number. =0 implies  $Ri=0$ , i.e. no effect. Only used if Start parameter SWRESAIR=1. (-)

**RESPLANU** Coefficients for determining the plant resistance as a function of root uptake rate previous time step ( $F_U(t-1)$ ).  
 $r_p(F_U(t-1))=a_p \cdot \exp(-b_p F_U(t-1))+r_{pMin} \max r_{pMin} \min r_{po}$ ; ( $r_{po}=RESPLANT$ )

RESPLANU(1):  $a_p$  (MPa s m<sup>2</sup> g<sup>-1</sup>)

RESPLANU(2):  $b_p$  (m<sup>2</sup> s g<sup>-1</sup>)

RESPLANU(3):  $r_{pMin}$  (MPa s m<sup>2</sup> g<sup>-1</sup>)

RESPLANU(4): Not used

**SRESCGRO**  $r_s(\psi_g)/r_{so}(\psi_g)$  [1]; Relative change of  $r_s(\psi_g)$ . Only used if SWRESCAN(5) > 0. (-)

**SRESCRAD**  $r_s(R_s)/r_{so}(R_s)$  [1]; Relative change of  $r_s(R_s)$ . Only used if SWRESCAN(2) > 0. (-)

**SRESCTEM**  $r_s(T_c)/r_{so}(T_c)$  [1]; Relative change of  $r_s(T_c)$ . Only used if SWRESCAN(4) > 0. (-)

**SRESCVPD**  $r_s(R_s)/r_{so}(vpd)$  [1]; Relative change of  $r_s(vpd)$ . Only used if SWRESCAN(3) > 0. (-)

**SRESCWAT**  $r_s(\psi_c)/r_{so}(\psi_c)$  [1]; Relative change of  $r_s(\psi_c)$ . Only used if SWRESCAN(1) > 0. (-)

**SRESRADD** [0]; For calculation of stomatal resistance ( $r_c$ ) as a function of stomatal resistance per unit leaf area and leaf area index (LAI). SRESRADD is the absolute change of LAI in this function.  
Only used if GROWTH-switch > 0. (-)

**SRESRADR** [1]; The same as for SRESRADD but the relative change of LAI.  
Only used if GROWTH-switch > 0. (-)

**STDENERG**  $\Delta_{Max}$  [0.1]; Maximum allowed deviation in the canopy energy balance. (W m<sup>-2</sup>)

**STDWATPO**  $\delta\psi_{cMax}$  [0.04]; Maximum allowed change in the canopy water potential during a time step of  $\delta t$  minutes. (MPa)

**STNETRAD**  $a_R, b_R, c_R$ : Coefficients in:  $R_n = a_R + b_R R_s + c_R R_n$ , determining net radiation above canopy ( $R_n$ ) as a function of DSOLRAD or DNETRAD. ( )  
 OBS! If  $c_R < 0$  then should be:  $a_R = b_R = 0$ , and vice versa.

STNETRAD(1):  $a_R$  [-23.0] ( $W\ m^{-2}$ )

STNETRAD(2):  $b_R$  [0.649] (-)

STNETRAD(3):  $c_R$  [0] (-)

**WATPOTCF** Coefficients for determining water potential ( $P_e$ ) as function of water content previous time step ( $m_v(t-1)$ ) (-)

$P_e(m_v(t-1)) = P_{cmax} - (P_{cmax} - P_{cmin}) * f$  where

$f = (\exp(a * (x - x^2)) - 1) / (\exp(a/2) - 1)$  where

$x = (1 - m_v(t-1)) / m_{vmax}$

NOTUSED if  $a=0$

WATPOTCF(1):  $a$  (-)

WATPOTCF(2): not used

## 4.4 OUTPUTS

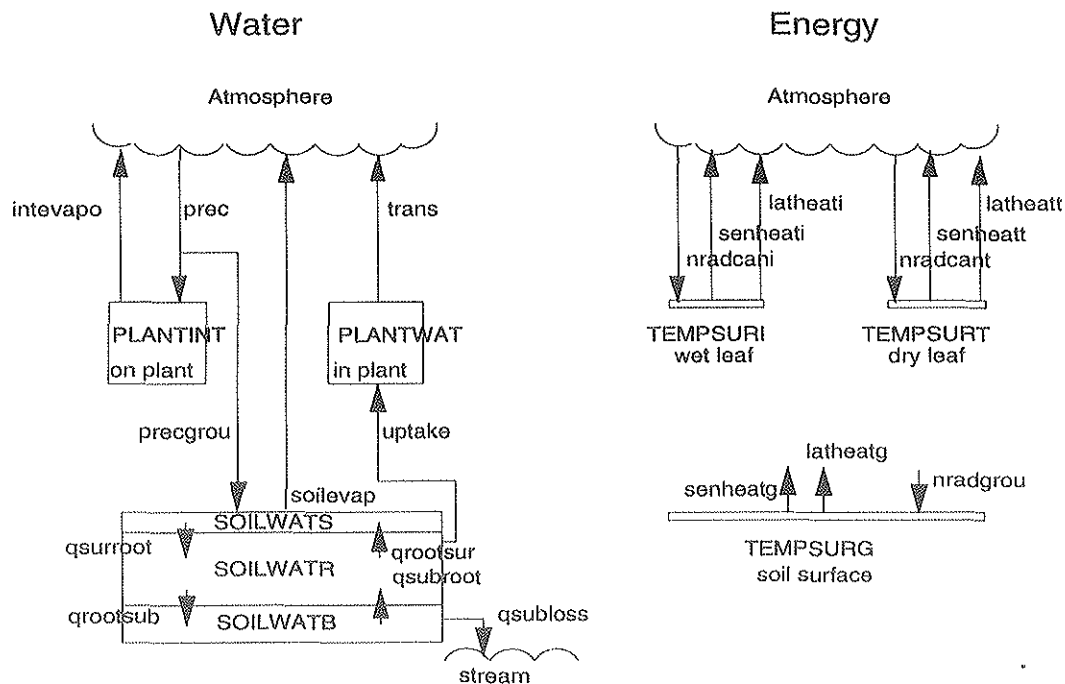


Figure. Schematic description of the SPAC model. Solid lines are flows of water or energy. For explanation of variables names see list below.

