Modelling the interactions between water availability and forest succession on a spatial basis

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ABSTRACT

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Transpiration is calculated as the minimum of the amount of water a tree can pump up (Hagen-Poiseuille), the potential transpiration (Penman-Monteith) and the available amount of water. The availability of water is a result of the water uptake by trees, precipitation, interception, run-on and runoff and the depth and radius of the root system. The effect of water on vegetation development is simulated by reducing the net primary production (NPP) with a factor that is a ratio of potential and actual transpiration. The model is validated with data sets from temperate forests and an orchard.

Keywords: FORSPACE, Hagen-Poiseuille, Imbosch, water balance, forest succession, Penman-Monteith, spatial, temperate forest ecosystems

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Contents

Summary

A model is presented that simulates the interaction between forest succession and water availability. An approach is chosen in which water stress has a negative impact on net primary production (NPP) of the simulated plant growth. In this way development of individual plants is related to water availability, thus influencing the succession of the simulated ecosystem.

Water stress occurs on two occasions, when the amount of available water in the soil is not sufficient to meet the demanded amount of water for the potential transpiration or when the amount of water that a tree can pump up from the soil is not sufficient. The amount of water a tree can pump up from the soil is calculated according to the Hagen-Poiseuille equation in which the variables are: the height of the canopy, the difference between soil water potential and the minimal leaf water potential and the diameter of xylem vessels.

Interception of water through the canopy and withdrawal of water from the soil influences the availability of water to plants.

The model is implemented in the already existing spatially explicit model FORSPACE. The spatial aspect of the water balance comes to expression through run on and runoff. This is modelled as the surplus of water that can not infiltrate the soil after a shower.

After the presentation of the model, we validated a part of the model and analysed the sensitivity of the model to maximum leaf area index that a tree can obtain, the leaf size of trees and the diameter of xylem vessels. This sensitivity analysis showed us that the sensitivity of NPP and transpiration through the canopy to LAI is important.

Then a scenario run is carried out on a temperate forest ecosystem in the centre of the Netherlands called “de Imbosch”.

1 Introduction

In current nature conservation in the Netherlands questions arise about what best practice is to keep biodiversity and landscape heterogeneity. Several ideas exist about the effects of grazing, controlled fires and the effect of natural processes like water shortages, spontaneous fires and storms. These processes can not really be controlled but have effects on the management measures that have to be taken in forest conservation measures. Therefore a model is developed to explore the effect of these factors (i.e. fire, grazing, storm or water availability) on the succession of a temperate forest ecosystem, called FORSPACE. The simulation model is on a spatial basis, and is meant to explore future scenarios under different management conditions.

Herbivory and fire are considered to be landscape forming processes, in the sense that they have a profound effect on the vegetation succession. On the other hand vegetation has an effect on the condition of the herbivores and the chance of fires occurring as a function of the accumulation of fuel load. This dynamic interaction is implemented in FORSPACE on a spatial basis.

Water limitation or excess can also be considered as landscape forming process, having effect on the succession of plants. Water however was not yet a plant influencing factor in the model. In this article we try to investigate one major facet of a water balance:

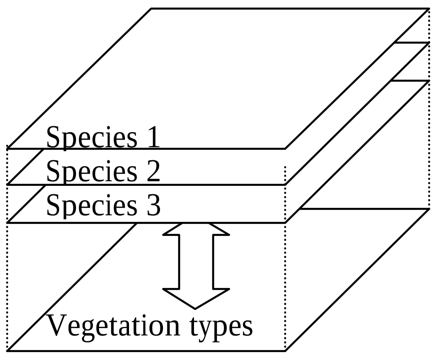
What is the effect of a water balance on the composition of a forest, considering tree species that are already included in the model?

The tree species that will be discussed include *Quercus robur*, *Pinus sylvestris*, *Fagus sylvatica* and *Betula pendula*. We will start with a brief description of the water balance as it is implemented in the current syntax of FORSPACE. Then we will validate the model and do sensitivity runs with the water balance. Finally we will examine scenario runs with a forested nature area in the central part of the Netherlands called "de Imbosch" under different water avaliability conditions.

2 Model description

2.1 Short introduction to the main model FORSPACE

The water balance is designed for the spatially explicit forest succession simulation model FORSPACE, which is modelled in PCRaster (Karssenberg 1996). It is a dynamic model that works with time steps of a month. This model works with a



1.

Figure 1.1, an overlay of cover maps of different species forms a vegetation map.

spatially heterogeneous landscape that is formed by digital maps, which have to be provided by the user. These maps are raster based, and every map indicates the cover of a plant species in each grid cell. The spatial aspect of succesion is translated by seed dispersal between raster cells of the species that are defined in the model. An overlay of the maps gives the vegetation type of each raster cell (see Figure 1.1). Development of the vegetation within a grid cell depends on incoming light, available space and, if herbivores are present, removal of biomass by herbivory. For each plant the LAI is calculated. With this LAI the amount of absorbed photosynthetically active radiation (PAR) is calculated with the Lambert-Beer equation with an extinction coefficient of 0.7 (see equation 2.2). For this calculation the canopy is divided in three layers: the herb, shrub and tree layer. Net primary production (NPP) is calculated by multiplying the amount of absorbed radiation with a radiation use efficiency (RUE, kg DM J^{-1}). NPP is allocated to the different organs of the plants according to their priority. The RUE and the growth rates of plants are depending on the soil type that is specified by means of a soil map. Soiltypes represent a growth class that is specified per species. This leads to different suitabilities of cells for several species which creates a different way of succession. The time span of a simulation run can be specified by the user. The output can be any variable, present in the model, that is speciefied by the user. Output can be a time serie of a specific cell or type of cells, or it can be a complete map that shows the spatial distribution of the model. For a more complete description of FORSPACE we refer to Kramer et al. (2000).

2.2 Water balance

Water in the model is calculated as a mass balance. This means that quantities are expressed in kg. The water balance operates with time steps of days although the main model works with time steps of months. We choose for time steps of days because we want to be able to have a distribution of precipitation within a month. This gives the possibility to simulate different precipitation patterns throughout the month. Next to that we want to be able to model the spatial distribution of water. For the latter time steps of hours or even minutes would be better. Because of modelling complexity and calculation time needed for simulation runs time steps of days are considered to be an appropriate option. Incoming water flows are precipitation and run-on from elevated plots. The outgoing flow consists of runoff, interception, drainage, transpiration and evaporation. The model is not developed for floodplains, and therefore water input from flooding is not included. Capillary rise is not included. We will discuss each of the input and output factors briefly, and after that we will discribe the effect of water stress on plant development. For a more detailed description we refer to Appendix I.

2.2.1 Precipitation

Precipitation is an input variable that is read from a meteorological data file. This file contains the daily precipitation figures of a "standard" year.

It is not yet possible in the present model to read meteorological data from subsequent years although this would make the simulation of variable weather patterns and a changing climate possible.

2.2.2 Run-on and Runoff

Run-on is defined as the runoff of an elevated grid cell. The direction to which the water flows is determined using a digital elevation model of the investigated area. Runoff is calculated according to the soil water content of the soil and amount of precipitation that reaches the soil surface. Length, inclination and roughness of the slope are not included.

2.2.3 Interception

One of the important effects of a forest on the water balance is interception of precipitation by the canopy. In the water balance we used a linear relation between LAI and intercepted rain adopted from Woodward (1987). In this approach we assumed the leaf distribution within a plot to be homogenous.

2.2.4 Drainage

Water that reaches the soil surface and doesn't run-off, infiltrates the topsoil layer. Once infiltrated in the soil, it is redistributed over the remaining soil layers. There are three soil layers in the model. The first two layers each have a thickness of 300 mm each, while the third layer is 900 mm to have an effective depth of 1.5 m. Redistribution is approached with the "tipping bucket" method in which a drainage coefficient of 0.5 is used. This means that half the amount of water in excess of field capacity seeps to the next layer each day. The amount of water that leaves the lowest soil layer is limited by a maximum drain rate (kg m^{-2} day^{-1}). A high drain rate indicates a good permeability. A zero value indicates an impermeable layer.

2.2.5 Transpiration

To calculate the potential transpiration by trees and shrubs the Penman-Monteith equation is used. The amount of water that is transpired per individual plant is calculated by the amount of net radiation that is absorbed by the plant, and the total area covered by the plant using the Penman-Monteith equation (equation 2.1). Differentiation in potential transpiration between plants is a result of different boundary layer resistances ($r_{b,i}$, d m^{-1}) and the difference in development of LAI and radius of the crown ($R_{cn,i}$, m). Boundary layer resistance is a function of the size of leaves and the wind speed. It must be mentioned that there is not a wind speed profile implemented in the forest, although forests have a great impact on wind speed. The amount of net radiation that is absorbed by a plant is calculated with the Lambert-Beer equation in which an extinction coefficient of 0.5 is used (equation 2.2). The abiotic factors are read from meteorological files that are similar to the precipitation input file. The only variable that is yet to be determined is the stomatal resistance ($r_{s,i}$, d m^{-1}). This value is determined with a function from Roberts et. al. (1990) in which stomatal conductance (the inverse of stomatal resistance) depends on actual vapour pressure and incoming long wave radiation.

Transpiration will not drop suddenly when soil water content drops below permanent wilting point, but will have a gradual decrease towards permanent wilting point. To simulate this we used the Hagen-Poiseuille equation (equation 2.3). This equation calculates the conductance of the xylem vessels given the length and the diameter of the vessels and the difference in water potential between the upper side and bottom side of the vessels. The difference in potential is given as the difference in soil water potential and the minimal water potential a tree leaf can generate. The transport of water takes place in the living part of the xylem, the sapwood. Of this sapwood the most recent rings take care of most of the transport. Therefore in the model only 1 to 3 year old sapwood is used to transport the water. The available amount of moisture in the soil constrains the amount of water to be transpired by plants. Available moisture is defined in the model as the amount of moisture in the soil between actual water content and water content at wilting point. For each plant the total mass of water available to its rooted soil volume is calculated as available water.

For herbs a more simplified approach is chosen in which the only transpiration reducing factor is the amount of available water.

2.2.6 Evaporation

Potential evaporation is calculated according to the amount of radiation that is not absorbed by plants, and prevailing atmospheric conditions. Instead of the second term that is used to calculate the potential transpiration (see equation 2.1) we used the original wind term of Penman (equation 2.4). Actual evaporation depends on the amount of rain that falls on a day. When more than 0.5 mm of rain falls, actual evaporation is considered to equal potential evaporation. When drier periods occur, a function of the square root of number of days without rain is used (eq. 2.5 after Stroosnijder et al. 1982).

2.2.7 Effects of water stress

Whenever the actual transpiration is reduced because the soil water potential is too low, or the amount of available water does not meet the atmospheric demand, a reduction in RUE occurs. This is calculated by using the ratio between "potential" stomatal conductance and actual stomatal conductance. This stomatal conductance is the inverse of the stomatal resistance we used in equation 2.1. The potential stomatal conductance is the one we used to calculate potential transpiration. When the actual transpiration is calculated, we can calculate the actual stomatal conductance with a transformed version of equation 2.1. The ratio between these to conductances is a reduction factor for the RUE (equation 2.6).

Table 2.1 parameters used in the water balance.

Name	Description	Units and values
Physical constants		
λ	heat of evaporation of water	2260 kJ kg^{-1}
γ	psychrometric coefficient	0.067 kPa ^{o}C^{-1}
η	viscosity of water	1 $\times$ 10-9 kPa ^{o}C^{-1}
ρc_p	volumetric heat capacity of air	1200 J m^{-3} ^{o}C^{-1}
c	conversion factor to calculate the second term of the Penman-Monteith equation from J Ind^{-1} to kJ Ind^{-1}	0.001 kJ J^{-1}
Plant constants		
$\Psi_{lf,i}$	minimal water potential plant species i can create in its leaves	MPa
k_{ext}	extinction coefficient for net radiation	-
$Rds_{xl,i}$	radius of vessels of species I	mm

Table 2.2 Deriving variables used in the water balance. These variables are read from data files and are not determined by the model itself.

Name	Description	Units and values
P	precipitation	kg H_2O m^{-2}
$R_{n,l}$	net irradiation per vegetation layer	kJ m^{-2} d^{-1}
s	slope of the saturated pressure curve with t	kPa $^oC^{-1}$
u	wind speed	m s^{-1}
VP	vapour pressure	kPa

Table 2.3 Variables used in the water balance.

