Modelling climate change impacts on forest: an overview

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1 Introduction

The part covered by forest areas, their structure and species composition has a fundamental influence on the hydrological behaviour of a landscape. However the hydrological regime of a forest influences the forest development. One of the vital attributes of forests that determine the hydrological properties is their long term structural development and the seasonal dynamics.

Climate change is general accepted as an established fact. Forests are sensitive to climate change and because of their large geo-spreading the variation is sensitivity would be large. There is hardly any geo-information about the sensitivity of forest to climate change. Besides temperature and CO_2 effects of climate change, hydrology has an important role on the impact of climate change on forests. Forest are situated on dry high sandy grounds or in areas which have a direct influence of the groundwater. These 'wet' forests are especially vulnerable to fluctuations of the water regime.

This rapport describes the most important processes in forests related to the hydrology. The values of these processes for Dutch forests found in literature are given in the chapter forest in the Netherlands. The general impact of climate change on Dutch forests is described in chapter four. An overview of the available models for simulation forest and hydrology processes is given in chapter five. The conclusion/discussion describes the choice of the model taking into account the aim of this study.

2 Forest hydrology

Forests play an important role in the water balance of the land surface. The water use of a forest can be considerably higher than that of vegetation of different structure and height. The combination of a high aerodynamic roughness, with a relative low and strongly controlled surface resistance, was the main cause for high evaporation rates from wet canopies and somewhat low transpiration rates from dry canopies. Forests not only use more water by evaporating more, they also influence the rainfall patterns and magnitude at regional and global scale by increasing the low level moisture convergence (supply of moisture through horizontal advection in the lower layers of the atmosphere) (Poker and Stein, 1999).

The controls of forest water use are essentially the same as those influence mesoscale weather: the relatively low albedo, the aerodynamically rough surface, and the tight physiological control on stomata. The first two of these are related to the structural characteristics of the tall and dense canopies that absorb considerable amount of solar radiation relatively easily. The tall irregular canopies of forests furthermore generate increased turbulence, which improves the efficiency of the transport processes over forests substantially. The stomatal control of forest relates to the balance between strength of the stomatal and aerodynamic resistance in the exchange pathway, with the stomatal, or canopy conductance presenting the larger resistance (Poker and Stein, 1999).

In a forest area, the precipitation can either fall on the canopy of trees or directly down on the undergrowth or on the ground. The part retained on the canopy and later evaporated is called interception. Drip and rain falling directly on the ground is called througfall. Water caught by the leaves, trunks and stems of the trees, which is not interception, continues in a downward movement as stemflow or falling drops. At ground surface, there are three alternative directions for the water- either it evaporates, infiltrates into the soil or runs off on the surface. Evaporated water will again enter the atmosphere, and surface runoff will be drained out from the area. Water that infiltrates will either enter soil moisture storage or percolate further down to form groundwater.

2.1 Interception

The process of precipitation intercept by the canopy and evaporate without reaching the soil surface is called interception-evaporation. The amount of interception-evaporation can be around 10 till 50% of the annual precipitation (Dolman and Moors, 1994). This high interception-evaporation amount can be caused by the turbulent exchange processes above forests which transport the vapour. The spatial distribution of amount of transpiration-evaporation between different forest types can be relatively large, depending on location and specific forest characteristics. The percentage interception of the annual precipitation in the summer period is larger than in the winter period (62% versus 53% for pine and 34% versus 16% for oak)(Dolman and Moors, 1994). The quantity of water lost by interception depends primarily on the type of cover and the intensity and frequency of rainfall. In light rain, almost 100 % of the rain may be lost by interception followed by evaporation of the intercepted rain. The mean interception lost as percentage of the annual precipitation is 26% for deciduous forest and 39% for Douglas. Transpiration is reduces during periods of interception.

2.2 *Transpiration*

Transpiration is the evaporation of water by stomata into the atmosphere from the leaves of the tree. The transpiration can be reduced due to the respond of the stomata on atmospheric variables and soil moisture. The mean transpiration of a Dutch forest is 305 mm (Dolman and Moors, 1994). The spatial variability of forest is generally larger than agriculture (Spieksma *et al.*, 1997). Gaps in the canopy and clustering of the crowns are common in a natural forest. Because of this the spatial distribution of precipitation reaching the soil surface (net precipitation) is large, corresponding in a variation in soil moisture.