All units expressed per unit of area refers to the ground surface. Note that units of output variables sometimes are multiples of the basic SI-system.

Variable	Symbol ; Explanation	(Unit)
----------	----------------------	--------

States:

<b>PLANTWAT</b>	$m_v$ ; Exchangeable water in canopy	$(g\ m^{-2})$
<b>PLANTINT</b>	$m_{vi}$ ; Water intercepted on the canopy	$(g\ m^{-2})$
<b>SOILWATB</b>	$(m_{gB})$ ; Soil water content of sub soil below root zone. Only used when the SOILWPOT-switch = 1.	$(g\ m^{-2})$
<b>SOILWATR</b>	$(m_{gR})$ ; Soil water content of root zone. Only used when the SOILWPOT-switch = 1.	$(g\ m^{-2})$
<b>SOILWATS</b>	$(m_{gS})$ ; Soil water content of surface layer. Only used when the SOILWPOT-switch = 1.	$(g\ m^{-2})$

Flows:

<b>INTEVAPO</b>	$E_i$ ; Evaporation of intercepted water.	$(g\ m^{-2}\ s^{-1})$
<b>IRRIGABO</b>	; Irrigation supplied above canopy	$(g\ m^{-2}\ s^{-1})$
<b>IRRIGGRO</b>	; Irrigation supplied on soil surface	$(g\ m^{-2}\ s^{-1})$
<b>PREC</b>	$P$ ; Precipitation above canopy.	$(g\ m^{-2}\ s^{-1})$
<b>PRECGROU</b>	$P_g$ ; Amount of water from precipitation falling to the ground.	$(g\ m^{-2}\ s^{-1})$

<b>QROOTDEP</b>	$\Delta m_{gRDepth}$ ; Change in water in the root zone due to increased root depth.	(g m <sup>-2</sup> s <sup>-1</sup> )
<b>QROOTSUB</b>	$q_{R \rightarrow B}$ ; Percolation of water from root zone to sub soil. Only used when the SOILWPOT-switch = 1.	(g m <sup>-2</sup> s <sup>-1</sup> )
<b>QROOTSUR</b>	$q_{R \rightarrow S}$ ; Capillary rise of water from root zone to surface layer. Only used when the SOILWPOT-switch = 1.	(g m <sup>-2</sup> s <sup>-1</sup> )
<b>QSUBLOSS</b>	$q_{Loss}$ ; Loss of water from sub soil. Only used when the SOILWPOT-switch = 1.	(g m <sup>-2</sup> s <sup>-1</sup> )
<b>QSUBROOT</b>	$q_{B \rightarrow R}$ ; Capillary rise of water from sub soil to root zone. Only used when the SOILWPOT-switch = 1.	(g m <sup>-2</sup> s <sup>-1</sup> )
<b>QSURROOT</b>	$q_{S \rightarrow R}$ ; Percolation of water from surface layer to root zone. Only used when the SOILWPOT-switch = 1.	(g m <sup>-2</sup> s <sup>-1</sup> )
<b>SOILEVAP</b>	$E_s$ ; Soil evaporation. Only used when the SOILWPOT-switch = 1.	(g m <sup>-2</sup> s <sup>-1</sup> )
<b>TRANS</b>	$E_T$ ; Transpiration	(g m <sup>-2</sup> s <sup>-1</sup> )
Auxiliaries:		
<b>BOWEN</b>	Bowen ratio ; $H_T/LE_T$ or $H_f/LE_f$ . When the INTERCEPT-switch = 2 this ratio concerns the whole canopy.	(-)
<b>LAI</b>	LAI ; Leaf area per unit of ground surface (leaf area index).	(m <sup>2</sup> m <sup>-2</sup> )
<b>LATHEATG</b>	$LE_g$ ; Latent heat flux to the atmosphere from soil surface. Only used when the SOILWPOT-switch = 1.	(W m <sup>-2</sup> )
<b>LATHEATI</b>	$LE_i$ ; Latent heat flux to the atmosphere from wet leaf surfaces.	(W m <sup>-2</sup> )
<b>LATHEATT</b>	$L(E_T$ or $E_{Tp})$ ; Latent heat flux to the atmosphere from dry leaf surfaces.	(W m <sup>-2</sup> )
<b>NRADABOV</b>	$R_n$ ; Net radiation of the site.	(W m <sup>-2</sup> )
<b>NRADCAN</b>	$R_{nc}$ ; Net radiation of the canopy.	(W m <sup>-2</sup> )
<b>NRADCANI</b>	$R_{nl}$ ; Net radiation energy available for the energy balance of the intercepted water. Only used when the INTERCEPT-switch = 2.	(W m <sup>-2</sup> )
<b>NRADCANT</b>	$R_{nT}$ ; Net radiation energy available for the energy balance of the water lost as transpiration. Only used when the INTERCEPT-switch = 2.	(W m <sup>-2</sup> )
<b>NRADGROU</b>	$R_{ng}$ ; Net radiation at the ground surface.	(W m <sup>-2</sup> )
<b>RESIAIR</b>	$r_a$ ; Aerodynamic resistance.	(s m <sup>-1</sup> )
<b>RESICAN</b>	$r_c$ ; Canopy stomatal resistance per unit of ground surface.	(s m <sup>-1</sup> )
<b>RESICGRO</b>	$r_s(\psi_g)$ ; Leaf stomatal resistance as a function of water potential in the root zone.	(s m <sup>-1</sup> )
<b>RESICRAD</b>	$r_s(R_s)$ ; Leaf stomatal resistance as a function of incident shortwave radiation on the leaves.	(s m <sup>-1</sup> )
<b>RESICTEM</b>	$r_s(T_c)$ ; Leaf stomatal resistance as a function of canopy temperature.	(s m <sup>-1</sup> )
<b>RESICVPD</b>	$r_s(vpd)$ ; Leaf stomatal resistance as a function of vapour pressure deficit.	(s m <sup>-1</sup> )
<b>RESICWAT</b>	$r_s(\psi_c)$ ; Leaf stomatal resistance as a function of canopy water potential.	(s m <sup>-1</sup> )
<b>RESIGROB</b>	$r_{gB}$ ; Soil resistance against water transport in sub soil.	(MPa s m <sup>2</sup> g <sup>-1</sup> )
<b>RESIGROR</b>	$r_{gR}$ ; Soil resistance against water transport in root zone.	(MPa s m <sup>2</sup> g <sup>-1</sup> )
<b>RESIGROS</b>	$r_{gS}$ ; Soil resistance against water transport in surface layer.	(MPa s m <sup>2</sup> g <sup>-1</sup> )