Name	Description	Units and values
$\Psi_{sl,i}$	average water potential of the soil over all the layers in which an individual of species i has fine roots	MPa
A_i	surface of transporting xylem of species i	m^2
$C_{s,a,i}$	actual stomatal conductance for species i	m d^{-1}
$C_{s,p,i}$	potential stomatal conductance for species i	m d^{-1}
E_a	actual evaporation	kg H_2O m^{-2} d^{-1}
E_p	potential evaporation	kg H_2O m^{-2} d^{-1}
f(u)	wind function of Penman	-
$F_{rue,i}$	reduction factor for RUE due to water stress for species i	-
I	water that infiltrates the soil	kg H_2O m^{-2} d^{-1}
L_i	total LAI of an individual of species i	m^2 m^{-2}
$L_{i,l}$	LAI per individual per layer of species i	m^2 m^{-2}
n	number of days without rain	d
$r_{b,i}$	boundary layer resistance of species i	d m^{-1}
$Rds_{cn,i}$	radius of the crown of individuals of species i	m
$R_{n,abs,i}$	absorbed net radiation by species i	kJ Ind^{-1} d^{-1}
$r_{s,i}$	stomatal resistance of species i	d m^{-1}
$T_{HP,i}$	transpiration per individual of species i according to the Hagen-Poiseuille equation	kg H_2O Ind^{-1} d^{-1}
$T_{PM,i}$	transpiration per individual of species i according to the Penman-Monteith equation	kg H_2O Ind^{-1} d^{-1}
z_i	height over which the water transport takes place	m

Table 2.4 The main equations of the water balance describing Transpiration, Radiation interception, Water uptake and Evaporation. Explanation of the symbols can be found in Table 2.1, Table 2.2 and Table 2.3

$$T_{PM,i} = \left(\frac{s \cdot R_{n,abs,i} + \frac{r c_p \cdot VPD}{r_{b,i}} \cdot L_i \cdot p \cdot Rds^2_{cn,i} \cdot c}{s + g\left(1 + \frac{r_{s,i}}{r_{b,i}}\right)} \right) \cdot \frac{1}{l} \qquad \textbf{eq. 2.1}$$

$$R_{n,abs,i} = Rds^2_{cn,i} \cdot p \cdot \sum_l \left(R_{n,l} \cdot \left(1 - e^{k_{ext} \cdot L_{i,l}}\right)\right) \qquad \textbf{eq. 2.2}$$

$$T_{HP,i} = A_i \cdot \left(\frac{Rds^4_{xl,i} \cdot p \cdot \left(\Psi_{sl,i} - \Psi_{lf,i}\right)}{8 \cdot h \cdot z_i} \right) \qquad \textbf{eq. 2.3}$$

$$f(u) = 3.7 + 4.0 \cdot u \qquad \textbf{eq. 2.4}$$

$$E_a = 0.6 \cdot E_p \cdot \left(\sqrt{n+1} - \sqrt{n}\right) + I \quad \text{if } P \le 0.5 \qquad \textbf{eq. 2.5}$$

$$= E_p \quad \text{if } P > 0.5$$

$$F_{rue,i} = \frac{C_{s,a,i}}{C_{s,p,i}} \qquad \textbf{eq. 2.6}$$

3 Application

3.1 Water balance validation

To test the water balance validation and sensitivity runs were executed with fictive and simplified forest maps. In the validation runs the water use efficiency (WUE, mmol DM/kg water transpirated) played an important role because this variable gives a good indication of the parameterisation of most of the plant influencing parameters. WUE gives a good and simple overview of the relation between production and transpiration. Next to that we examined the total transpiration and evaporation of the forest.

Finally we examined the spatial aspect of the waterbalance by a runoff dataset from an orchard situated in the south of the Netherlands.

3.2 Water balance sensitivity analysis

For sensitivity analysis the WUE is not such a good indicator because it is the ratio of two variables. It is better to test the effect of parameter change on just one variables. We chose to evaluate evapo-transpiration, transpiration, net primary production (NPP) and the rate of increase of the diameter of the stem at breast height (Rdbh).
The gerenal FORSPACE model is meant to explore future changes in forested areas.

3.3 Water balance scenario runs

For scenario runs with and without the water balance, we chose for an area in the centre of the Netherlands, the Imbosch. The vegetation in the Imbosch consists mainly of pine forest and heather vegetation. The main tree species in the area are *Quercus robur, Pinus sylvestris*, *Fagus sylvatica* and *Betula pendula.* The main herb species in the area are *Calluna vulgaris*, *Deschampsia flexuosa*, *Vaccinium spp*. and *Pteridium aquilinum.*

The model is run with average weather data from the Netherlands, excluding herbivores, concerning precipitation (kg H_2O m^{-2}), temperature (°C), irradiance (kJ m^{-2} d^{-1}), water vapour pressure (kPa) and wind speed(ms^{-1}). The research area consists mainly of dry humus podzol soils (Hd see figure 1), and has an initial vegetation composition as in Figure 2. The water tables in this area is below 30 meters, and justifies the ignoring of the capillary rise as an input factor. On the vegetation of the Imbosch a simulation run with the plain FORPSPACE model was executed as well as a run including the water balance in FORSPACE. The results of the runs will be discussed in chapter 4.3.

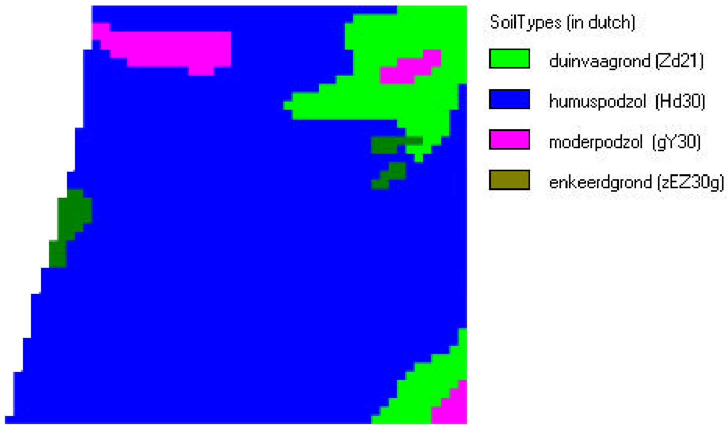


Figure 3.1 The distribution of soil types in "de Imbosch"

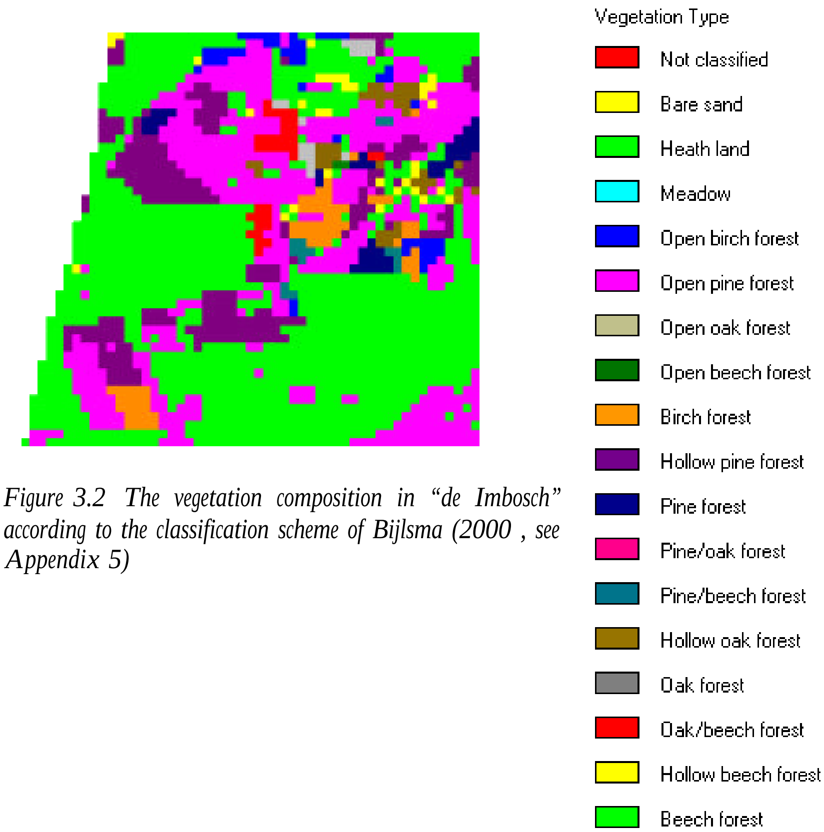


Figure 3.2 The vegetation composition in "de Imbosch" according to the classification scheme of Bijlsma (2000 , see Appendix 5)

4 Simulations

For the validation we begin to examine the WUE that is calculated by the model. LAI has an important effect on the WUE so secondly we will examine this effect and why it is so important. Then we will calculate the total evapo-transpiration in the model and compare this with measured values from Hendriks et al. (1990). Then we will make a comparison between the runoff in the model and the runoff as it was measured in the field by Ritsema (1996). After the validation a sensitivity analysis of the model to maximum LAI of species, the leaf size and the radius of the xylem will take place. The sensitivity of the first two parameters can be easily investigated because they can be considered to have a continuos effect of plant growth. The sensitivity to the leaf size is much harder to determine because this parameter has only an effect when drought occurs. We choose to look at the average reduction in RUE and the final age that *Q.robur* can obtain under these circumstances. Finally we will look at the simulation runs.

4.1 Validation

The effect of the water balance on plant species was in first instance tested on individual plant species, by making simulation runs on one grid cell with a size of 400 m^2. This is the size that is used for larger scenario runs as well. The idea is that 400 m^2 represents gaps in a forest. Trees were initialised as 25 cm high saplings with a cover of 100%. The trees were grown on a podzol soil. Validation of the parameterisation is done by looking at the water use efficiency (WUE, mmol fixed carbon per liter of transpired water) of trees and the total transpiration. In figure 4.1 we can see the results of the comparison between values found in literature and values that are calculated by simulations from the water model. The simulated values are for the first 5 years of the trees. The outcomes of *B.pendula* and *P.sylvestris* broadly agree with the values found in literature, while the outcome of *Q.robur* is giving a significant difference between literature and simulated values (student t-test, $\alpha = 0.05$). The two literature values of *F.sylvatica* derive widely (377.8 and 94.4 mmol l^{-1}) making an appropriate test not meaningful. An other important thing to mention is the fact that WUE is only measured for young saplings. There is no information on WUE available for older trees because of the impossibility to measure WUE for mature trees. Whenever we look to the WUE of the trees in the simulation for a longer period than only the first 5 years, we see a decrease in WUE when the tree grows older (figure 4.2). The variable that corresponds dynamically best with this decrease is LAI (figure 4.2). LAI has an important effect on the relation between production and transpiration. This can be visualised by plotting production and transpiration per area of leaf against LAI. This is done in figure 4.3 for the percentage of maximum production and maximum transpiration which shows that both variables decrease with an increasing LAI, but that production per leaf area decreases relatively more than transpiration per leaf area. The reason for this is the difference in extinction coefficient for photosynthetically active radiation (PAR) and that for net radiation, which were set on 0.7 and 0.5 respectively. The consequence of this is that trees that can realise a high LAI have an advantage as long as water is sufficiently available, but that as water becomes scarcer, the advantage becomes less.

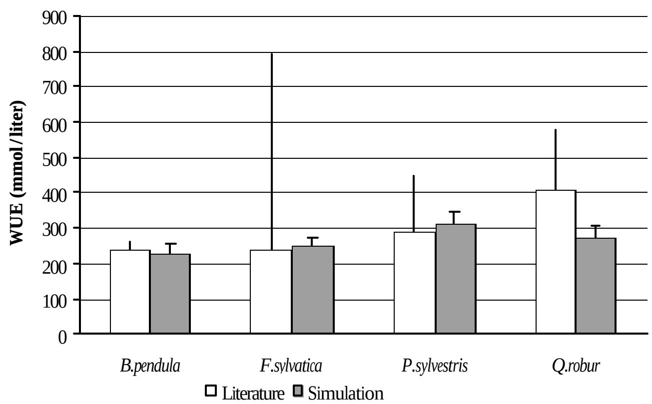


Figure 4.1 WUE (mmol liter^{-1}) for the main tree species of the model, from literature (mesh) and from the simulation (dashed)

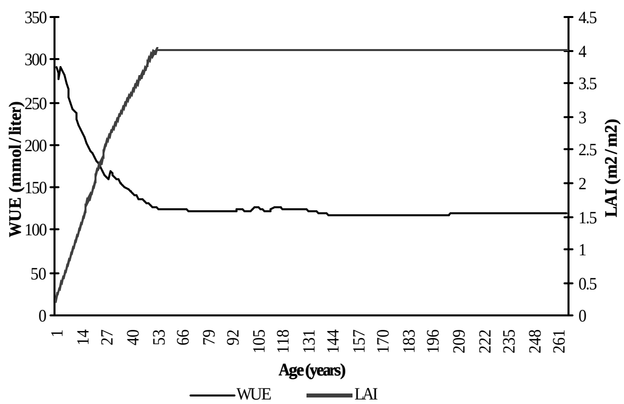


Figure 4.2 WUE (mmol liter^{-1}) and LAI (m^2 m^{-2}) of Q.robur *dynamically*

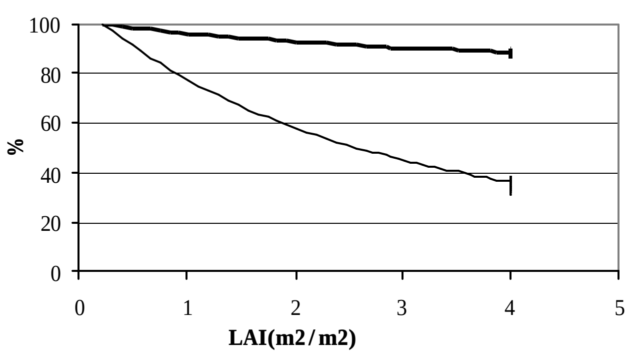


Figure 4.3 percentage of the maximum value of production (kg DM m^{-2} d^{-1}) and transpiration (kg H_2O m^{-2} d^{-1}) plotted against LAI (m^2 m^{-2}) for Q.robur.

We also looked at total evapo-transpiration, and compared it with measured data from Hendriks et al. (1990) to validate the total transpiration part. Hendriks et al. investigated the evapo-transpiration of deciduous woods in the Netherlands. To allow for comparison, the same initial forest situation as was described by Hendriks et al. was initialised. That means an oak forest, with a little birch (7% of the total cover) and an height of 17.4m on a podzol soil. The meteorological conditions are from the Loobos meteorological station, a station nearby the measuring site of Hendriks et. al. As we can see in figure 4.4 the simulated transpiration is higher than the measured evapo-transpiration, indicating that the parameter values for the model need adjustment. One parameter that might play an importand role in this is the drainage coefficient that is used in the model. This parameter is very roughly estimated, being very difficult to determine in the field. The role of this parameter can be underestimatd though. Callibration of this parameter with the figures of Hendriks et al. is needed. It should be mentioned, though, that the influence of the weather files is of utmost importance. When weather data was collected by Hendriks et al. that could be used in stead of data from the loobos meteorological station the difference might have been smaller as well. The main aim of this water balance is the effect on the vegetation development. But because FORSPACE is a spatial model, the run-on and runoff aspect should be tested as well. Not so much to validate the spatial aspect, but merely to see whether the error made by this aspect is not becoming too large. The spatial aspect of the water model (i.e. runoff and run on) is checked with a data set from Ritsema et. al. (1996) that contained actual runoff data measured in Ransdaal, an orchard in the south of the Netherlands. Although an orchard is not completely comparable to a forest, it is the best fitting situation of which runoff data is available. Of this data set, a digital elevation model (DEM), type of vegetation, precipitation, and total discharge was available. We initialised the model with this information, and checked the simulated runoff from the total area with the measured total discharge. The simulated discharge was 21.6 m^3 while the measured discharge was 23.6 m^3. This suggests that the runoff model works appropriate although it should be tested with more data sets for a better indication of the error marge.