Transpiration can be 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 data and gives more accurate results (Groen *et al.*, 2000). Next to this the Makkink formula is much simpler than the Penman-Monteith combination equation. However the Makkink is an empirical equation, which is only valid in temperate zones. And next to this, no distinction can be made between different plant species. The advantage of the Penman-Monteith equation 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 droughts (and water excess) on different species. There are through, 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 (or excess) and thus reducing transpiration is difficult to determine. In many water balances the so-called "reduced water content" is used to determine this point. However, there is little data on forest available for this approach. Another method can be used, 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.
Secondly the total transpiration of the canopy is the sum of all 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 add up per plot.

The general form of the Penman-Monteith equation looks as follows

$$\lambda E = \frac{sR_n + \dfrac{\rho c_p VPD}{r_b}}{s + \gamma\left(1 + \dfrac{r_s}{r_b}\right)} \qquad 1$$

where

λE = latent heat loss (W m^{-2})
s = slope of the saturated vapour pressure curve (hPa °C^{-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} °C^{-1})
VPD = vapour pressure deficit (kPa)
r_b = boundary layer resistance (s m^{-1})
r_s = stomatal resistance (s m^{-1})
γ = psychometric coefficient (0.67 hPa °C^{-1})

The Makkink equation is

$$\lambda E = \alpha \frac{s}{s+\gamma} K \downarrow \qquad 2$$

where
α = (empirical) constant (-)
$K\downarrow$ = global radiation (W m^{-2})

2.3 Soil evaporation

Soil evaporation is the evaporation from the forest litter and the soil. In most forest there is accumulation of organic matter on the soil surface. This layer will intercept a part of the net precipitation, store and evaporate again. Furthermore the litter layer has a large influence on the soil heat balance and the moisture content of the soil (Spieksma *et al.*, 1997).

2.4 Soil moisture

The available amount of soil moisture plays an important role in the regulation of transpiration of trees. The depth of the root zone and the soil composition determine the amount of water which is available for transpiration. Initially the roots use the moisture of the upper layer of the unsaturated zone and later on the moisture derived from capillary rise. The maximum difference between the amount of soil moisture in the winter and summer period can be seen as an indication of the amount of water which can be stored in the soil. Subsequently this amount of moisture can be used for transpiration. According to Dolman *et al.* (2000) this amount is around 150 mm for most of the Dutch forests. They also assume that in dry periods deep roots are capable to extract moisture from groundwater deeper than 3 meter.

The rooting systems of a tree are able to adapt to the local soil moisture content and hence to optimise their water uptake so that they can very effectively use the tree available soil moisture in their rooting zone. In dry periods the deep root zone enables to continue transpiration by taking water from deeper soil layers with adequate water supply (Wattenbach *et al*, 2005).

When the level of the groundwater is in the rooting systems of a tree, oxygen deficit occurs, which causes a reduction of roots. As a result the tree is more vulnerable to fall down. The next dry period the tree has more drought problems because of the shallow rooting system. The time, duration, rate of increase of groundwater level, soil type, type of tree, age of tree and rate of establishment of species are factors which play a role in the impact of groundwater rise on forests. In a period with high precipitation excess groundwater will rise more suddenly and causes more damage. A sudden groundwater rise causes stronger anaerobic conditions in the rooting system, so roots have more difficulties to adapt to the higher groundwater level. Aerobic micro-organisms consume the available oxygen within two days, depending on the temperature and the available organic matter. After a period of two or three weeks with high groundwater level, forest mortality can be expected (Poels *et al.*, 2000).

Problems can be expected when the mean highest groundwater level for beech and Douglas is less than 40 cm below surface level and for other trees less than 25 cm below surface level (Poels *et al.*, 2000). The alder (Dutch: els) is more adapted to anaerobic situations. More important is the fluctuation of the groundwater level throughout the year. When trees are in their winter situation they are able to deal with higher groundwater levels over a longer period than trees with foliage. Spring seems to be extra vulnerable.

To predict the effects of drought and wet situations the knowledge of the depth and intensity of the rooting system is important. The distribution of the fine root biomass (< 5 mm diameter) according to De Visser and De Vries (1989) are shown for coniferous - (Table 1) and deciduous forest (Table 2).

Table 1. Percentage distribution of fine root biomass for different soil compartments for coniferous forest.