<b>RESIGROU</b>	$r_g$ ; Soil-root resistance between soil and root surface.	(MPa s m <sup>2</sup> g <sup>-1</sup> )
<b>ROOTDEPTH</b>	$z_r$ ; Root depth	(m)
<b>SENHEATG</b>	$H_g$ ; Sensible heat flux to the atmosphere from soil surface. Only used when the SOILWPOT-switch = 1.	(W m <sup>-2</sup> )
<b>SENHEATI</b>	$H_i$ ; Sensible heat flux to the atmosphere from wet leaf surfaces.	(W m <sup>-2</sup> )
<b>SENHEATT</b>	$H_T$ ; Sensible heat flux to the atmosphere from dry leaf surfaces.	(W m <sup>-2</sup> )
<b>SOILWATRS</b>	$\theta_s$ ; Soil water content at saturation. Only used when the SOILWPOT-switch = 1.	(g m <sup>-2</sup> )
<b>TEMPDIFI</b>	$T_{cr}-T_a$ ; Temperature difference between wet canopy surface and ambient air.	(°C)
<b>TEMPDIFT</b>	$T_{cr}-T_a$ ; Temperature difference between dry canopy surface and ambient air.	(°C)
<b>TEMPSURG</b>	$T_g$ ; Soil surface temperature. Only used when the SOILWPOT-switch = 1.	(°C)
<b>TEMPSURI</b>	$T_{el}$ ; Temperature of wet leaf surfaces.	(°C)
<b>TEMPSURT</b>	$T_{er}$ ; Temperature of dry leaf surfaces.	(°C)
<b>THETA</b>	$\theta$ ; Soil relative water content (root zone). Only used when the SOILWPOT-switch = 1.	(vol %)
<b>THETASUB</b>	$\theta_{gb}$ ; Soil relative water content (sub soil). Only used when the SOILWPOT-switch = 1.	(vol %)
<b>THETASUR</b>	$\theta_{gs}$ ; Soil relative water content (soil surface). Only used when the SOILWPOT-switch = 1.	(vol %)
<b>TRANSPOT</b>	$E_{Tp}$ ; Potential transpiration (only $E_{Tp}$ values > 0 are accumulated)	(g m <sup>-2</sup> s <sup>-1</sup> )
<b>TRANSRAT</b>	$E_T/E_{Tp}$ ; Actual to potential transpiration ratio.	(-)
<b>UPTAKE</b>	$F_U$ ; Water uptake by root.	(g m <sup>-2</sup> s <sup>-1</sup> )
<b>VPRESAIR</b>	$e_a$ ; Vapour pressure in the ambient air.	(hPa)
<b>VPRESSUR</b>	$e_{cs}$ ; Saturated vapour pressure in the stomata cavities.	(hPa)
<b>WATPOTC</b>	$\psi_c$ ; Canopy water potential.	(MPa)
<b>WATPOTG</b>	$\psi_g$ ; Soil water potential used for the actual transpiration calculations.	(MPa)
<b>WATPOTGM</b>	$\psi_m$ ; Upper limit for soil water potential in Brooks & Corey relationship. Only used when the SOILWPOT-switch = 1.	(MPa)
<b>WATPOTGB</b>	$\psi_{gb}$ ; Soil water potential in sub soil; simulated. Only used when the SOILWPOT-switch = 1.	(MPa)
<b>WATPOTGR</b>	$\psi_g$ ; Soil water potential in root zone; simulated. Only used when the SOILWPOT-switch = 1.	(MPa)
<b>WATPOTGS</b>	$\psi_{gs}$ ; Soil water potential in surface layer; simulated. Only used when the SOILWPOT-switch = 1.	(MPa)
Other "States":		
<b>ACCBAL</b>	; Water mass balance check	(g m <sup>-2</sup> )
<b>ACCINPUT</b>	$\Sigma_{Acc}(\text{Input})$ ; Accumulated input of water to the system. If SOILWPOT-switch = 0: (P+F <sub>U</sub> ). If SOILWPOT-switch = 1: (P).	(g m <sup>-2</sup> )
<b>ACCINTEV</b>	$\Sigma_{Acc}(E_i)$ ; Accumulated intercepted evaporation	(g m <sup>-2</sup> d <sup>-1</sup> )