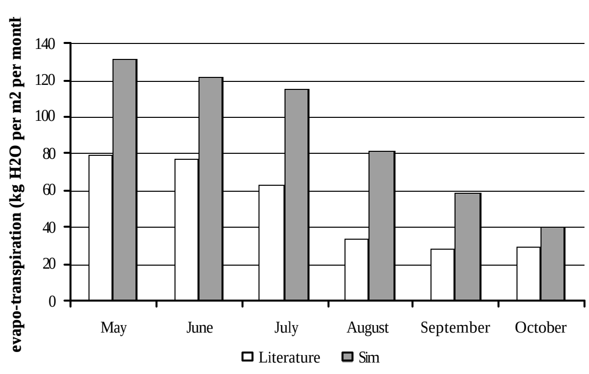


Figure 4.4 total evapo-transpiration per month (kg H2O per m2 per month) of the simulation and the measured values

4.2 Model sensitivity

Next to validation a sensitivity analysis was done to identify the parameters that are of most importance. The main parameters that should be analysed are: diameter of the xyleem, minimal leaf water potential, leaf size, and maximum LAI. Model sensitivity to leaf size and maximum LAI is measured as the propagation of variation in input parameters. Input variation was plus and minus 10 and 30 percent of the original input value. Output variables that were examined were evapo-transpiration (ET), Transpiration (T), NPP and rate of increase in diameter at breast height (RDbh). We concidered one sensitivity index:

$$S_1 = \frac{(O_1 - O_2)/|O_0|}{|(p_1 - p_2)/\, p_0|} \qquad 4.1$$

indicating the response of the vegetation relative to the standard situation, in which S is the sensitivity index, O_1 is the outcome for the tested variable when increasing the value of a parameter and O_2 is the outcome of the tested variable when the value of the parameter is decreased. O_0 is the output with the default value for a parameter. p_1 is the increased value for a parameter and p_2 is the decreased value for a parameter. p_0 is the default value for a parameter.

The response was taken as the average of the first 5 years of vegetation developpement and as the average of the 45-50 years of vegetation developpement after the start of a simulation run. Table 4.1 shows the outcomes of this sensitivity analysis. The values of the parameters were changed by ± 15% and ± 30%

Table 4.1 S_1-values (Equation 4.1) for the model variables: Evapotranspiration (ET), Tranpiration(T), Net Primary Production (NPP) and Rate of increase in Diameter at Breast height (RDbh). Input parameters that have been changed are maximum LAI (MxLAI) and the size of the leafs (LfSize). We used a variation of ±10% and ±30 % around the originally used parameter values.

	10%				30%			
	ET	T	NPP	RDbh	ET	T	NPP	RDbh
MxLAI (1-5 yr)	-0.082	0.997	1.116	0	-0.090	0.987	1.101	0
(45-50 yr)	0.285	0.982	0.560	-0.072	0.271	0.938	0.852	-0.025
LfSize (1-5 yr)	0.003	0.058	0	0	0.003	0.059	0	0
(45-50 yr)	0.011	0.017	0	0	0.012	0.017	0	0

We can see that MxLAI has a greater influence on the model output than LfSize. Especially transpiration (T) and NPP are sensitive to a change in MxLAI. What is also interesting to see is that ET experiences a slight negative influence in the beginning, but this influence disappears when the stand becomes older. An explanation for this is that the canopy of the stand is in not closed the beginning, resulting in a higher relative influence of evaporation on the total ET. The influence of MxLAI on RDbh is very small and not even noticeable in the first 5 years of the development of the stand. LfSize has a very small influence on transpiration and evaporation and no influence on NPP and RDbh, which is to be expected because in the model there are no direct links between production and LfSize. The only relation between NPP and RDbh is by means of production reduction due to water stress. The LfSize can be very influencing when it comes to this threshold effect of water stress.

For diameter of the xylem equation 4.1 gives not a suitable S-value, because these two parameters are discontinuous having only an effect when a drought occurs. The sensitivity of the model to this parameter was tested by calculating the average reduction in RUE (Equation 4.2).

$$S_2 = \frac{\left| \frac{\sum_{t=1}^{end} O_1}{\#timesteps} - \frac{\sum_{t=1}^{end} O_0}{\#timesteps} \right|}{\frac{\sum_{t=1}^{end} O_0}{\#timesteps}} \cdot 100 \qquad 4.2$$

And, because a more constraining parameter should lead to a quicker reduction in transpiration and therefore in production, the age that tree species can reach with these different values was considered too. The relative effect of decrease and increase in diameter of xylem on maximum age and Reduction in RUE is shown in figure 4.5. The sensitivity of *Q.robur* to the reduction in diameter of xylem is not that pronounced when we look at the average reduction in RUE. The effect on the maximum age however is very clear. This leads to the conclusion that not the value of reduction is important, but the moment at which this reduction occurs.

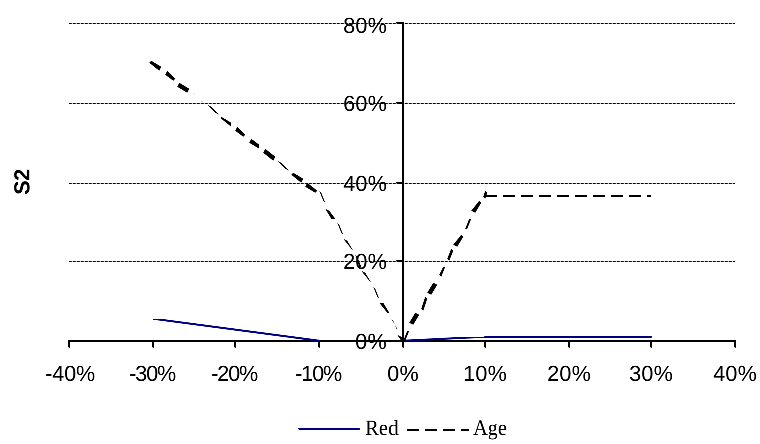


Figure 4.5 S_2-values (Equation 4.2) for Q. robur *to changes in diameter of xylem. Examined variables are: maximum age a tree can obtain (Age) and the average reduction factor for the radiation use efficiency (Red).*

4.3 Scenario runs

At last the effect of the water balance on landscape scale is tested. This is done by running the model on the Imbosch, a forested area in the central part of the Netherlands. The output from a landscape run is very extensive, making analysis difficult. However there were some analysis methods developed. The first impression of a scenario run is given by taking a glance at the vegetation output maps. The vegetation types are derived from species cover maps, as is described in paragraph 2.1, using a classification according to Bijlsma (1999, unpubl., see appendix 5 (§7.5)). When we look at the two scenario runs that are made (Figures 4.9,4.10 and 3.2), we see that in both scenarios after a period of 50 years the forest is almost completely gone. Partly this is because of the main model FORSPACE that is still in development. The mortality of trees and age related decline in production are still factors that appear difficult to simulate because it is difficult to define parameters. But there are differences in the water balance and in the plain FORSPACE model. It is however difficult to extract these differences from the maps. Therefore we should make a graph of the basal area of each tree species, as well as at the number of cells in which a tree species occurs. When we examine the graph of the basal area (figure 4.6), we see that for each species a decline appears. But we can also see that the decline for the water run is for each species larger than the decline when running the plain FORSPACE model. This indicates that the production in the water balance model has had a reduction due to water stress. We can see that the effect is most pronounced on *Q.robur* and *P.sylvestris*. The basal area that we take into account is the average basal area of cells in which a tree species occurs. This means that when new cells with young trees appear, these younger trees can cause a reduction in the average basal area as well. This makes it useful plot the number of cells in which the species occur (figure 4.7). For each species we see a decline in number of cell in which the species is present. This implies that juvenile trees do not cause the reduction in basal area. Therefore it should be drought that causes these differences in decline.

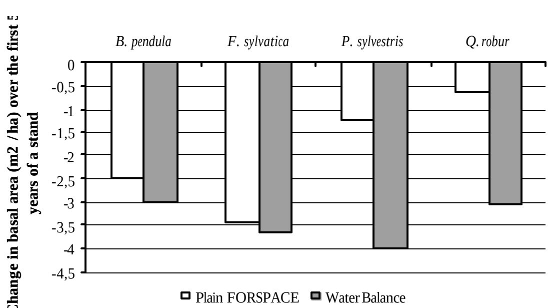


Figure 4.6 Change in basal area (m^2 ha^{-1}) for each species. this change is the average change over all cells in which these species occur.

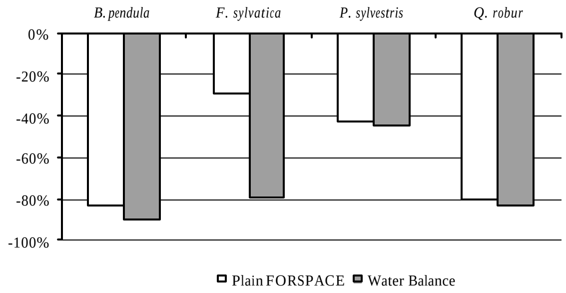


Figure 4.7 Change in number of cells in which a species occurs after 50 years as the percentage of number of cells that were occupied ny the species at initialisation.

The second thing that catches the eye is the fact that for *F.sylvatica* we have a reverse pattern as we can see for *Q.robur* and *P.sylvestris.* The difference in change in number of cells that are occupied by *F.sylvatica* is pronounced, while the decrease in basal area keeps up with the decrease that we notice in the plain FORSPACE model. A reason can be that *F.sylvatica* disappeared from a lot of cells, causing that the decrease in basal area wasn't as pronounced as it was for *Q.robur* and *P.sylvestris.* A final graph that shows us the effect of the water balance is figure 4.8. In this figure we see the relative number of cells occupied by the different species for the plain FORSPACE run and the water run after 50 years. As we can see in figure 4.8 the water balance does not only have an effect on the production of trees, but also an effect on the over all composition of the area. We already mentioned in chapter 4 that *P. sylvestris* and *Q. robur* suffered most under water stress conditions, and also from this figure we see the shift in the composition of the species. *P. sylvestris* and *Q. robur* both have a maximum LAI of 4 while *B. pendula* and *F. sylvatica* have a maximum LAI of 5 and 6 respectively. This is different from what we expect according to water use efficiency (WUE) calculations in chapter 4. We will go into this in the discussion.

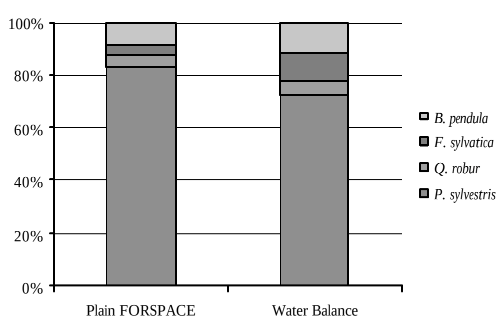


Figure 4.8 Relative number of cells occupied by the four different tree species after 50 years.

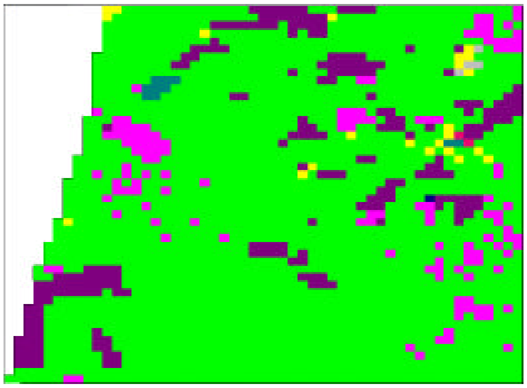


Figure 4.9 the situation in the Imbosch after 50 years with a plain (i.e. without the water balance) FORSPACE run.

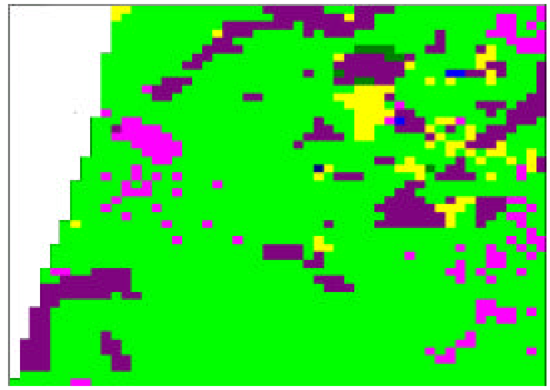


Figure 4.10 the situation in the imbosch after 50 years with a water balance run

5 Discussion

Most of the processes that play a role in water availability have been included in the model, interception, run on and runoff, evapo-transpiration and reduction in growth. One major proces is missing though, leaf abscission. The process of leaf abscission is not included in the model but might make a usefull contribution to the validity of the model. We can also see that a more extended data set is needed to test the evapo-transpiration part of the model more thoroughly.
The modeling of transpiration by means of the Penman-Monteith equation might raise some discussion. There is a second possible equation, the Makkink equation. The Makkink equation is simpler than the Penman-Monteith, and gives better results. The problem is that the Makkink formula calculates a reference evapo-transpiration that has to be multiplied with a crop factor to calculate the real potential evapo-transpiration. In the FORSPACE model however we deal with a changing vegetation, and we want the evapo-transpiration to change according to the developing vegetation. Also we want to calculate the transpiration for different plant species separately, so that competition is simulated by means of a different effect on the radiation use efficiency (RUE). For these two reasons we chose for an approach in which we used the Penman-Monteith equation.
A remark should be made about the Hagen-Poiseuille equation (equation 2.3). This equation is less applicable to gymnosperm trees and herbs because they lack xylem vessels, and mainly transport water through tracheids that have a much smaller diameter and are much shorter. For gymnosperm trees it is not easy to find a simple solution.
For herbs it might be a good idea to imply the Manning formula after all to calculate the transpiration. Next to that an alternative method exists to calculate the effect of drought on plants, that might be more applicable to herbs. This method calculates actual transpiration as a fraction of potential transpiration, according to some kind of wilting point approach. This method is well described by e.g. van Laar (1997).
An other point that should be mentioned is the difficulty that we have to determine a good drainage coefficient. Calibration of this coefficient with extensive data sets is recommended.