	Depth root zone (cm)				
Compartment (cm)	20	30	60	70	80
0-10	65	60	50	45	45
10-20	35	30	20	20	15
20-30		10	10	10	10
30-40			10	10	10
40-50			5	5	5
50-60			5	5	5
60-70				5	5
70-80					5

Table 2. Percentage distribution of fine root biomass for different soil compartments for deciduous forest.

	Depth root zone (cm)				
Compartment (cm)	20	30	60	70	80
0-10	60	45	30	25	25
10-20	40	35	20	20	20
20-30		20	20	20	15
30-40			15	15	15
40-50			10	10	10
50-60			5	5	5
60-70				5	5
70-80					5

2.5 Leaf Area Index

The basic value to reflect and describe the structural changes of a forest is the leaf area index (LAI) because it is a stand density and age dependent value. The LAI of a Scots pine stand for example can decline by natural mortality and management actions from 6.5 in a 25 years old forest to under 2.0 in a 120 year old stand (Wattenbach *et al, 2005).* This forces a massive decrease in interception losses and especially in the first decades, an increase in transpiration. The same pattern can be observed for deciduous tree species as well.

Taking this into consideration it seem to be essential to take the temporal and seasonal dynamics of interception and transpiration into account when modelling landscape change impacts on eco-hydrological processes related to forest area and structure changes (Wattenbach *et al, 2005).*

3 Forests in the Netherlands

The total area of forest in the Netherlands is estimated on 330.000 ha. Most of the forest is situated on dry grounds. The area of wet forest (lowland riparian forest) is estimated on 2500 ha (Jans *et al.*, 2001).

According to modelled annual water balances for the period 1960-1990 for a Douglas fir stand on a sandy soil (Tiktak and Bouten, 1993), the annual median precipitation was 834 mm, calculated median interception loss 317 mm, median transpiration 363 mm, median soil water evaporation 32 mm and median vertical drainage at 150 cm depth 195mm. Transpiration shows smaller variations (11%) between the years than throughfall (54%) and vertical drainage (112%). Although the median value of transpiration reduction resulting from water stress is low (4%), some years showed extreme water shortage, the highest transpiration reduction being 31% for 1976. Although total transpiration reduction during median years are low, short periods with considerable drought stress occur during these years.

Dolman and Moors (1994) estimated the interception lost of a Dutch Douglas forest on 293 mm and transpiration on 348 mm (annual precipitation is 750 mm). For a deciduous forest they estimated the interception lost on 150 mm and transpiration on 284 mm.

De Visser and de Vries (1989) simulated the yearly water balance for different forest type on sandy soils in the Netherlands. They simulated the water balance with SWATRE (precursor of SWAP) for the year 1973 (779 mm precipitation). The interception is calculated with a dynamic simulation according to Massmann. The potential evapotranspiration is calculated with the Penman open water evaporation multiplied with a crop factor. The calculation of the potential evapotranspiration is reduced with a factor for the potential transpiration and potential soil evaporation. The different crop factors are based on literature data and calibration. The actual transpiration depends on the pressure head. Below pF 1.0 and above pF 4.2 there is no water uptake due to respectively oxygen- and moisture deficit.

Table 3 shows the calculated yearly water balance for different forest types, heather and grass.

Table 3. Interception, potential transpiration and soil evaporation (mmy^{-1}) for different vegetation types (de Visser and de Vries, 1989).

Process	Douglas	Pine	Deciduous forest	Heather	Grass
Interception	305	274	176	78	46
Potential transpiration	417	378	397	324	450
Soil evaporation					
- potential	97	90	98	111	37
- actual	56	75	55	85	33
Throughfall	475	506	604	702	733
Infiltration	418	432	549	617	700

The amount of interception from the shrub layer is taking into account for pine and deciduous forest. The values for interception and potential transpirations are, with respect to the forest vegetation, relative high for Douglas, which correspond to the high water consumption of this type. The potential transpiration of grass is also high, because of the low interception which hardly reduces the transpiration.

The actual transpiration is clearly lower than the potential transpiration. The transpiration deficit dependents on the storage capacity and the capillary rise. Large transpiration deficits relatively occurs at soils with a deep groundwater level. There is hardly any difference in annual transpiration for different soils with identical groundwater levels (see Table 4).

Table 4. Actual transpiration (mmy^{-1}) of douglas , pine and deciduous forest at different groundwater classes (de Visser and de Vries, 1989).