<i>ACCOUT</i>	$\Sigma_{Acc}(\text{Output})$ ; Accumulated output of water from the system. If SOILWPOT-switch = 0: $(E_i+P_g)$ . If SOILWPOT-switch = 1: $(E_i+E_g+q_{Loss})$ .	$(g\ m^{-2})$
<i>ACCSTORE</i>	; Total storage of water in the system. If SOILWPOT-switch = 0: $(m_v+m_{vI})$ . If SOILWPOT-switch = 1: $(m_v+m_{vI}+m_s)$ .	$(g\ m^{-2}\ d^{-1})$
<i>ACCTRANS</i>	$\Sigma_{Acc}(E_T)$ ; Accumulated transpiration	$(g\ m^{-2}\ d^{-1})$
<i>ACCTRPO</i>	$\Sigma_{Acc}(E_{Tp})$ ; Accumulated potential transpiration	$(g\ m^{-2}\ d^{-1})$
<i>PLANTWAP</i>	$m_{vp}$ ; Exchangeable water for the potential transpiration	$(g\ m^{-2})$

Other "Flows":

<i>DELTA</i>	$\delta m_v$ ; Exchangeable water in canopy	$(g\ m^{-2}\ s^{-1})$
<i>DELTA</i>	$\delta m_{vp}$ ; Exchangeable water for the potential transpiration	$(g\ m^{-2}\ s^{-1})$

# SIMVB MANUAL

The description below holds for the SIMVB.EXE version 1.4 program dated 1997-08-18. The description is taken from SOILN User's manual (Eckersten et al. 1996) and modified and shortened to fit this report. The objectives of the SIMVB program are to enable the user to run the model technically in a simple way, to give possibility of both a strict and flexible presentation of input and output of the model, to enable a simple way of using the model as a tool for evaluation of possible changes in input, calibration, validation and to bring order to input and output files.

## 5.1 How to run SPAC

### ■ Run under DOS

Firstly, we make a short summary of which programs and files that are involved when running SPAC under DOS program in an ordinary way.

The SPAC model is executed by the program file SPAC.EXE. There are some associated files to this program. A help-file with variable descriptions etc (SPAC.HLP), a file with standard parameter values and other informations needed by the model (SPAC.DEF) and a file including titles and units of the output variables (SPAC.TRA).

The model is run by using a program file named PREP.EXE. This program helps you preparing the simulation and make the simulation, i.e. you can select parameter values, input files, simulation period etc. The PREP program illustrates well the in- and outputs of the model (type for instance, >prep spac). All information needed for PREP can be stored in a parameter file (xxxx.PAR-file). You can give instructions to PREP to take the information from that file. PREP is the program that can activate SPAC.EXE, i.e. to start the simulation. Output from the simulation are stored in two files, SPAC\_001.BIN and SPAC\_001.SUM. The first file (.BIN) includes the values of the simulated variables. The second file (.SUM) includes both a summary of all outputs (averages, sums, etc.) and the prerequisites for the simulation (i.e. the inputs) which can be used to repeat the simulation if it is renamed to xxxx.PAR.

You can get presentations of the results and make further evaluations of the simulation outputs (SPAC\_001.BIN) with help of a special program, PG.EXE.

### ■ Run under WINDOWS (SIMvb)

The principal idea of programming SIMvb is to make use of already developed DOS programs and applications. The programming is restricted to this "administration" of the operative programs and routines. SIMvb.EXE is programmed in Windows-VisualBasic and is possible to run under WINDOWS if the VBRUN300.DLL file is available.

You start SIMvb from the run option of WINDOWS, or by double click on the icon (if installed) or by writing under DOS: >win simvb

In the program SIMvb you always start with the bottom denoted "Start here". Note, that in the SIMvb program you should always use only single click. Then you select model to be used and then application, which should be stored on a hard disk (or floppy). Thereafter you normally continue with "GIVE INPUT". (If you already have made a complete preparation, and want to have free access to any part of the program, you select "Check off". The Check option only checks the order in which you select options in the program from preparation to presentation of output during one run. If you leave the program the Check option is reseted.)

The program itself enables a good overview of the principal way of using the model. If a complete run ("GIVE INPUT", "Simulation", etc) has been made the different options in the schedule, in principal, can be chosen in any order at any time. However, for the first run you have to choose them in the following order:

(i) GIVE INPUT

Copies input files to the working directory. Note, that the routines under this option overwrites files at the working directory, without warnings.

(ii) SHOW INPUT

Variables in input file named AIN\_CLIM.BIN are presented.

(iii) SIMULATION

The results are stored in files named SPAC\_CUR.bin and SPAC\_CUR.sum (CUR denotes the current simulation).

(iv) SHOW OUTPUT

Variables in SPAC\_CUR.bin are presented. Variables that are presented are grouped in accordance to subjects. You can also compare results with the previous run and/or simulations that have been stored, see below. You can view the summary file of the simulation as well.

(v) Store files

Here you can store the simulation results (SPAC\_CUR.\*) under a different name. You can also recover a previous stored simulation to the name (SPAC\_CUR.\*), thereby making it available for use in the presentation options etc.

(vi) EXIT the program.

You exit the program by pressing the "EXIT" bottom on the main menu.

## 5.2 Alternative use of SIMvb

### ■ Help

Documentaion and description of variables are available under several options in the program.

### ■ Give comments

By putting the mouse arrow on space between boxes and by making a click on the right bottom you can give comments, on whatever you want. The comments should be stored or cancelled (MAIN MENU) immediately after they have been given.