The main conclusion that can be drawn from the results as they have been presented is that the effect of implementing a water balance in the model causes a reduction in the development of the vegetation. This is because growth parameters of trees are at the moment calibrated without the water balance. Especially the RUE on which the water balance has a direct effect should be re-calibrated whenever the water balance is going to be used. The effect of the water balance for temperate forest systems should be that whenever the water balance is active the same production as is accomplished in the current model should be realised. Only when drier years occur the water balance should have its effect on production and in that way on the composition of species in the area. For possible future application of the model to savannah and mediterranean vegetation types the water balance should have a continuous effect on the production, except for the wet season. Furthermore a spatial pattern should be created because of the run on and runoff part of the water balance. This requires a correct digital elevation model of the researched area, in order to define the flow direction of run-off water.

In paragraph 4.1 we stated that a higher maximum LAI should lead to a lower WUE, resulting in a disadvantage whenever drought occurs. In paragraph 4.3 however the opposite occurred. Probably in this very one example the advantage of a higher LAI is still higher than the disadvantage of a lower WUE. Further simulation runs with severe drought conditions as well as runs with water surpluses should be made to test the hypothesis that a higher LAI becomes a disadvantage when drought occurs.
In retrospect to the main question quoted in chapter 1 we can conclude that at this moment more scenario runs and simulations are needed to obtain a good picture on the effect of water availability on forest development. Although results at the moment indicate that *B.pendula* and *F.sylvatica* have an advantage over *Q.robur* and *P.sylvestris.*
An interesting research question that can be investigated whenever the water balance and the FORSPACE model are sufficiently validated, would be:

What is the minimum amount of precipitation needed to sustain a temperate forest?

Next to that when the model is also adapted for mediterranean and savannah vegetations the following research question is interresting:

What is the influence of rainfall patterns and periodicity on vegetation devellopement in arid regions?

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Appendix A

A1 Model description

Water balance for FORSPACE - model description

General concept

This water balance is specially developed for the forest simulation model FORSPACE. This model is developed using the package PCRaster (Karssenberg 1996), a Geographic Information System for personal computers that works on raster base and allows the easy development of dynamic spatial models and linking with ARC-INFO. Several maps describe the initial situation, each describing the cover and height of a single species. A map also describes soil types. For each species a site index per soil type is defined. The site index gives the suitability of the soil for a species. To these site indexes the differentiating plant parameters are linked. The water balance uses vegetation dynamics as they are implemented in FORSPACE, but also has its own effect on the development of the vegetation, thus creating an interaction between vegetation and water availability. For a precise description of FORSPACE I refer to Kramer (2000).

FORSPACE works with time steps of months. For the water balance this is not suitable because we want a spatial distribution of water and we want a distribution in time for precipitation. Therefore within the FORSPACE model a day loop is implemented. Because of reasons of simplicity every month has 30 days. This makes it possible to calculate the water balance on a daily basis. Averaging the daily effect on radiation use efficiency approaches the effect on the development of plants.

Initialisation

Soil

In the water balance the soil is divided in three different compartments, soil layers. Of each soil layer the thickness (Thc_l, mm) is defined, the first two layers are 30 cm deep, while the third is 90 cm deep thus creating an effective depth up to 1.5 m. In this part of the soil, water interactions play a role. Plants can't root any deeper than 1.5 meter in the model. Of each soil layer per soil type, soil characteristics are given. These are water content at wilting point ($WtrCntWp_l$), water content at field capacity ($WtrCntFc_l$, %), water content when saturated ($WtrCntSt_l$, %), water content when air dry ($WtrCntAd_l$) and the coefficients for the pF-curves of each soil type. The water content ($WtrCnt_l$, %) of each soil type and layer is initialised at a value of 0.3 %. From this water content, the initial pF (pF_l, -) and the initial water potential of the soil ($WtrPotSl_l$, %) are calculated. We fitted the relation for the pF-curves of the different soil types to get a relationship between soil water content and pF value. In this way the parameters for pF were determined. When introducing new soil types, new curves have to be fit. The general equation is like equation1.

$$pF_l = \max(0, \min(7, C1pF_l \cdot WtrCnt_l^3 + C2pF_l \cdot WtrCnt_l^2 + C3pF_l \cdot WtrCnt_l + C4pF_l)) \qquad 2$$

For a few soil types, the constants are given in table1

Table 5, coefficients for pF relations for soil types as used in the FORSPACE model for the Imbosch (data source coefficients: Wösten et. al. 1987, data source soil types: Stiboka 1979)

Soil types	$C1pF_l$	$C2pF_l$	$C3pF_l$	$C4pF_l$
Zd21	-265.97	194.16	-48.829	6.4175
Hd30	-75.196	48.787	-23.741	7.7173
gY30	-683.51	385.08	-68.472	5.2666
zEZ30g	-75.196	48.787	-23.741	7.7173
Lower soil layers	-75.196	48.787	-23.741	7.7173

After this pF has to be converted to soil water potential in MPa. We convert pF to soil water potential ($WtrPotSl_l$, MPa) by equation 2.

$$WtrPotSl_l = 9.8 \cdot 10^{-5} \cdot (10^{pF_l}) \qquad 3$$

Plant state variables

Roots

The roots are already initialised in the main FORSPACE model, but only as a biomass. For the water balance we need the roots to have a size, so that we can determine the rooted soil volume and with that the amount of water available to the roots. However it is very difficult to find figures on spreading rates of roots for different plant species. We circumvent this problem by making the radius of the root system ($RdsRtTr_{tl,t}$, m) the same size as the radius of the crown ($RdsCnTr_{tl,t}$, m). In this way we create an overlap in root systems of different plants, because of the overlap of cover between different layers. An overlap correction factor(CorFOvl, -) is calculated to compensate for this overlap when it comes to calculation of available water to the root system.

$$TotSrfRt = \sum_{tl,t} RdsRtTr_{tl,t}^2 \cdot p \cdot NTr_{tl,t} \qquad 4$$

$$CorFOvl = \frac{PlotSize}{TotSrfRt} \qquad 5$$

The length of the roots is calculated according to their biomass. In first instance the coarse root biomass ($WCrTr_{tl,t}$, kgDM Ind^{-1}) is calculated according to a formula in which a relationship between diameter at breast height (DBH, cm) and Coarse root biomass is assumed (after Olsthorn, 1998)

$$WCrTr_{tl,t} = 0.01 \cdot DbhTr_{tl,t}^{2.63} \qquad 6$$

After this, the biomass of fine roots($WFrTr_{tl,t}$ kgDM Ind^{-1}) can be calculated as the difference between total root biomass ($WrtTRr_{tl,t}$, kgDM Ind^{-1}) and coarse root biomass.

$$WFrTr_{tl,t} = WrtTr_{tl,t} - WCrTr_{tl,t} \quad 7$$

After calculation of the fine root biomass, we calculate the required length of roots ($RqrLngRtTr_{tl,t}$ mm) per soil volume with the root density (m m^{-3}) (equation 7) and with that length the required root biomass ($RqrWghRtTr_{tl,t}$ kgDM Ind^{-1}) with the specific root length, ($SrlTr_{t,l}$, m kg^{-1}) (equation 8).

$$RqrLngFrTr_{tl,t,l} = RdsRtTr_{tl,t}^{2} \cdot p \cdot \frac{CThc_l}{1000} \cdot CRtDnsTr_{t,l} \quad 8$$

$$RqrWghFrTr_{tl,t,l} = \frac{RqrLngRtTr_{tl,t,l}}{SrlTr_{t,l}} \quad 9$$

When for each soil layer the required fine root biomass is calculated, we can calculate the rooting depth with the aid of the weight of fine roots. Whenever enough fine root biomass is available to fill up the first soil layer, the length of roots in that layer equals the thickness of that layer, and the length of roots in the second layer is calculated. The same is done whenever there is enough biomass available for the second soil layer, and the length of roots in the third and last layer is calculated.

$$LngRtTr_{tl,t,l} = \frac{WFrTr_{tl,t}}{RqrWghFrTr_{tl,t,l}} \cdot CThc_l \quad 10$$

Dynamic

Input

Precipitation

Precipitation (Prc_d, kg m^{-2} d^{-1}) is an input value on a daily basis. For precipitation a file is needed (Prc.tbl) that specifies the amount of rain for each day of the month for the whole year. It is not yet possible to specify precipitation for subsequent years.

Run-on

The second type of input is run-on ($Runon_d$, kg m^{-2} d^{-1}). The amount of run-on on a plot is determined by the amount of runoff ($Runoff_d$, kg m^{-2} d^{-1}) on a higher situated plot the day before. The directions to which water flows are determined by a digital elevation model (dem.imp) of the area, from which a local drain direction map (ldd.imp) is created. A ldd is used by PCRaster to determine the flow direction.

$$Runon_d = upstream(LocalDrain, Runoff_d) \quad 11$$

Output

Interception

The amount of precipitation that reaches the soil surface is dependent on cover and LAI. A homogeneous distribution of LAI in the different layers in a plot is assumed, to make calculation of throughfall through the different layers possible. To predict the interception a linear relation is assumed between LAI and intercepted precipitation. This relation is adopted from Woodward (1990), who estimates that 5% is intercepted with a LAI of 1 and 17% is intercepted with a LAI of 9. The rain that is intercepted by the first canopy layer is calculated according to the total LAI of this canopy and its cover:

$$Int\Pr cTl_d = \Pr c \cdot CvrTl \cdot (C1Int \cdot LaiTl + C2Int) \qquad 12$$

In which (C1Int·LAI + C2Int) stands for the linear relation between LAI and the amount of intercepted water. the values for C1Int and C2Int are 0.015 and 0.035 respectively. The throughfall through this layer is:

$$ThrTl_d = \Pr c - Int\Pr cTl_d \qquad 13$$

Now the intercepted rain by Layer 2 and the throughfall can be calculated by:

$$Int\Pr cSl_d = ThrTl_d * CvrSl * (C1Int * LaiSl + C2Int) \qquad 14$$

$$ThrSl_d = ThrTl_d - Int\Pr cSl_d \qquad 15$$

And finally also for Layer 3:

$$Int\Pr cHl_d = ThrSl_d * CvrHl * (C1Int * LaiHl + C2Int) \qquad 16$$

$$ThrHl_d = ThrSl_d - Int\Pr cHl_d \qquad 17$$

The amount of precipitation that reaches the soil surface is equal to the Throughfall of Layer3. Next to the precipitation, there is run-on from neighbouring plots.

Runoff

Of the total amount of water that comes on the plot a part infiltrates the soil, and the remainder is runoff. Runoff occurs when the rate of water supply at the soil surface exceeds the infiltration capacity and the excess water accumulated at the soil surface exceeds the surface storage capacity. Infiltration capacity is a function of the water content of the topsoil layer and the soil characteristics. The fact that the time steps for the hydrological balance of Forspace are in days makes a complicated integration of runoff and run-on practically impossible. Infiltration capacity and intensity of the rain are hard to implement in these calculations, for these are processes that take place on time steps of minutes. Therefore an empirical relation between runoff and rainfall is used (Van Laar et. al., 1997):

$$Runoff = \max\left(0\,,\,0.15\cdot(ThrHl_d + Runon_d - 10)\,,\,ThrHl_d + Runon_d - \frac{(WtrCntSt_{l1}\cdot CThc_{l1} - WtrCnt_{l1}\cdot CThc_{l1})}{2}\right) \quad 18$$

To which neighbouring cell the runoff is going, depends on the topographic position of the neighbouring cells compared to the position of the cell in consideration. A ldd (Local Drain Direction) map determines this direction. The working of this principle in pcraster goes beyond this description, and we refer to the PCRaster Manual.