Groundwater classes	Douglas	Pine	Deciduous forest
III	378	373	383
V	363	334	374
VI	325	296	339
VII	292	296	296
VII*	261	241	279

De Visser and de Vries also calculated the water balance by season. The variation of throughfall depends on the precipitation distribution and the variation of interception evaporation. The throughfall is calculated for the year 1973 (see Table 5). The seasonal dynamics for soil evaporation, infiltration and mean actual transpiration are shown at Table 6 through Table 8. Almost all transpiration takes place in the growing season from April through September.

Table 5. Througfall (mm) for different season period (de Visser and de Vries, 1989).

Day number	Douglas	Pine	Deciduous forest
0-90	70	80	96
90-180	121	130	152
180-270	125	125	151
270-365	159	172	205

Table 6. Soil evaporation (mm) for different season period (de Visser and de Vries, 1989).

Day number	Douglas	Pine	Deciduous forest
0-90	18	15	18
90-180	17	32	32
180-270	14	22	0
270-365	7	6	5

Table 7. Infiltration (mm) for different season period (de Visser and de Vries, 1989).

Day number	Douglas	Pine	Deciduous forest
0-90	52	15	18
90-180	104	32	32
180-270	111	22	0
270-365	152	6	5

Table 8. Actual transpiration (mm) for different season period (de Visser and de Vries, 1989).

Day number	Douglas	Pine	Deciduous forest
0-90	0	0	0
90-180	163	142	142
180-270	157	155	186
270-365	10	6	15

4 Climate change

A probably climate change scenario for The Netherlands is: a temperature increase of 1-3 °C in 50 years and a precipitation increase in winter and a decrease in summer. The chance and the severity of a storm will increase. Another factors are the increase of carbon dioxide in the atmosphere and the greenhouse effects on carbon dioxide in the atmosphere (Nabuurs *et al.*, 1997).

Until 2020, climate change will have a limited impact on the forest ecosystem. Through feedback mechanisms in trees, the enhanced photosynthesis will probably be compensated for. Any growth response will be difficult to detect due to natural fluctuations in the weather conditions. Components of the ecosystem that will be most vulnerable in this period are the understory, seedlings, and older trees.

In the longer term (beyond 2000), the effects of climate change will be drastic (Nabuurs *et al.*, 1997). In principle growth will increase with temperature and carbon dioxide concentration due to longer growing season, but the higher temperatures will also result in higher transpiration. Especially under increased summer drought, an increased drought stress will occur. Complete compensation of this drought stress due to a higher water use efficiency (under higher carbon dioxide concentration) is unlikely. Due to a combination of an earlier start of the growing season and summer drought, the growing season will concentrate on the first months.

After an enhanced temperature, a slow migration of species to the north will occur. However, because of the intensively cultivated landscape in the Netherlands, this natural migration will be hampered. Wherever migration is possible, species or provenances from southern regions will become more important in The Netherlands.

Especially in a transition phase (second half of the next century), where the present species and provenances will lose terrain, but where better adapted species have not yet established (or have not yet been introduced by management), the sustainability of the present forest ecosystems will be at danger.

Already know, forest management can incorporate certain changes to anticipate climate change. Some measures can both reduce the effects of climate change. The measures consist of both risk reduction and monitoring of the state of the forest. Possible measures are:

- To reduce the effects of man-induced drought by storing the system water as long as possible and by reducing drainage.
- To spread the risk by aiming at management of mixed forests with a higher degree of biodiversity
- To reduce the deposition of nitrogen, since it increases the impacts of drought.
- To reduce the degree of regeneration with species like Norway spruce and Douglas-fir. Under climate change, the role of these species in the Dutch forest will most likely be reduced.
- Changes in species towards species from southern regions may be simulated.
- Small scale forest management aiming to reduce the impact of storms.

Lasch *et al.* (2002) applied a forest simulation model in a regional impact assessment to investigate impacts of climate change on forest structure and function in the Federal state of Brandenburg, Germany. The forest model FORSKA-M was linked to GIS that included soil, groundwater table and land-use maps. They assumed that soil conditions and depth of water table remain unchanged under climate change. The used soil water model is only applicable at sites with low groundwater table because capillary rise of water was ignored.