### ■ Type of User

You can select three type of users (Student, Teacher, Research) under "Help etc" (MAIN MENU). Different users will get access to different parts of the SIMvb program.

### ■ Edit files

You can change a single parameter or initial state value by select "GIVE INPUT\*" and "Parameters\*". Be aware of that you should write the parameter/variable name correctly. As concerns changes in parameter files: Note that changes of parameter values preferably are introduced in the AIN\_MAN.PAR since values in this file have the highest priority (if you make a change in AIN\_PLAN.PAR and the parameter name also appears in AIN\_MAN.PAR the latter holds). Note that in initial state file at least the first position on a row should be an empty space, then write name, space and value.

### ■ Use PREP-program manually

The PREP-program can be run in a standard (interactive) way within SIMvb. If you have made "Preparation" the prepared AIN\_xxxx.PAR files are read by PREP. The files are read in the following order: AIN\_SOIL.PAR, AIN\_PLAN.PAR, AIN\_OUT.PAR, AIN\_TIME.PAR, AIN\_MAN.PAR. Simulation results are stored in SPAC\_cur.bin as in the normal simulation.

If you do not want to load the parameters files you have chosen with "GIVE INPUT", then select "One par-file only" and "Check off" (under "Help etc", MAIN MENU) before entering PREP. Note that output file now is named SPAC\_xxx.bin (where xxx is a number from 001-999) and if you want to make use of presentation of output options it has to be restored to SPAC\_cur.bin (use "Store files" (MAIN MENU)).

### ■ Use PG-program manually

The PG-program can be used in a standard (interactive) way within SIMvb. SIMvb brings you only to the proper file. Select "PG ON" under "Help etc" (MAIN MENU).

### ■ Use Excel-program manually

In case Excel is loaded and there is a path to it, the Excel-program can be used in a interactive way within SIMvb. Select "Excel ON" under "Switches etc" (MAIN MENU). SIMvb converts the PG-binary-file concerned to dbf or lotus123 format and brings you automatically into Excel. With help of the presentation routines of SIMvb you can select variables to be exported to Excel.

### ■ Using only one parameter file

There are two possibilities to run SIMvb with only one parameter file: one (1) is to completely govern the simulation with a single parameter file and the other (2) is to still make use of output routines of SIMvb so that presentations programs can be used in a normal way. In case of 1) store the file under name AIN\_ONE.PAR and select switch "one par-file" under "Help etc" (MAIN MENU). In case of 2) store the parameter file under the name AIN\_MAN.PAR and take away (i) the declaration of file names except for FILE(9), which should be named ain\_fert.bin if it is used, and (ii) the UTFORN switch. All the other parameter files have to exist but could be empty except for a ";" at the end of the file (ain\_out.par is delivered by SIMvb automatically).

### ■ Making the five parameter files

Under the option "GIVE INPUT", "Normal" (MAIN MENU) the five parameter files ain\_soil.par, ain\_plan.par, ain\_out.par, ain\_time.par and ain\_man.par can be created automatically from the last simulation (i.e. from SPAC\_CUR.SUM-file).

### ■ Multiple runs

Up to 6 multiple simulations can be done and plotted. (It is the presentation of output that limits the number of simulations.)

### ■ Initial states of previous run

Make a simulation using outputs of the previous simulation as initial states in the new simulation.

### ■ File list

In the "GIVE INPUT" option of SIMvb files can be selected arbitrarily by selecting "file list" in the list menus. This is a complement to the other preparation options.

### ■ Alternative applications under directory ...\XXXX\...

Often several versions of the same main application is wanted to be run by SIMvb. Using the "Standard" application one way of running these versions and to store them separately is to do as follows:

- 1) Store the main application with a full set up of input files under ...\XXXX\N\NA, as usual.
- 2) Store the files changed due the specific version under a separate directory named f.i. VERSION1, i.e. ...NA\VERSION1. Do not change the name of the files and remember to store the INFO.LIS file in which you give an identification of the application stored on the directory.
- 3) Copy files from VERSION1 directory to working directory by pressing "Prep. from SubDir..." (this option is available if "Teacher ON" is selected under "Help etc." (MAIN MENU)).