Infiltration

The amount of rain that reaches the ground and doesn't runoff, will infiltrate the topsoil layer.

$$Inf_{l1} = ThrHl_d + Runon_d - Runoff_d \quad 19$$

Next to this a redistribution of the water over the different soil layers will take place. The distribution of rain over the different soil layers forms a problem because this is a process that takes place on a very small time coefficient. Therefore the tipping bucket approach is applied, in which a drainage coefficient of 0.5 is used, which means that each day half of the surplus water in excess of field capacity is drained to the adjacent lower layer.

$$\begin{aligned}
Inf_{l2} &= \max\left(0, \min\left(\frac{WtrCnt_{l1}\cdot CThc_{l1} - WtrCntFc_{l1}\cdot CThc_{l1}}{2}, WtrCntSt_{l2}\cdot CThc_{l2} - WtrCnt_{l2}\cdot CThc_{l2}\right)\right)\\
Inf_{l3} &= \max\left(0, \min\left(\frac{WtrCnt_{l2}\cdot CThc_{l2} - WtrCntFc_{l2}\cdot CThc_{l2}}{2}, WtrCntSt_{l3}\cdot CThc_{l3} - WtrCnt_{l3}\cdot CThc_{l3}\right)\right) \quad 20\\
Drain &= \max\left(0, \min\left(\frac{WtrCnt_{l3}\cdot CThc_{l3} - WtrCntFc_{l3}\cdot CThc_{l3}}{2}, MxDrn\right)\right)
\end{aligned}$$

Evaporation and Transpiration

Introduction

The usefulness of a water balance in the model is mainly to be able to investigate the effects of drought or sufficient water availability on the succession of the vegetation. This means that water stress should have a different effect on plant growth for different species. The modelling of transpiration is described by several formulas, of which the Penman Monteith combination equation and the Makkink formula are the best known. The Makkink formula is of a more recent date and gives more accurate results (CHO-TNO 1988). Next to this the Makkink formula is much simpler than the Penman Monteith combination equation (or short 'Penman'). However, the Makkink formula is an empirical formula, which is only valid in temperate zones. And next to this, no distinction can be made between different species. The advantage of the Penman is that species dependent stomatal resistance can be used to differentiate the effect of different plant species on the total transpiration. This makes it also possible to estimate the different effect of drought on different species. Because of the possibility to differentiate between plants, and the fact that Penman can be applied also to other regions in the world, we chose to use the Penman for the

calculation of the evapo-transpiration. There are though, two mayor difficulties to overcome.
Firstly, as a result of water stress stomatal resistance will increase, which causes a reduced transpiration. The point at which soil water content is limiting and thus reducing transpiration is difficult to determine.
In many water balances the so-called "reduced water content" is used to determine this point. For a clear description of this approach I refer to Van Laar 1997, p.36-38. However, there is little data on forests available for this approach. Therefor we chose a different approach, in which the point at which wilting occurs is calculated on the hand of soil water potential and the potential a leaf can create to pump up the water. We will go into this in the section *"ACTUAL TRANSPIRATION"*.
Secondly the total transpiration of the canopy is a result of the sum of al the different species. How to integrate the transpiration per species to a total transpiration, related to the vegetative cover on a plot is a point of discussion. The most convenient way is to calculate the transpiration per plant per layer, and ad up the total per plot. In the section potential transpiration we will come back to this.

The Penman-Monteith equation

The general form of the Penman equation looks as follows

$$lE = \frac{sR_n + \dfrac{r c_p VPD}{r_b}}{s + g\left(1 + \dfrac{r_s}{r_b}\right)} \qquad 21$$

where

λE	is the latent heat loss (W m^{-2})
s	slope of the saturated vapour pressure curve (hPa $^oC^{-1}$)
R_n	net incoming radiation (W m^{-2})
ρ	density of air (kg m^{-3})
c_p	specific heat of air (J kg^{-3} $^oC^{-1}$)
VPD	vapour pressure deficit (kPa)
r_b	boundary layer resistance (s m^{-1})
r_s	stomatal resistance (s m^{-1})
γ	psychrometric coefficient (0.67 hPa $^oC^{-1}$)
λ	latent heat of evaporation (2.4×10^6 J kg^{-1} at 30 ^oC with only a small temperature dependence)

In the model this equation is split up in two halves, the radiation part (eq. 22) and a "drying-power" term (eq 23).

$$PotLHLRTr_{tl,t} = \frac{Slp \cdot ANRadTr_{tl,t}}{Slp + CPsc \cdot \left(1 + \dfrac{StmRIndTr_{tl,t}}{BndLRTr_t}\right)} \qquad 22$$

$$PotLHLDTr_{tl,t} = \frac{CVlmHc \cdot VPD / BndLRTr_t}{Slp + CPsc \cdot \left(1 + \frac{StmRIndTr_{tl,t}}{BndLRTr_t}\right)} \cdot LaiTrPerLayer_{tl,t} \cdot p \cdot RdsTr_{tl,t}^2 \qquad 23$$

In which $ANRadTr_{tl,t}$ stands for the amount of absorbed radiation of a tree. The canopy is divided in three layers Upp (>8 m), Mid (> 2m, <8m) and Low, (<2 m).
The amount of absorbed radiation by one tree is calculated according to the following set of formulas

$$ANRadUppTr_{tl,t} = NRad \cdot 1 - e^{-CExtNRadLaiUppTr_{tl,t} \cdot p \cdot RdsTr_{tl,t}^2} \qquad 24$$

$$TotANRadUppTr = \sum_t NTr_{tl,t} \cdot ANRadUppTr_{tl,t} \qquad 25$$

$$NRadMid = \frac{(NRad \cdot PlotSize) - TotAnRadUppTr}{PlotSize} \qquad 26$$

$$ANRadMidTr_{tl,t} = NRadMid \cdot 1 - e^{-CExtNRadLaiMidTr_{tl,t} \cdot p \cdot RdsTr_{tl,t}^2} \qquad 27$$

$$TotANRadMidTr = \sum_t NTr_{tl,t} \cdot ANRadMidTr_{tl,t} \qquad 28$$

$$NRadLow = \frac{(NRadMid \cdot PlotSize) - TotAnRadMidTr}{PlotSize} \qquad 29$$

$$ANRadLowTr_{tl,t} = NRadLow \cdot 1 - e^{-CExtNRadLaiLowTr_{tl,t} \cdot p \cdot RdsTr_{tl,t}^2} \qquad 30$$

$$TotANRadLowTr = \sum_t NTr_{tl,t} \cdot ANRadLowTr_{tl,t} \qquad 31$$

The calculation of the amount of net radiation (NRad) will be explained further on in this chapter. The extinction coefficient (CExtNRad) used in these equations for net radiation has an average value of 0.5, which is the value used in the model.

Vapour pressure deficit (VPD) can be calculated with

$$VPD = SVP - AVP_d \qquad 32$$

$$SVP = 0.611 \cdot e^{\frac{17.4 * TmpD_d}{(TmpD_d + 239)}} \qquad 33$$

where temperature (TmpD, the extra D is to distinguish this temperature from the already used temperature in the main FORSPACE model) and actual vapour pressure (e_a) are input variables, which are fetched from meteorological data sets. The formula for the saturated vapour pressure (e_s) is an empirical equation, adopted from Goudriaan (1994).

The slope of the saturated vapour pressure curve can be calculated with the following empirical formula,

$$Slp = \frac{4158.6 \cdot SVP}{(TmpD_d + 239)^2} \tag{34}$$

taken from van Laar (1997).

c_p and ρ are mostly treated as one figure (CVlmHc, in the model), representing the volumetric heat capacity of the air with a value of 1200J m^{-3} $^oC^{-1}$.

For boundary layer resistance (d m^{-1}) we used a relation adopted from Jones (1992)

$$BndLRTr_t = \frac{1}{C1Bnd \cdot \left(\frac{Wnd_d}{CWdtLfTr_t} \right)^{C2Bnd} \cdot 12 \cdot CLngHour} \tag{35}$$

In which Wnd_d stands for wind speed (m s^{-1})and is read from a meteorological data file, and $CWdtLfTr_t$ stands for the characteristic dimension of the leaf (m). C1Bnd has the value of "6.62·1.5·0.001" in which 6.662 is a parameter from Jones, 1.5 is meant to compensate for the fact that this equation is originally meant for smooth isothermal plates, with only laminar flow (no turbulence). The factor 0.001 converts the data from s mm^{-1} to s m^{-1}. Finally 12·CLngHour converts the value to d m^{-1}.

For r_s we used relations as Roberts et al. describe them (1993), where stomatal conductance is related to solar radiation and vapour pressure deficit. Stomatal conductance (g_s) is the inverse of stomatal resistance:

$$g_s = \frac{1}{r_s} \tag{36}$$

Between vapour pressure deficit and stomatal conductance there is a negative linear relation. Between stomatal conductance and solar radiation though, there is little linearity. Therefor Roberts et. al. (1993) defined solar radiation classes in which a relation between g_s and VPD is valid as can be seen in table 2.
Only Roberts et. al. use specific humidity deficit which is expressed in g kg^{-1}, in stead of VPD in Pa. Specific humidity (q) is closely related to absolute humidity (χ) and is defined as the mass of water vapour per unit mass of moist air and has the advantage that it is independent of temperature. When ρ is the density of the moist air then q can be calculated as

$$q = \frac{c}{r} \tag{37}$$

For the model it is most easy to keep ρ constant at 1.293 kg m^{-3}, the density of air under standard conditions (T=237K, p=p_0).

So al we need to calculate q is χ, which is related to temperature and vapour pressure according to the following formula (Monteith and Unsworth 1990)

$$c = \frac{2165 \cdot e_a}{Tmp + 273} \qquad 38$$

Where *e* is vapour pressure in kPa and *Tmp* is in Celsius.

In the model this is implemented as

$$SpcHum = \frac{2165 \cdot AVP_d}{(TmpD_d + 273) \cdot CDnsAir} \qquad 39$$

Table 6 Linear statistics for stomatal conductance (mmol m2 s-1) with specific humidity deficit (g kg-1) in five radiation classes. Adjusted after Roberts et. al. 1993

Solar Radiation Class (Wm^{-2})	$C1StmRUppTr_{tl,t}$	$C2StmRUppTr_{tl,t}$
700-1000	259	-12.0
600-700	208	-8.8
500-600	226	-11.6
400-500	194	-12.8
0-400	137	-8.0

Then the amount of radiation absorbed by each part of the canopy is determined.

Therefore the same division is made as with the calculation of absorbed net. The amount of absorbed radiation is calculated as follows

$$\begin{aligned} IrrTl &= Irr_d \\ IrrSl &= Irr_d \cdot e^{-0.5 \cdot LaiTl} \\ IrrHl &= Irr_d \cdot e^{-0.5 \cdot (LaiTl + LaiSl)} \end{aligned} \qquad 40$$

After this the coefficients for the relation between vapour pressure and stomatal conductance are determined according to table 7.

With these coefficients the canopy conductance (mmol m^{-2} s^{-1}) is calculated per layer

$$\begin{aligned} CCUppTr_{tl,t} &= (SpcHum \cdot C2StmRUppTr_{tl,t}) + C1StmRUppTr_{tl,t} \\ CCMidTr_{tl,t} &= (SpcHum \cdot C2StmRMidTr_{tl,t}) + C1StmRMidTr_{tl,t} \\ CCLowTr_{tl,t} &= (SpcHum \cdot C2StmRLowTr_{tl,t}) + C1StmRLowTr_{tl,t} \end{aligned} \qquad 41$$

Then the canopy conductance (mmol m^{2} s^{-1}) has to be converted to a stomatal resistance (s m^{-1})

$$StmRUppTr_{tl,t} = \frac{1}{CCUppTr_{tl,t} / 1000} * 42.2297$$
$$StmRMidTr_{tl,t} = \frac{1}{CCMidTr_{tl,t} / 1000} * 42.2297 \qquad 42$$
$$StmRLowTr_{tl,t} = \frac{1}{CCLowTr_{tl,t} / 1000} * 42.2297$$

As we can see stomatal resistance will in first instance be in s mm^{-1} this has to be converted to s m^{-1} by multiplying by 1000 as is done with boundary layer resistance. Then the stomatal resistance per individual (d m-1) is calculated according to

$$StmRIntTr_{tl,t} = \frac{1}{\left(\left(\frac{LaiUppTr_{tl,t}}{StmRUppTr_{tl,t}}\right) + \left(\frac{LaiMidTr_{tl,t}}{StmRMidTr_{tl,t}}\right) + \left(\frac{LaiLowTr_{tl,t}}{StmRLowTr_{tl,t}}\right)\right) \cdot (12 \cdot CLngHour)} \qquad 43$$

The calculation of net incoming radiation is rather complicated and is displayed here in a simplified notation (so not in model abbreviations) to keep in understandable. Net incoming radiation (R_n) is dependent on the incoming short wave radiation ($R^{\downarrow}$), the reflected outgoing short wave radiation, depending on the albedo of the surface, and the net outgoing long wave radiation ($K^{\uparrow}$).

$$R_n = (1 - Albedo) \cdot R^{\downarrow} - K^{\uparrow} \qquad 44$$

In the forspace model the photosynthetically active radiation (PAR) is calculated. From this radiation we estimate $R^{\downarrow}$ according to Monteith (1990) with:

$$R^{\downarrow} = 2.5 \cdot PAR \qquad 45$$

The albedo is a composition of that of the soil and that of the canopy.

$$albedo = albedo_{soil} \cdot e^{-0.5LAI} + albedo_{canopy} \cdot (1 - e^{-0.5LAI})$$
$$albedo_{soil} = 0.25 \cdot \left(1 - \frac{0.5 \cdot WtrCntSt_{l1}}{WtrCnt_{l1}}\right) \qquad 46$$
$$albedo_{canopy} = 0.25$$

We assumed an albedo of 0.25 for the canopy and an albedo for the soil depending on its soil moisture content. The albedo of soils is also related to its colour, ranging from 0.15 (clay) to 0.4 (dune sand). Here we use an average of 0.25. The relation to soil water content is described in the formula above according to ten Berge (1989).

For the calculation of $K^{\uparrow}$ an approximation by three semi-empirical functions by Penman (1956, derived from the Brunt formula (1932)) is used. In this formula temperature, vapour pressure in the atmosphere and sky clearness is taken in to account.

$$K^{\uparrow} = BlackBodyRad \cdot FVapour \cdot FClear \cdot 86400$$
$$BlackBodyRad = s \cdot T_{abs}^{4} \qquad 47$$
$$FVapour = 0.56 - 0.079\sqrt{10 \cdot e_a}$$
$$FClear = 0.1 + 0.9 \cdot Clear$$

The clearness of the sky (*Clear*) is original the n / N ratio, in which n is the actual sunshine duration (h d^{-1}) and N is the maximum possible sunshine. It is also possible to estimate this ratio with the Ångström formula.

$$n / N = \frac{\frac{R^{\downarrow}}{Angot} - A}{B} \qquad 48$$

In which Angot stands for the Angot's value i.e. the radiation intensity at the top of the atmosphere. This value depends on the latitude of the place in consideration and changes over the year.