The effects of vegetation changes and management under current climate and climate change on different forest function (biodiversity, habitat value, and groundwater recharge) were evaluated. The simulations suggests that the impact of climate warming on forest growth are mainly negative in this region, because changes in the water balance will lead to increased drought stress. Simulation studies with a variety of climate change scenarios have indicated that positive growth responses could also occur in temperate forests if increasing precipitation balances the increases evaporative demand under elevated temperatures. The analysis of effects of climate change on groundwater recharge indicated that the decreasing precipitation and increasing temperature will lead to a reduction of percolation rates and finally of groundwater recharge in consequence of increasing transpiration demand. Hence, the total impact of climate change may imply more than vegetation changes only.

There is no literature available which focuses especially at impact of climate change on existing forest types under changing hydrological regime with special attention to stress due to low moisture content and stress due to high moisture content.

5 Forest-hydrology models

Most of the models which are used in forest-hydrology research consist of three components: a interception -, a transpiration - and a soil moisture model. There are models which focus only at the processes in a forest, as specific models for interception, transpiration and stomatal conductance. In some models the soil moisture part is neglected or only as limiting factor. Combination models have generally only few attention for the spatial aspect of soil moisture and groundwater.
A overview of existing forest-hydrology models will be given below.

5.1 Gap Models

Gap models have a rich history of being used to simulate individual tree interactions that impact species diversity and patterns of forest succession. Gap models define and keep track of individual trees, which do not have specific spatial coordinates, competing and growing in a restricted area, the gap. Gap models are mainly used to understand the forest successional patterns and processes in a canopy gap area. The first gap model, JABOWA, was developed by Botkin *et al.* (1972) to simulate the dynamics of a mixed broadleaved forest. In FORET (Shugart and West, 1977), a major modification consisted of describing the vertical distribution of foliage from treetop to crown base instead of accumulating it at the top of the tree. The JABOWA and FORET models still form the conceptual bases for new gap models (Porté and Bartelink, 2002). Many gap models have been developed, e.g. FORECE, FORCLIM, FORGRA, FORSUM, FORSKA, LINKAGES etc.

In contrast to many process-based models, gap models have traditionally been based on rather descriptive representations of species-specific growth processes. Attempts to incorporate stomatal, photosynthetic and energy exchange dynamics into physiology-based models of forest succession have been successful. The below-ground components of gap models have not, however benefited from the same degree of model improvement (Wullschleger *et al.*, 2001).

Soil water is a primary limitation to the growth of trees in many locations of the world for at least part of the growing season. Moreover, one of the most important aspects of global change for ecosystems will be changes in land-surface hydrology, particularly as a result of the intra-annual variation in the timing and amount of precipitation. Few gap models have been developed that treat below-ground competition with sufficient spatial and temporal detail to capture these complex processes.
Although several traditional and physiology-base gap models include multiple soil layers, most do so for the purpose of better estimating evaporation and the effects of water-deficits on transpiration. Little consideration given, however, to how spatial detail could be used to represent the effects of soil moisture on different species or size classes of a single species that might otherwise differ in their root distribution within the soil profile . A benefit of implementing a root development approach would be a more dynamic representation of roots within the soil profile, allowing roots to be distributed to potentially greater soil depths that might otherwise be specified by a fixed coefficient approach. As a

result, trees would have increased access to deep soil water reserves, thus limiting the unrealistic negative impacts of drought on growth in the models.
Most of the gap models assume that the forest floor in a patch is flat. This assumption simplifies model structure by ignoring runoff from one patch to another. It also, by definition, eliminates the possibility that microsite differences in soil water content will be modelled in a realistic manner. However, a landscape or catchment is more complex than an isolated patch because spatial considerations such as lateral flow of water, topography, site aspects, and differences in vegetation water use are important.
Based on existing scenario's of climate change, many regions of the world will experience higher temperatures and altered rates of precipitation. Higher temperatures will directly affect forest ecosystems through effects on plant physiology but indirect effects such as higher water demand may have a greater impact on some water-sensitive forest ecosystems (Staktiv and Major, 1997). As the water balance of a forest becomes increasingly important, assumptions about lateral flow of water will also become more important.

The link between water availability and LAI illustrates the concept of hydro- ecological equilibrium in the natural soil-vegetation system. This equilibrium highlights not only the limitation of forest productivity on dry sites, but also feedback of a decreasing leaf biomass in order to limit, in the following year, transpiration water losses. For example, due to increased water availability, valley bottoms and north facing slopes have a higher LAI than do ridge tops.