## 6 LIST OF SYMBOLS

Symbol	Description	Unit
$\Psi_a$	Water potential corresponding to air entry pressure	MPa
$\Psi_c$	Canopy water potential	MPa
$\Psi_{cMin}$ $\Psi_{cMax}$	Minimum and maximum canopy water potential	MPa
$\Psi_g$	Soil water potential	MPa
$\Psi_m$	Soil water potential at upper limit of Brooks & Coreys eq.	MPa
$\delta$	Generally used for a difference during a time step	-
$\Delta$	Slope of saturated vapour pressure curve in Penman eq.	Pa °C <sup>-1</sup>
$\Delta_{Max}$	Maximum allowed deviation in canopy energy balance	W m <sup>-2</sup>
$\Delta m_{gRDepth}$	Change of water in the root zone due to increased root depth	g m <sup>-2</sup> s <sup>-1</sup>
$\Delta \Psi_{cMax}$	Maximum allowed change of $\Psi_c$ from one iteration to another for accepting the water balance.	MPa
$\gamma$	Psychrometric constant (=67)	Pa K <sup>-1</sup>
$\kappa$	Radiation extinction coefficient related to leaf area	-
$\kappa_p$	Rain interception coefficient related to leaf area	-
$\rho_a$	Specific density of moist air (=1204.7)	g m <sup>-3</sup>
$\rho_g$	Density of bulk soil	g m <sup>-3</sup>
$\rho_w$	Specific density of water (=1·10 <sup>6</sup> )	g m <sup>-3</sup>
$\theta$	Soil relative water content (root zone)	-
$\theta_{gs}$	Soil relative water content of soil surface layer	-
$\theta_m$	Difference between $\theta_s$ and relative water content at upper limit of Brooks & Corey eq.	-
$\theta_r$	Relative water content, lower limit for use of Brooks & Corey eq.	-
$\theta_{rss}$	Relative water content coefficient used for soil surface resistance estimates	-
$\theta_s$	Soil relative water content at saturation	-
$a_g$	Coefficient of saturated soil hydraulic conductivity	g m <sup>-2</sup> s <sup>-1</sup>
$a_i, b_i, c_i, d_i, e_i$	Coefficient names: $i = \tau$ (water use eff.), $=c$ ( $r_s(\Psi_c)$ ), $=d$ (displacement height), $=e$ (saturated vapour pressure), $=h$ (canopy height), $=L$ (Lohammar eq.), $=Li$ (Lindroth eq.), $=o$ (roughness height), $=r$ ( $r_s(R_s)$ ), $=R$ (net radiation), $=ra$ (aerodynamic resistance), $=ras$ (within canopy aerodynamic resistance), $=rp$ (plant resistance), $=rr$ (soil-root resistance), $=rss$ (soil surface resistance), $=v$ ( $r_s(R_s, vpd)$ ), $=m_v$ (plant water), $=w$ (analytic humidity)	differs
$b_g$	Root density resistance factor	MPa
$c_{BC}$	Pore size distribution coefficient in Brooks & Coreys eq.	-
$c_g$	Soil pore size distribution factor	-
$C_p$	Specific heat per unit mass of air (=1.004)	J g <sup>-1</sup> K <sup>-1</sup>
$e_a$	Vapour pressure of the air above canopy	hPa
$E_i$	Evaporation rate of intercepted water	g m <sup>-2</sup> s <sup>-1</sup>
$E_g$	Soil (ground) surface evaporation	g m <sup>-2</sup> s <sup>-1</sup>
$e_s$	Saturated vapour pressure of the air.	hPa
$e_{cs}$	Saturated vapour pressure of the air inside the stomata cavities.	hPa
$E_T$	Transpiration rate	g m <sup>-2</sup> s <sup>-1</sup>
$E_{Tp}$	Potential transpiration rate	g m <sup>-2</sup> s <sup>-1</sup>
$F_U$	Water uptake by roots	g m <sup>-2</sup> s <sup>-1</sup>
$g$	Gravitational acceleration	m s <sup>-2</sup>
$h_a$	Relative air humidity above canopy	-
$H_i$	Sensible heat flux from wet canopy to the air	W m <sup>-2</sup>

$H_g$	Sensible heat flux from ground surface to the air	$W m^{-2}$
$H_T$	Sensible heat flux from dry canopy to the air	$W m^{-2}$
$j$	Number of water balance iteration	number
$k$	von Karman's constant ( $\approx 0.41$ )	
$L$	Latent heat of water vaporisation ( $\approx 2451.8$ )	$J g^{-1}$
$LAI$	Leaf area per unit ground surface (leaf area index)	-
$m_{gB}$	Water in the layer below root zone	$g m^{-2}$
$m_{gBMax}$	Water in the layer below the root zone at saturation	$g m^{-2}$
$m_{gR}$	Water in the root zone	$g m^{-2}$
$m_{gRMax}$	Water in the root zone at saturation	$g m^{-2}$
$m_{gS}$	Water in the soil surface layer	$g m^{-2}$
$m_{gSMax}$	Water in the soil surface layer at saturation	$g m^{-2}$
$m_V$	Easily exchangeable water in the plant	$g m^{-2}$
$m_{VI}$	Water intercepted on the canopy surface (per unit ground surface)	$g m^{-2}$
$m_{VIMax}$	Maximum water intercepted on the canopy surface (per unit ground surface)	$g m^{-2}$
$m_{VIo}$	Maximum water intercepted on the canopy surface per unit leaf area	$g m^{-2}$
$m_{VMMax}$	Maximum easily exchangeable water in the plant (per unit ground surface).	$g m^{-2}$
$m_{Vo}$	Maximum easily exchangeable water in the plant per unit leaf area.	$g m^{-2}$
$P$	Precipitation above canopy	$g m^{-2} s^{-1}$
$P_g$	Precipitation to the ground	$g m^{-2} s^{-1}$
$q_{Loss}$	Loss of water from soil through percolation and runoff	$g m^{-2} s^{-1}$
$q_{S \rightarrow R}$	Loss of water from surface layer to root zone	$g m^{-2} s^{-1}$
$q_{R \rightarrow B}$	Loss of water from root zone to soil layer below root zone	$g m^{-2} s^{-1}$
$r_a$	Aerodynamic resistance	$s m^{-1}$
$r_{aH}$	Aerodynamic resistance specially for heat	$s m^{-1}$
$r_{as}$	Aerodynamic resistance from soil surface to above canopy	$s m^{-1}$
$r_c$	Stomatal resistance per unit ground surface	$s m^{-1}$
$r_c(\psi_c)$	Sub function of the stomatal resistance only dependent on the canopy water potential	$s m^{-1}$
$r_c(\psi_g)$	Sub function of the stomatal resistance only dependent on the water potential in the root zone	$s m^{-1}$
$r_c(R_s, vpd)$	Sub function of the stomatal resistance dependent on the radiation and vapour pressure deficit of the air.	$s m^{-1}$
$r_c(R_s)$	Sub function of the canopy resistance dependent on the radiation	$s m^{-1}$
$r_c(T_c)$	Sub function of the stomatal resistance only dependent on the canopy temperature	$s m^{-1}$
$r_c(vpd)$	Sub function of the stomatal resistance dependent on the vapour pressure deficit of the air.	$s m^{-1}$
$r_{cMax}$	Maximum stomatal resistance	$s m^{-1}$
$r_{cMin}$	Minimum stomatal resistance	$s m^{-1}$
$r_g$	Soil-root resistance	$MPa s m^2 g^{-1}$
$r_{ss}$	Soil surface resistance	$s m^{-1}$
$Ri$	Richardson number	-
$R_n$	Net radiation above canopy	$W m^{-2}$
$R_{nc}$	Net radiation of the canopy	$W m^{-2}$
$R_{ng}$	Net radiation of soil surface	$W m^{-2}$
$R_{nl}, R_{nr}$	Net radiation of the wet and the dry part of the canopy, respectively	$W m^{-2}$
$r_p$	Plant resistance	$MPa s m^2 g^{-1}$