The Angot's value can be calculated by the set of equations as presented in Box 1

Table 7 Indicative values for empirical constants in the Ångström formula in relation to latitude and climate used by the FAO (Frère & Popov, 1979)

	A	B
Cold and temperate zones	0.18	0.55
Dry tropical zones	0.25	0.45
Humid tropical zones	0.29	0.42

Table 8 Calculation of Angot's value. rad = *Conversion factor from degrees to radians,* Lat = *Latitude (degrees),* Dec = *Declination of the sun,* SinLD = *Seasonal offset of sine of solar height,* CosLD = *Amplitude of sine of solar height,* AOB = *Intermediate variable,* DayLengt = *Speaks for itself (h),* DSinB = *Daily total of sine of solar height (s) (After Van Laar et.al. 1997). A and B are empirical constants, which are related to the climate as can be seen in Table 5*

$$Dec = \sin^{-1}\left(\sin(23.45 \cdot rad)\cos\left(2 \cdot p \cdot \frac{DayNumber + 10}{365}\right)\right)$$

$$SinLD = \sin(rad \cdot Lat)\sin(Dec)$$

$$CosLD = \cos(rad \cdot Lat)\cos(Dec)$$

$$AOB = \frac{SinLD}{CosLD}$$

$$DayLength = 12.0 \cdot \left(1 + 2 \cdot \frac{\sin^{-1}(AOB)}{p}\right)$$

$$DSinB = 3600\left(DayLength \cdot SinLD + \frac{24 CosLD \sqrt{1 - AOB^2}}{p}\right)$$

$$SolarCons = 1370(1 + 0.033\cos\left(2p\frac{DayNumber}{365}\right)$$

$$Angot = SolarCons \cdot DSinB$$

Potential Transpiration

For our goal we want potential transpiration in kg H_2O per plant per day. As we could see the penman equation is split up in two equations. A radiation part and a "drying power" part. The first equation gives its results in KJ d^{-1} Ind^{-1} the latter in J d^{-1} Ind^{-1}. Therefore the latter must be divided by 1000 to get the same units. The two can be summed up and divided by the latent heat of evaporation (CEvap, 2.4×10^6 J kg^{-1}).

$$PotTrspTr_{tl,t} = \frac{\frac{PotLHLDTr_{tl,t}}{1000} + PotLHLRTr_{tl,t}}{CEvap} \qquad 49$$

Water Stress

Plants will transpire the potential amount of water when there is sufficient soil moist available. Whenever water in the soil is not sufficient enough, transpiration will decrease due to increase in stomatal resistance. The point however at which transpiration is reduced, and through this a loss of CO2 fixation occurs, is difficult to determine. There is a good technique developed that calculates the point at which water stress occurs on the basis of the so-called reduced water content. This technique uses information about the evaporative demand (potential transpiration) at

which the reduction in transpiration starts halfway the available soil water content. There is however little information about this for trees available. Therefor we chose a different technique, in which we compare the evaporative demand with the amount of water that a plant can deliver to its leaves, in relation to soil and leaf water potential.
The relation between transport through xylem and difference in soil water potential is approximated by the Hagen-Poiseuille equation.

$$Q = \frac{pR^4(y_{sl} - y_{lf})}{8hL} \qquad 50$$

Where Q is the water flow ($mm^3\ mm^{-2}\ s^{-2}$), y_{sl} and y_{lf} are the soil water potential and the leaf water potential respectively(MPa), R is the average width of the capillaries through which the water flows (mm), L is the length over which the transport takes place, and h is the viscosity constant (1.00×10^{-3} Pa s). So the potential amount of water transported by the plant will be

$$Qlf = Q \cdot SrfXyl_{plant} \cdot LDay \qquad 51$$

In the model this is implemented according to:

$$WtrFlwTr_{tl,t} = \frac{p \cdot RdsXylTr_t^4 \cdot \left(WtrPotLfTr_t - WtrPotSlTr_{tl,t}\right)}{8 \cdot CVsc \cdot \left(HghTrPerLayer_{tl,t} - \left(0.5 \cdot LngCnTr_{tl,t}\right)\right) \cdot 1000} \cdot SrfXylTr_{tl,t} \cdot 12 \cdot CLngHour \qquad 52$$

So for this equation we need to know the xylem area of plants, their xylem radius and the length between the point of uptake and the point of transpiration. This length will be defined as the length between the forest floor too halfway the crown of the plant.

$$SrfXylTr_{tl,t} = p \cdot \left(\frac{0.5 \cdot DbhTr_{tl,t}}{100}\right)^2 - p \cdot \frac{WhwTr_{tl,t} + 0.7 \cdot WswTr_{tl,t}}{WstTr_{tl,t}} \cdot \left(\frac{0.5 \cdot DbhTr_{tl,t}}{100}\right)^2 \qquad 53$$

Now when we know the soil water potential and the evaporative demand, we can calculate the minimum leaf water potential needed to fulfil this demand. Whenever this leaf water potential becomes lower than the minimal leaf water potential a plant can create, transpiration will be reduced. We can calculate the amount of water that can be delivered by the plant to its leaves (based on soil- and minimum leaf water potential), and that will be the actual transpiration.
Now the amount of water available is not only depending on the soil water potential, but also on the rooted space of the soil. Soil water potential will be calculated on the hand of the weighted average soil water potential of the soil layers in which the plant is rooting.

$$WtrPotSlTr_{tl,t} = \frac{LngRtTr_{tl,t,l1} \cdot WtrPotSl_{sl1} + LngRtTr_{tl,t,l2} \cdot WtrPotSl_{sl2} + LngRtTR_{tl,t,l3} \cdot WtrPotSl_{sl3}}{(LngRtTr_{tl,t,l1} + LngRtTr_{tl,t,l2} + LngRtTr_{tl,t,l3})} \qquad 54$$

Actual transpiration and Effects on Net Primary Production

Now when the transpiration is reduced because of too low water potentials in the soil, a reduction in net primary production (NPP) will occur because of increase in stomatal resistance. The ratio between "potential" stomatal resistance(r_{sp}) and "actual" stomatal resistance(r_{sa}) will be a good reduction factor for NPP, because the binding of carbon dioxide is inversely related to stomatal resistance as is transpiration.

However the water balance is on a daily basis and the model is on a monthly basis. Therefor an average of the daily ratio r_{sa}/r_{sp} is taken to calculate the effect of drought on NPP. r_{sa} is calculated when the actual transpiration is known. The actual transpiration is equal to the amount of water that can be delivered by the plant system by prevailing soil water potential and minimal leaf water potential,

$$Q = \frac{pR^4(y_{sl} - y_{lf\,\min})}{8hL} \qquad 55$$

or by the amount of moist available to the plant from the rooted space between pF 4.2 and pF 2.0.

$$ActTrspTr_{tl,t} = \max(0, \min(AvlWtrSlTr_{tl,t}, WtrFlwTr_{tl,t}, PotTrspTr_{tl,t})) \qquad 56$$

The calculation of available water in the soil ($AvlWtrSlTr_{tl,t}$) is explained further on in the text. After this by rewriting the Penman Monteith equation the actual stomatal resistance can be calculated according to

$$ActStmRInd\,Tr_{tl,t} = \left(\frac{\frac{p \cdot RdsTr_{tl,t}^2 \cdot CVlmHc \cdot VPD \cdot LaiTrPerLayer_{tl,t} \cdot 0.001}{BndLRTr_t} + (Slp \cdot ANRadTr_{tl,t})}{ActTrspTr_{tl,t} \cdot CEvap} - Slp - CPsc \right) \cdot \frac{BndLRTr_t}{CPsc} \qquad 57$$

This actual stomatal resistance (ActStmRIndTr) is used to calculate the reduction factor that has its influence on RUE.

$$\operatorname{Re} dNppTr_{tl,t} = if\left(ActStmRIndTr_{tl,t} > StmRIndTr_{tl,t}, \frac{StmRIndTr_{tl,t}}{ActStmRIndTr_{tl,t}}, 1 \right) \qquad 58$$

This reduction factor is calculated for each day. The average reduction factor of each month is taken for the interaction of the water balance on the main FORSPACE model.

$$Tot\operatorname{Re} dNppTr_{tl,t} = \sum \frac{\operatorname{Re} dNppTr_{tl,t}}{30} \qquad 59$$

Uptake of transpired water from the soil

The amount of moist taken from a soil layer is calculated related to the relative amount of moist in the soil and the thickness of the layers. To simulate this water uptake, we assume that moisture uptake is evenly distributed over the rooted depth in a uniformly wetted profile. In the soil profile in our model soil moist is distributed over soil layers, and within these soil layers moist is distributed uniformly. To distribute water uptake over the layers, a root activity coefficient is introduced (after van Laar, 1997), which varies between 0 and 1 and is inversely related to the relative amount of available water in each soil layer.
This factor creates the effect that roots in dryer parts of the soil have a lower uptake of moist than roots in wetter parts.

$$RtAct_l = \max(0, \min(1, (-2.8828 \cdot FAvlWtrCnt_l^2 + 3.0993 \cdot FAvlWtrCnt_l + 0.1626)) \quad 60$$

$$TotRtActTr_{tl,t} = \sum RtAct_l \cdot LngRtTr_{tl,t,l} \quad 61$$

$$AvRtActTr_{tl,t} = \frac{ActTrspTr_{tl,t}}{TotRtActTr_{tl,t}} \quad 62$$

$$TrspTr_{tl,t,l} = LngRtTr_{tl,t,l} \cdot AvRtActTr_{tl,t} \cdot RtAct_l \quad 63$$

When this transpiration is known, we can calculate the total loss of water due to transpiration according to

$$Trsp_l = \frac{TrspTr_{tl,t,l} \cdot NTr_{tl,t}}{PlotSize} \quad 64$$

Potential Evaporation

The evaporation is an important flow of moist out of the soil system. Especially under low cover conditions, evaporation constitutes a great part of evapo transpiration. Next to this evaporation continues until the soil is air dry, although the rate of evaporation decreases when soil water content decreases.

$$PotEvpSoil = \frac{(NotANRad \cdot Slp) + VPD \cdot CPsc \cdot 0.1 \cdot (3.7 + 4 \cdot Wnd_d)}{(CPsc + Slp) \cdot CEvap} \quad 65$$

The effect of soil dryness is simulated by a formulation adopted from Stroosnijder (1982) which uses the number of days since the last rain.

$$NDayNPrc = NDayNPrc + RNDay \quad 66$$

$$RNDay = if((ThrHl_d + Runon_d) > 0.5, -(NDayNPrc - 1), 1) \quad 67$$

Actual Evaporation

When calculating actual evaporation, a distinction is made between days with and without rain. Days with an effective precipitation below 0.5 mm are not considered as day with rain.

$$ActEvpSoil = if((ThrHl_d + Runon_d) > 0.5, EvpRain, EvpDry) \qquad 68$$

Days with rain have an evaporation, which is equal to the potential evaporation with the limitation that the topsoil layer cannot be depleted beyond air dryness.

$$EvpRain = \min(PotEvpSoil, (WtrCnt_{l1} \cdot CThc_{l1}) - (WtrCntAD_{l1} \cdot CThc_{l1}) + Inf_{l1}) \qquad 69$$

For days with rain we use the experimental field observation that cumulative evaporation is proportional to the square root of time(Stroosnijder, 1982). The proportionality factor is assumed to be equal to 60% of the potential evaporation rate (after van Laar,1997).

$$EvpDry = \min(PotEvpSoil, 0.6 \cdot PotEvpSoil \cdot \left(\sqrt{NDayNPrc + 1} - \sqrt{NDayNPrc}\right) + Inf_{l1} \qquad 70$$

When the actual evaporation is known, the extraction of evaporated water from the different layers is calculated. Firstly we calculate a coefficient that determines the amount of water that will be extracted from each layer.

$$PotXtrWtr_{l1} = Max(WtrCnt_{l1} \cdot CThc_{l1} - WtrCntAd_{l1} \cdot CThc_{l1}, 0.1) \cdot e^{-CExtWtr \cdot 0.5 CThq_1} \qquad 71$$

$$PotXtrWtr_{l2} = Max(WtrCnt_{l1} \cdot CThc_{l1} - WtrCntAd_{l1} \cdot CThc_{l1}, 0.1) \cdot e^{-CExtWtr(CThq_1 + 0.5 \cdot CThq_2)} \qquad 72$$

$$PotXtrWtr_{l3} = Max(WtrCnt_{l1} \cdot CThc_{l1} - WtrCntAd_{l1} \cdot CThc_{l1}, 0.1) \cdot e^{-CExtWtr(CThq_1 + CThq_2 + 0.5 \cdot CThq_3)} \qquad 73$$

$$PotXtr = \sum PotXtrWtr_l \qquad 74$$

After the calculation of these parameters the evaporation loss from each soil layer can be calculated

$$Evp_l = ActEvpSoil \cdot \frac{PotXtrWtr_l}{PotXtr} \qquad 75$$

Integration

The input and output from the soil layers is integrated each day by firstly calculating the rate of change,

$$\begin{aligned} RWtrCnt_{l1} &= Inf_{l1} - Inf_{l2} - Evp_{l1} - Trsp_{l1} \\ RWtrCnt_{l2} &= Inf_{l2} - Inf_{l3} - Evp_{l2} - Trsp_{l2} \\ RWtrCnt_{l3} &= Inf_{l3} - Drain - Evp_{l3} - Trsp_{l3} \end{aligned} \qquad 76$$

and then integrating this rate over the state variable.

$$WtrCnt_l = \max\left(0, \min\left(WtrCntSt_l, \frac{WtrCnt_l \cdot Thc_l + RWtrCnt_l}{Thc_l}\right)\right) \quad 77$$

After this also the available amount water(AvlWtrCnt$_l$, %) and the relatively available amount of water per soil layer(FAvlWtrCnt$_l$, -) can be calculated.