$r_s$	Stomatal resistance per unit leaf area	$s\ m^{-1}$
$R_s$	Incident radiation intensity (300-3000nm) on a horizontal surface	$W\ m^{-2}$
$R_{sMin}$	Radiation limit below which the stomatal resistance achieves its maximum value.	$W\ m^{-2}$
$t$	Time	differs
$t_1$	Time at the beginning of a time-step	s
$t_2$	Time at the end of a time-step	s
$T_a$	Air temperature	$^{\circ}C$
$T_{ct}, T_{cr}$	Canopy surface temperature of wet and dry surfaces	$^{\circ}C$
$T_c$	Canopy surface temperature	$^{\circ}C$
$t_0$	t at start of simulation	day number
$T_g$	Soil surface temperature	$^{\circ}C$
$U$	Wind speed above canopy	$m\ s^{-1}$
$vpd$	Vapour pressure deficit of the air	hPa
$z_b$	Depth of whole soil profile	m
$z_d$	Displacement height	m
$z_0$	Roughness height	m
$z_r$	Root depth	m
$z_{surf}$	Depth of soil surface layer	m
$z_U$	Height above ground of wind measurements above canopy	m

## 7 REFERENCES

Papers and reports published with relevance for the SPAC model and publications referred to in the text.

- Burujeny M, 1992. Dygnsvariation i bladvattenpotential hos raps och senap. Mätningar och simuleringar. Examensarbete. Division of Agricultural Hydrotechnics, Communications 92:3, Dep. of Soil Sci., Swed. Univ. of Agric. Sci., Uppsala. ISRN SLU-Hy-AVDM--92/3--SE. 27 pp.
- Cienciala E, Eckersten H, Lindroth A, Hällgren JE, 1994. Simulated and measured water uptake by *Picea abies* under non-limiting soil water conditions. *Agric. and Forest Meteor.* 71:147-164.
- Eckersten, H. 1985. Transpiration of *Salix* simulated with low and high time resolution weather data. Research Reports, Biotechnical Univ. E.K. of Ljubljana, Suppl. 10, pp 49-55.
- Eckersten, H. 1986a. Willow growth as a function of climate, water and nitrogen. Department of Ecology & Environmental Research, Swedish University of Agricultural Sciences, Report 25, 38 pp.
- Eckersten, H. 1986b. Simulated willow growth and transpiration: the effect of high and low resolution weather data. *Agricultural and Forest Meteorology* 38:289-306.
- Eckersten, H. 1991a. SPAC-GROWTH, model description. Division of Agricultural Hydrotechnics, Report 164, Dep. of Soil Sci., Swed. Univ. of Agric. Sci., Uppsala. ISRN SLU-Hy-R--164--SE. 36 pp.
- Eckersten, H. 1991b. SPAC-GROWTH model, User's manual. Division of Agricultural Hydrotechnics, Communications 91:4, Dep. of Soil Sci., Swed. Univ. of Agric. Sci., Uppsala. ISRN SLU-Hy-AVDM--91/4--SE. 31 pp.
- Eckersten, H. 1995. Simulation of water flow in plant communities. -SPAC model description, exercises and user's manual. Division of Agricultural Hydrotechnics, Communications 95:7, Dep. of Soil Sci., Swed. Univ. of Agric. Sci., Uppsala. ISRN SLU-Hy-AVDM--95/7--SE. 49 pp.
- Eckersten, H., Jansson P-E. and Johnsson H., 1994. SOILN model (ver 8.0), User's manual. Division of Agricultural Hydrotechnics, Communications 94:4, Dep. of Soil Sci., Swed. Univ. of Agric. Sci., Uppsala. ISRN SLU-Hy-AVDM--94/4--SE. 58 pp.
- Eckersten, H., Jansson P-E. and Johnsson H., 1996. SOILN model (ver 9.1), User's manual. Division of Agricultural Hydrotechnics, Communications 96:1, Dep. of Soil Sci., Swed. Univ. of Agric. Sci., Uppsala. 93 pp