$$AvlWtrCnt_l = \max(0, WtrCnt_l - WtrCntWp_l) \quad 78$$

$$FAvlWtrCnt_l = \frac{AvlWtrCnt_l}{WtrCntFc_l - WtrCntWp_l} \quad 79$$

Also the amount of moist available to the plant is calculated by

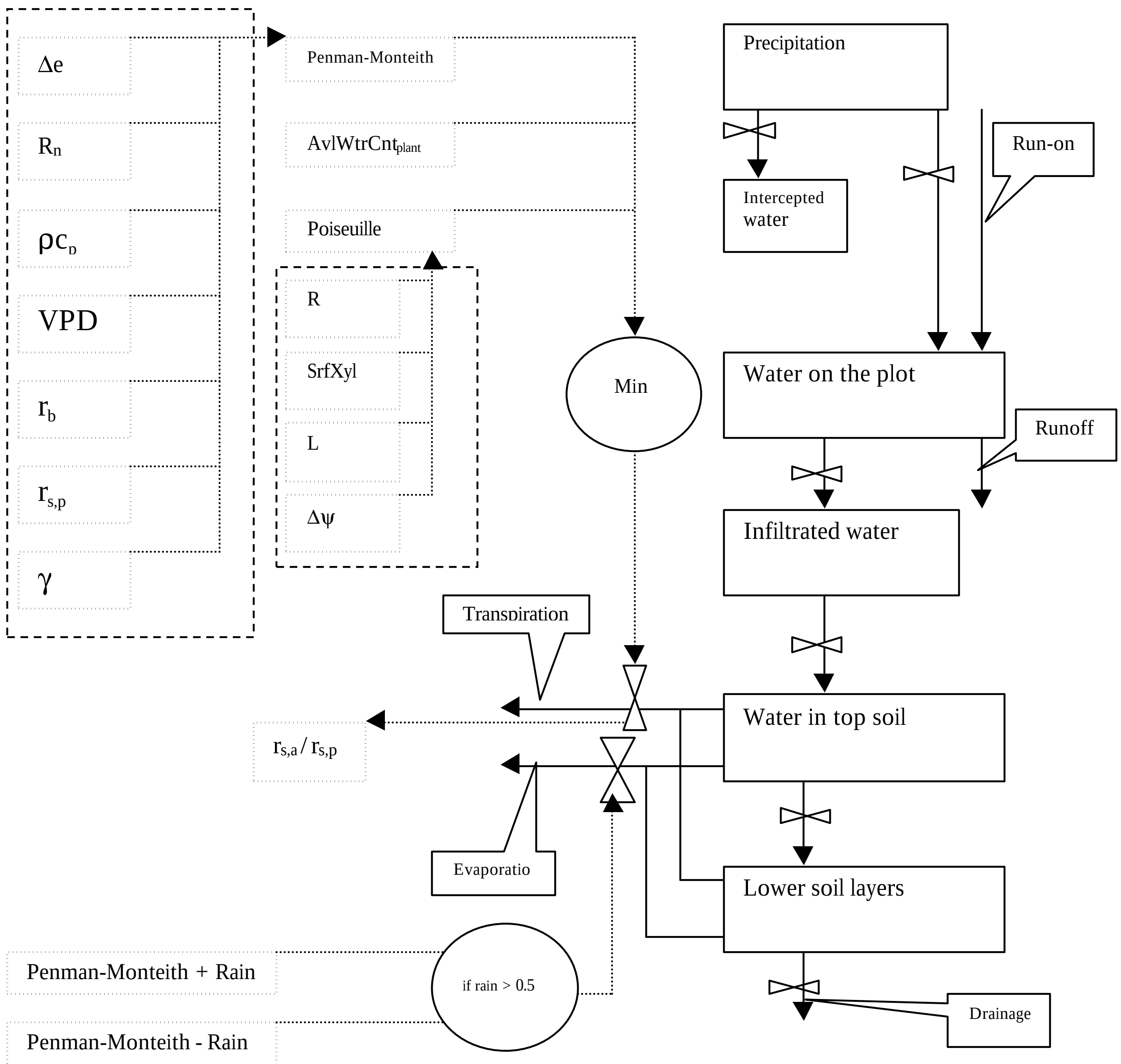
$$AvlWtrSlTr_{tl,t} = \sum (AvlWtrCnt_l \cdot LngRtTr_{tl,t,l}) \cdot p \cdot RdsRtTr^2_{tl,t} \cdot CorFOvl \quad 80$$

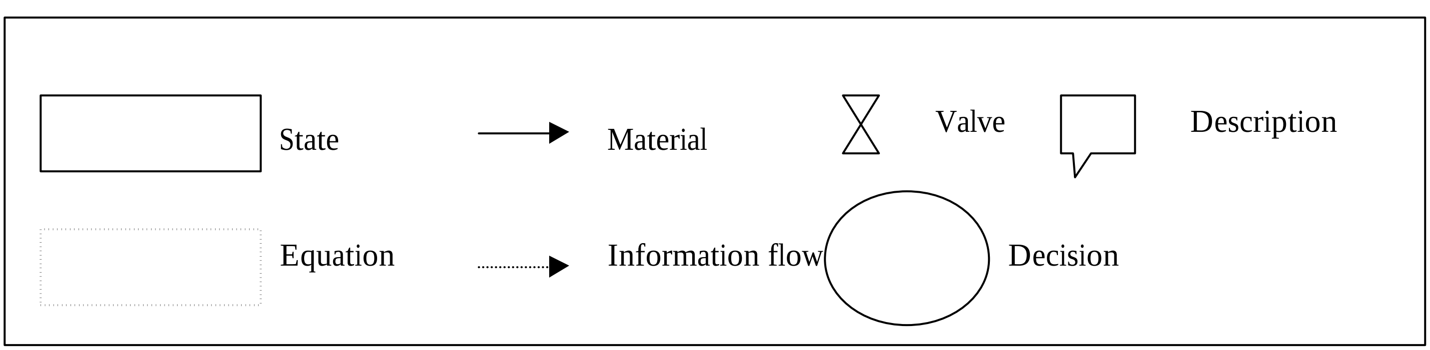
Water Use Efficiency

To check the model outcomes, Water Use Efficiency (WUE) is reported as a derived variable, so that results can be compared with other studies, which use WUE.

$$WUETr_{tl,t} = \frac{NppTr_{tl,t} \cdot 1000}{\sum_{month} ActTrspTr_{tl,t}} \quad 81$$

A2 Flowchart of the water balance





A3 List of used abbreviations

Variable	Description	Unit
ActEvpSoil	Actual evaporation of the soil	kg H_2O m^{-2} d^{-1}
$ActStmRIndTr_{tl,t}$	Actual stomatal resistance a tree obtains under water stress	d m^{-1}
$ActTrspTr_{tl,t}$	Actual transpiration of an individual tree	kg H_2O Ind^{-1} d^{-1}
$ANRadLowTr_{tl,t}$	Absorbed net radiation by the lower part of the tree crown	kJ Ind^{-1} d^{-1}
$ANRadMidTr_{tl,t}$	Absorbed net radiation by the middle part of the tree crown	kJ Ind^{-1} d^{-1}
$ANRadTR_{tl,t}$	Absorbed net radiation by a tree	
$ANRadUppTr_{tl,t}$	Absorbed net radiation by the upper part of the tree crown	kJ Ind^{-1} d^{-1}
AreaRt	Area of a plot occupied by roots of living plants	m^2
$AvlWtrCnt_l$	Available water content per soil layer	%
$AvlWtrSlTr_{tl,t}$	Available water content of the soil for an individual plant	mm
AVP_d	Actual vapor pressure	kPa
$AvRtActTr_{tl,t}$	Average Root activity	mm
$BndLRTr_t$	Boundary layer resistance	d m^{-1}
C1Bnd	Coefficient for calculation of boundary layer resistance	-
$C1StmRUppTr_{tl,t}$	Coefficient for calculation of stomatal resistance	-
C2Bnd	Coefficient for calculation of boundary layer resistance	-
$C2StmRUppTr_{tl,t}$	Coefficient for calculation of stomatal resistance	-
CCLowTrtl,t	Canopy conductance of the lower part of the crown	mmol m^{-2} s^{-1}
CCMidTrtl,t	Canopy conductance of the middle part of the crown	mmol m^{-2} s^{-1}
CCUppTrtl,t	Canopy conductance of the upper part of the crown	mmol m^{-2} s^{-1}
CDnsAir	Density of air	kg m^{-3}
CEvap	Latent heat of evaporation	J kg^{-1}
CExtNRad	Extinction coefficient for net radiation	-
CExtWtr	"extinction coefficient" for water extraction from the soil	-
CLngHour	Length of an hour in seconds	s $hour^{-1}$
CorFOvl	Correction Factor for overlap in root systems of different species	-
CPsc	Psychrometric constant	hPa $^oC^{-1}$
$CRtDnsTr_{t,l}$	Root density per soil layer	m m^{-3}
$CThc_l$	Thickness of the soil layer per soil layer	mm
CvrHl	Total cover of the herb layer	-
CvrSl	Total cover of the shrub layer	-
CvrTl	Total cover of the tree layer	-
CVsc	Viscosity constant	Pa s
$CWdtLfTr_t$	Specific leaf size (width)	m
$DbhTr_{tl,t}$	Diameter at breast height per tree	cm
Drain	Drainage from the lowest layer (L3)	mm d^{-1}
EvpDry	Evaporation when it is not raining	kg H_2O m^{-2} d^{-1}
Evp_l	Evaporation per soil layer	mm d^{-1}
EvpRain	Evaporation when it is raining	kg H_2O m^{-2} d^{-1}
$FAvlWtrCnt_l$	Relatively available water content per soil layer	%
$HghTrPerLayer_{tl,t}$	Height of a tree	m
h_l	Pressure head for a soil type	cm
Inf_l	Infiltration per soil layer	mm d^{-1}
$IntPrcHl_d$	Intercepted precipitation by the herb layer per day	mm d^{-1}
$IntPrcSl_d$	Intercepted precipitation by the shrub layer per day	mm d^{-1}
$IntPrcTl_d$	Intercepted precipitation by the tree layer per day	mm d^{-1}
Irr_d	Irradiation per day	kJ m^{-2} d^{-1}
IrrHl	Irradiation in the herb layer	kJ m^{-2} d^{-1}
IrrSl	Irradiation in the shrub layer	kJ m^{-2} d^{-1}
IrrTl	Irradiation above the canopy	kJ m^{-2} d^{-1}

LaiHl	Lai of the total herb layer	m m^{-1}
$LaiLowTr_{tl,t}$	Lai of the lower part of the crown	m m^{-1}
$LaiMidTr_{tl,t}$	Lai of the middle part of the crown	m m^{-1}
LaiSl	Lai of the total shrub layer	m m^{-1}
LaiTl	Lai of the total tree layer	m m^{-1}
$LaiTrPerLayer_{tl,t}$	LAI per tree species	m m^{-1}
$LaiUppTr_{tl,t}$	Lai of the upper part of the crown	m m^{-1}
$LngCnTr_{tl,t}$	Lenght of the crown of a tree	m
$LngRtTr_{tl,t,l}$	Length of roots per layer	mm
MxDrn	Maximum possible drainage	mm d^{-1}
MxLngRt	Maximum root length	mm
NDayNPrc	Number of days without precipitation	d
NotANRad	Not absorbed net radiation	kJ m^{-2} d^{-1}
$NPPTr_{tl,t}$	Net primary production	kg DM ind^{-1} $month^{-1}$
NRad	Net radiation	kJ m^{-2} d^{-1}
NRadLow	Net radiation in the lower part of the canopy	kJ m^{-2} d^{-1}
NRadMid	Net radiation in the middle part of the canopy	kJ m^{-2} d^{-1}
$NTr_{tl,t}$	Number of individuals of a tree species per cell	#
pF_l	pF for a soil type per layer	-log(cm)
Plot size	Size of the plots (cells)	m^2
PotEvapSoil	Potential evaporation of water from the soil	kg H_2O m^{-2} d^{-1}
$PotLHLDTr_{tl,t}$	Potential latent heat loss of trees due to "drying power"	J ind^{-1} d^{-1}
$PotLHLRTr_{tl,t}$	Potential latent heat loss of trees due to radiation	kJ ind^{-1} d^{-1}
$PotTrspTr_{tl,t}$	Potential transpiration of an individual tree	kg H_2O d^{-1}
PotXtr	Potential extraction of water over al soil layers (expressed as a fraction)	-
$PotXtrWtn_l$	Potential extraction of water from the soil layers (expressed as a fraction)	-
Prc	Precipitation	mm d^{-1}
$RdsRtTr_{tl,t}$	Radius of soil rooted by plant roots	m
$RdsTr_{tl,t}$	Radius of the tree crown	m
$RdsXylTr_t$	Radius of the Xylem vessels of trees	mm
$RedNPPTr_{tl,t}$	Reduction factor of NPP per day	-
$RLngRt_{tl,t}$	Rate of root elongation	mm d^{-1}
RNDay	Rate in increase of days	d
RNDayNPrc	Rate of increase of number of days without precipitation	d
$RqrLngFrTr_{tl,t,l}$	Required length of fine roots to obtain optimal root density per layer	m
$RqrWghFrTr_{tl,t,l}$	Required weight of roots to obtain optimal root density per layer	kg DM
$RtAct_l$	Root activity	-
Runoff	Runoff on a plot	mm d^{-1}
$Runon_d$	Run on on a plot	mm d^{-1}
$RWtrCnt_l$	Rate of water content increase	mm d^{-1}
Slp	Slope of the saturated vapor pressure curve	hPa $^oC^{-1}$
SpcHum	Specific humidity	g kg^{-1}
$SrfXylTr_{tl,t}$	Surface of the xylem	m^2
$SrlTr_{t,l}$	Specific root length	m kg^{-1}
$StmRIndTr_{tl,t}$	Stomatal resistance of tree species for the complete individual	d m^{-1}
$StmRLowTr_{tl,t}$	Stomatal resistance of the lower part of the tree	s m^{-1}
$StmRMidTr_{tl,t}$	Stomatal resistance of the middle part of the tree	s m^{-1}
$StmRUppTr_{tl,t}$	Stomatal resistance of the upper part of the tree	s m^{-1}
SVP	Saturated vapor pressure	kPa
$ThrHl_d$	Throughfall for the herb layer	mm d^{-1}