- Eckersten, H., Jansson P-E., Karlsson, S., Lindroth, A., Persson, B., Perttu K. and Andersson J., 1995. En introduktion till biogeofysik (An introduction to biogeophysics). Division of Agricultural Hydrotechnics, Communications 95:6, Dep. of Soil Sci., Swed. Univ. of Agric. Sci., Uppsala. ISRN SLU-Hy-AVDM--95/6--SE. 72 pp. (in Swedish)
- Eckersten, H. & Kowalik, P.J. 1986. Measured and simulated leaf-air temperature differences in a willow stand. In: Eckersten, H. (ed.). Willow growth as a function of climate, water and nitrogen. Department of Ecology and Environmental Research, Swedish University of Agricultural Sciences. Report 25, 31 pp.
- Eckersten, H., Kowalik, P. & Lindroth, A. 1986. Simulation of diurnal changes of leaf temperature, transpiration and interception loss in willow energy forest. In: Institute of Water Engineering and Water Management (Ed.). Hydrological processes in the catchment. Cracow Technical University, Volume 1, 17-21 pp.
- Eckersten, H. & Lindroth, A. 1986. Vattnet flödar i energiskogen. Pilarna har det svettigt. Uppsatser och Resultat Nr 53 (Biomassa och Energi 4), Inst. för skogsteknik, Sv. Lantb. Univ., Garpenberg, pp. 19-21.
- Eckersten, H., Nilsson, L.O. & Perttu, K. 1984. Environment and production of energy forests. Poster abstract. In: Proc. from Bio Energy 1984, Göteborg, Sweden. Vasastadens bokbinderi, Göteborg. pp. 38.
- Jansson, P-E. 1991. Simulation model for soil water conditions, description of the SOIL model. Division of Agricultural Hydrotechnics, Report 165, Dep. of Soil Sci., Swed. Univ. of Agric. Sci., Uppsala. ISRN SLU-Hy-R--165--SE. 72 pp.
- Kowalik, P.J. & Eckersten, H. 1984. Water transfer from soil through plants to the atmosphere in willow energy forest. *Ecological Modelling* 26:251-284.
- Kowalik, P.J. & Eckersten, H. 1989. Simulation of diurnal transpiration from willow. In: K.L. Perttu & P.J. Kowalik (Editors), *Modelling of energy forestry - Growth, water relations and economy*. Simulation Monographs, Pudoc, Wageningen, pp 97-119.
- Kowalik, P.J. & Turner, N.C. 1983. Diurnal changes in the water relations and transpiration of a soybean crop simulated during the development of water deficits. *Irrig. Sci.*, 4:225-238.
- Rosenberg NJ, Blad BL, Verma SB, 1983. *Microclimate, the biological environment*. Second edition. John Wiley & Sons, New York, Chisester, Brisbane, Toronto, Singapore, 495pp

Förteckning över utgivna häften i publikationsserien

SVERIGES LANTBRUKSUNIVERSITET, UPPSALA. INSTITUTIONEN FÖR MARKVETENSKAP.  
AVDELNINGEN FÖR LANTBRUKETS HYDROTEKNIK. AVDELNINGSMEDDELANDE. Fr o m 1994

- 94:1 Tabell, L. Tjäle i torvjord. 46 s
- 94:2 Halldorf, S. Runoff water as a soil forming factor in arid zones. 62 s.
- 94:3 Jansson, P-E. SOIL model. User's Manual. Third edition. 66 s.
- 94:4 Eckersten, H., Jansson, P-E. & Johnsson, H. SOILN model. User's manual. Second edition. 58 s.
- 94:5 Persson, R. (ed.). Proceedings, NJF-seminar no 247, Agrohydrology and nutrient balances, October 18-20, 1994, Uppsala, Sweden. 111 s.
- 95:1 Alavi, G. Radial stem growth and transpiration of Norway spruce in relation to soil water availability. Granens tillväxt och transpiration i relation till markvattnets tillgänglighet (Licenciatavhandling). 13 + 11 + 14 s.
- 95:2 Johansson, W. & Fellin, O. Biogas från vall. Teknik och ekonomi vid odling, skörd, transporter, ensilering samt rötning med tvåstegsteknik. 38 s.
- 95:3 Svensson, E., Linnér, H. & Carlsson, H. Utvärdering av växtanalys i fabrikspotatis. 53 s.
- 95:4 Andersson, A. Vattentillgångar för bevattning i Kalmar län. I. Litteraturöversikt. II. Intervjuundersökning rörande vattenmagasin. 48 s.
- 95:5 Wesström, I. Bestämning av markens salthalt genom mätning med konduktivitetssond. 18 s.
- 95:6 Eckersten, H., Jansson, P-E., Karlsson, S., Persson, B., Perttu, K. & Andersson, J. En introduktion till biogeofysik. 72 s.
- 95:7 Eckersten, H. Simulation of water flow in plant communities. SPAC model description, exercises and user's manual. 49 s.
- 95:8 Nabieian, F. Simulering av vattenbalans för energiskog på en torvmark. 25 s.
- 96:1 Eckersten, H., Jansson, P-E., & Johnsson, H. SOILN model, user's manual. Version 9.1. 93 s.
- 96:2 Eckersten, H., Jansson, P-E., Karlsson, S., Lindroth, A., Persson, B., Perttu, K. & Andersson, J. En introduktion till biogeofysik, 2:a upplagan. 110 s.
- 96:3 Carlsson, H., Larsson, K. & Linnér, H. Växtnäringsstyrning i potatis. 69 s.
- 97:1 Uppenberg, S., Wallgren, O. & Åhman, M. Saturated hydraulic conductivity in an acid sulphate soil. A minor field study in the the Vietnamese Mekong delta. 45 s.
- 97:2 Djodjic, F. Avrinningsmönster i ett litet åkerområde under 40 år av successiv urbanisering. 38 s.
- 97:3 Vukovic, M. The effect of soil hydraulic properties on ground water fluctuations in a heavy clay soil. Measurements and simulations. 43 s.
- 97:4 Eckersten, H., Jansson, P-E., Karlsson, S., Lindroth, A., Persson, B., Perttu, K., Carlsson, M., Lewan, L. & Blombäck, K. En introduktion till biogeofysik, 3:e upplagan. 130 s.
- 97:5 Eckersten, H. Simulation of water flow in plant communities. SPAC model description, exercises and user's manual. 2<sup>nd</sup> edition. SPAC version 5.0. 52 s.