$ThrSl_d$	Throughfall for the shrub layer	mm d^{-1}
$ThrTl_d$	Throughfall for the tree layer	mm d^{-1}
$TmpD_d$	Temperature per day	^oC
$TotANRadLowTr_{tl,t}$	Absorbed net radiation by the lower part of the tree crowns of the trees	kJ Ind^{-1} d^{-1}
$TotANRadMidTr_{tl,t}$	Absorbed net radiation by the middle part of the tree crowns of the trees	kJ Ind^{-1} d^{-1}
$TotANRadUppTr_{tl,t}$	Absorbed net radiation by the upper part of the tree crowns of the trees	kJ Ind^{-1} d^{-1}
$TotRedNPPTr_{tl,t}$	Total reduction of NPP for a tree per month	-
$TotRtActTr_{tl,t}$	Total Root Activity	-
TotSrfRt	Total surface that roots of a all plant present occupy	m^2
$Trsp_l$	Total extraction of transpirated water per soil layer	kg H_2O m^{-2} d^{-1}
$TrspTr_{tl,t,l}$	Extraction of transpirated water from the soil layer per tree species	kg H_2O Ind^{-1} d^{-1}
VPD	Vapor pressure deficit	kPa
$WCrTr_{tl,t}$	Weight of coarse roots of tree species	kg DM
$WFrTR_{tl,t}$	Weight of fine roots of tree species	kg DM
$WhwTr_{tl,t}$	Weight of heart wood of a tree	kg DM
Wnd_d	Wind speed	m s^{-1}
$WrtTr_{tl,t}$	Weight of total root biomass of tree species	kg DM
$WstTr_{tl,t}$	Weight of the stem of a tree	kg DM
$WswTr_{tl,t}$	Weight of sap wood of a tree	kg DM
$WtrCntAD_l$	Water Content when air dry	-
$WtrCntFc_l$	Water Content at Field capacity per soil layer	-
$WtrCnt_l$	Water Content per soil layer	-
$WtrCntSt_l$	Water Content at Saturation per soil layer	-
$WtrCntWp_l$	Water Content at wilting point per soil layer	-
$WtrFlwTr_{tl,t}$	Water flow a tree can induce as a result of leaf water potential	kg H_2O Ind^{-1} d^{-1}
$WtrPotLfTr_t$	Water Potential a tree leaf can create	MPa
$WtrPotSl_l$	Water Potential in the soil per layer	MPa
$WtrPotSlTr_{tl,t}$	Water potential in the soil layers in which a tree has its roots (averaged to the length of roots)	MPa
$WUETr_{tl,t}$	Water use efficiency	g DM (l H2O)$^{-1}$

A4 Input Parameters

Lookup Tables	Description	Units
PrcTbl	Precipitation	mm d^{-1}
WndTbl	Wind speed	m s^{-1}
TmpTbl	Temperature	ºC
IrrTbl	Irradiance	kJ m^{-2} d^{-1}
AVPTbl	Actual Vapour Pressure	kPa
CMxDrnTbl	Maximum drain speed per soil type	kg H_2O m^{-2} d^{-1}
CWtrCntStTbl	Water content at saturation	Fraction
CWtrCntFcTbl	Water content at Field Capacity	Fraction
CWtrCntWpTbl	Water content at Wilting Point	Fraction
CWtrCntAdTbl	Water content when Air Dry	Fraction
C1pFTbl	coefficient for pF relations of the soils	-
C2pFTbl	coefficient for pF relations of the soils	-
C3pFTbl	coefficient for pF relations of the soils	-
C4pFTbl	coefficient for pF relations of the soils	-
C1StmRTbl	Coefficients to calculate the Stomatal resistance	-
C2StmRTbl	Coefficients to calculate the Stomatal resistance	-

Tree coefficients

Coefficient	Species	Value
WdtLfTr	Quercus	0.02
WdtLfTr	Betula	0.03
WdtLfTr	Fagus	0.05
WdtLfTr	Pinus	0.001

Density of roots per soil layer (m m-3)

Coefficient	Species	Soil Layer	Value
CRtDnsTr	Quercus	Layer1	85000
CRtDnsTr	Quercus	Layer2	20000
CRtDnsTr	Quercus	Layer3	10000
CRtDnsTr	Betula	Layer1	4850
CRtDnsTr	Betula	Layer2	1216
CRtDnsTr	Betula	Layer3	410
CRtDnsTr	Fagus	Layer1	4850
CRtDnsTr	Fagus	Layer2	1216
CRtDnsTr	Fagus	Layer3	410
CRtDnsTr	Pinus	Layer1	4850
CRtDnsTr	Pinus	Layer2	1216
CRtDnsTr	Pinus	Layer3	410

Specific root length per soil layer (m kg-1)

Coefficient	Species	Soil Layer	Value
SrlTr	Quercus	Layer1	16166
SrlTr	Quercus	Layer2	14500
SrlTr	Quercus	Layer3	17000
SrlTr	Betula	Layer1	7123

SrlTr	Betula	Layer2	4267
SrlTr	Betula	Layer3	3568
SrlTr	Fagus	Layer1	7123
SrlTr	Fagus	Layer2	4267
SrlTr	Fagus	Layer3	3568
SrlTr	Pinus	Layer1	7123
SrlTr	Pinus	Layer2	4267
SrlTr	Pinus	Layer3	3568

Minimal water potential that a tree leaf can provide (MPa)

Coefficient	Species	Value
WtrPotLfTr	Quercus	2
WtrPotLfTr	Betula	2
WtrPotLfTr	Fagus	2
WtrPotLfTr	Pinus	2

Radius of xylem vessels (mm)

Coefficient	Species	Value
RdsXylTr	Quercus	0.2
RdsXylTr	Betula	0.06
RdsXylTr	Fagus	0.06
RdsXylTr	Pinus	0.2

Shrub coefficients

Characteristic leaf dimension fot the calculation of the boundary layer resistance (m)

Coefficient	Species	Value
WdtLfSrb	Salix	0.02
WdtLfSrb	Sambucus	0.02
WdtLfSrb	Sorbus	0.02

Density of roots per soil layer (m m-3)

Coefficient	Species	Soil Layer	Value
CRtDnsSrb	Salix	Layer1	4850
CRtDnsSrb	Salix	Layer2	1216
CRtDnsSrb	Salix	Layer3	410
CRtDnsSrb	Sambucus	Layer1	4850
CRtDnsSrb	Sambucus	Layer2	1216
CRtDnsSrb	Sambucus	Layer3	410
CRtDnsSrb	Sorbus	Layer1	4850
CRtDnsSrb	Sorbus	Layer2	1216
CRtDnsSrb	Sorbus	Layer3	410

Specific root length per soil layer (m kg-1)

Coefficient	Species	Soil Layer	Value
SrlSrb	Salix	Layer1	7123
SrlSrb	Salix	Layer2	4267

SrlSrb	Salix	Layer3	3568
SrlSrb	Sambucus	Layer1	7123
SrlSrb	Sambucus	Layer2	4267
SrlSrb	Sambucus	Layer3	3568
SrlSrb	Sorbus	Layer1	7123
SrlSrb	Sorbus	Layer2	4267
SrlSrb	Sorbus	Layer3	3568

Minimal water potential that a tree leaf can provide (MPa)

Value	Species	Value
WtrPotLfSrb	Salix	2
WtrPotLfSrb	Sambucus	2
WtrPotLfSrb	Sorbus	2

Radius of xylem vessels (mm)

Value	Species	Value
RdsXylSrb	Salix	0.2
RdsXylSrb	Sambucus	0.06
RdsXylSrb	Sorbus	0.06

Herb coefficients

Characteristic leaf dimension fot the calculation of the boundary layer resistance (m)

Value	Species	Value
WdtLfHrb	Deschampsia	0.005
WdtLfHrb	Grass	0.005
WdtLfHrb	Vaccinium	0.01
WdtLfHrb	Calluna	0.005
WdtLfHrb	Pteridium	0.2
WdtLfHrb	GrassWet	0.005
WdtLfHrb	GrassDry	0.005
WdtLfHrb	RuigteWet	0.005
WdtLfHrb	RuigteDry	0.005
WdtLfHrb	Urtica	0.05
WdtLfHrb	Cultuur	0.005

Soil coefficients

Thickness of the soil layer (mm)

Coefficient	Soil Layer	Value
CThc	Layer1	300
CThc	Layer2	300
CThc	Layer3	900

Water content at saturation point (St) at field capacity (Fc) at wilting point (Wp) or when Air dray (Ad) per soiltype per layer

Coefficient	Soil Layer	1	2	3	4	5	6	7	8
CWtrCntStTbl	Layer1	0	0.43	0	0.41	0.33	0	0.41	0
CWtrCntStTbl	Layer2	0	0.41	0	0.41	0.41	0	0.41	0
CWtrCntStTbl	Layer3	0	0.41	0	0.41	0.41	0	0.41	0
CWtrCntFcTbl	Layer1	0	0.275	0	0.335	0.075	0	0.335	0
CWtrCntFcTbl	Layer2	0	0.335	0	0.335	0.335	0	0.335	0
CWtrCntFcTbl	Layer3	0	0.335	0	0.335	0.335	0	0.335	0
CWtrCntWpTbl	Layer1	0	0.04	0	0.165	0.01	0	0.165	0
CWtrCntWpTbl	Layer2	0	0.165	0	0.165	0.165	0	0.165	0
CWtrCntWpTbl	Layer3	0	0.165	0	0.165	0.165	0	0.165	0
CWtrCntAdTbl	Layer1	0	0.01	0	0.01	0.01	0	0.01	0
CWtrCntAdTbl	Layer2	0	0.01	0	0.01	0.01	0	0.01	0
CWtrCntAdTbl	Layer3	0	0.01	0	0.01	0.01	0	0.01	0

Constants for the pF functions per layer

Coefficient	Soil Layer								
C1pFTbl	Layer1	0	-265.97	0	-75.196	-683.51	0	-75.196	0
C1pFTbl	Layer2	0	-75.196	0	-75.196	-75.196	0	-75.196	0
C1pFTbl	Layer3	0	-75.196	0	-75.196	-75.196	0	-75.196	0
C2pFTbl	Layer1	0	194.16	0	48.787	385.08	0	48.787	0
C2pFTbl	Layer2	0	48.787	0	48.787	48.787	0	48.787	0
C2pFTbl	Layer3	0	48.787	0	48.787	48.787	0	48.787	0
C3pFTbl	Layer1	0	-48.829	0	-23.741	-68.472	0	-23.741	0
C3pFTbl	Layer2	0	-23.741	0	-23.741	-23.741	0	-23.741	0
C3pFTbl	Layer3	0	-23.741	0	-23.741	-23.741	0	-23.741	0
C4pFTbl	Layer1	0	6.4175	0	7.7173	5.2666	0	7.7173	0
C4pFTbl	Layer2	0	7.7173	0	7.7173	7.7173	0	7.7173	0
C4pFTbl	Layer3	0	7.7173	0	7.7173	7.7173	0	7.7173	0

Initial water content (fraction)

Coefficient	Soil Layer	Value
IniWtrCnt	Layer1	0.3
IniWtrCnt	Layer2	0.3
IniWtrCnt	Layer3	0.3

A5 Classification scheme to identify vegetation types

type	subtype	CLS	cover% TL =CT	cover% SL =CS,CSt	%cover in TL	%cover in SL	additional constraints
zand		1	0	0			cov% HL<10 bod =Zd/Zn
cultuur		2	<20	CS<20			NOT 1 Clt>(SumHerbs)
heide		3	<20	CS<60			NOT (1,2)
struweel		4	<20	CS≥60			
open bos	berk	5	≥20<60		Bet>(Pin,Que,Fag)		
	den	6	≥20<60		Pin≥Bet Pin>(Que,Fag)		
	eik	7	≥20<60		Que≥(Bet,Pin) Que>Fag		
	beuk	8	≥20<60		Fag≥(Bet,Pin,Que)		
bos	berk	9	≥60		Bet>(Pin,Que,Fag)		
	den/den	10	≥60	CSt≥20	Pin≥Bet Pin>(Que,Fag)	Pin>(Bet,Que,Fag)	
	den/berk	11	≥60	CSt≥20	Pin≥Bet Pin>(Que,Fag)	Bet>(Que,Fag) Bet≥Pin	
	den/eik	12	≥60	CSt≥20	Pin≥Bet Pin>(Que,Fag)	Que>Fag Que≥(Bet,Pin)	
	den/beuk	13	≥60	CSt≥20	Pin≥Bet Pin>(Que,Fag)	Fag≥(Bet,Pin,Que)	
	den/hol	14	≥60		Pin≥Bet Pin>(Que,Fag)		NOT (10-13)
	eik/eik	15	≥60	CSt≥20	Que≥(Bet,Pin) Que>Fag	Que>Fag Que≥(Bet,Pin)	
	eik/beuk	16	≥60	CSt≥20	Que≥(Bet,Pin) Que>Fag	Fag≥(Bet,Pin,Que)	
	eik/hol	17	≥60		Que≥(Bet,Pin) Que>Fag		NOT (15,16)
	beuk/beuk	18	≥60	CSt≥20	Fag≥(Bet,Pin,Que)	Fag≥(Bet,Pin,Que)	
	beuk/hol	19	≥60		Fag≥(Bet,Pin,Que)		NOT 18