The historic omission of below-ground processes in gap models was partly a consequence of the goals and interests of the developers of the model. In addition, there was – and to a large extent remains – a lack of sufficient data on below-ground processes and species-specific differences for model initialization, validation and performance testing of the models. This lack of information poses a serious obstacle to incorporate below-ground processes in gap models and thereby threatens the goal of better understanding how forest productivity and succession will be impacted by future changes in climate.

So there are a number of gap models, which are able to simulate the development of single trees of forest stands under different scales of complexity. However, all of them have a forest science focus aiming to simulate environmental impacts on forest growth and ecology and, to a lesser extent, looking at interaction of forests with the environment and the landscape scale. Therefore gap models are not suitable for our study because interaction on the level of individual trees is too detailed for the aim of the study.

5.2 *FORSPACE*

FORSPACE simulates forest dynamics in spatially changing environment due to fire and grazing large herbivores (Kramer *et al.,* 2001*)*. FORSPACE is a spatial explicit process-based model, with monthly time steps. A water balance module is optionally (Groen *et al*., 2000). The water availability influences the development of individual plants and thus the succession of the simulated ecosystem.

The water balance module in FORSPACE is calculated as the mass balance. The time steps of the water balance are days although the main model operates with time steps of months. Precipitation and run-on are the incoming water flow and the outgoing water flow consists of runoff, interception, drainage, transpiration and evaporation. The run-on and runoff from elevated plots generate the spatial effect of the water balance. Runoff is calculated as the excess of water that can not infiltrate the soil after precipitation. FORSPACE is not developed for floodplains and capillary rise is not included. The present model reads only meteorological data from one year so simulation of variable weather patterns and climate change is not be possible.

Interception of precipitation by the canopy is an important effect on the water balance. FORSPACE applied a linear relation between Leaf Area Index (LAI) and intercepted rain. This relationship is adopted from Woodward (1987), 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:

$$I = P \cdot C \cdot (0.015 \cdot LAI + 0.035) \tag{3}$$

where
I = intercepted precipitation by the tree layer per day (mm d^{-1})
P = precipitation (mm d^{-1})
C = total cover of the tree layer (-)
LAI = LAI of the total tree layer (m m^{-1})
The leaf distribution within a plot is assumed to be homogenous.

The remaining water after interception and runoff infiltrates in the topsoil layer. The infiltrated water is redistributed over the different soil layers with the "tippet bucket" method in which a drainage coefficient of 0.5 is used. The amount of water that leaves the lowest soil layer is limited by a maximum drain rate.

The potential transpiration by trees and shrubs is calculated with the Penman-Monteith equation. The amount of water that is transpired per individual plant is calculated by the amount of net radiation that is absorbed by the plant, an the total covered by the plant using the Penman-Monteith equation. Differentiation in potential transpiration between plants is a result of different boundary layer resistances and the difference in development of LAI and radius of the crown. The amount of net radiation that is absorbed by a plant is calculated with the Lambert-Beer equation in which an extinction of 0.5 is used.

Transpiration will not drop suddenly when soil water content drops below permanent wilting point , but will have a gradually decrease towards permanent wilting point. This is simulated with the Hagen-Poiseuille equation. 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 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. The amount of moist available to the plant from the rooted space is between pF 4.2 and pF 2.0.

Potential evaporation is calculated to the amount of radiation that is not absorbed by plants, and prevailing atmospheric conditions. 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.

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 radiation use efficiency (RUE) occurs. This is calculated by using the ratio between "potential" stomatal conductance and actual stomatal conductance. The stomatal conductance is the inverse of the stomatal resistance. The potential stomatal conductance is the one which is used to calculate potential transpiration. When the actual transpiration is calculated, the actual stomatal conductance can be calculated. The ratio between these two conductances is a reduction factor for the RUE.

LAI has an important effect on the relation between production and transpiration. Trees with a high LAI have an advantage as long as water is sufficiently available, but that as water becomes scarcer, the advantage becomes less.

FORSPACE simulates transpiration higher than measured evapo-transpiration, indicating that the parameter values for the model need adjustment. One parameter that might play an important role in this is the drainage coefficient used in the model. This parameter is very roughly estimated, being very difficult to determine in the field. The main aim of the water balance is the effect on the vegetation development. But because FORSPACE is a spatial model, the run-on and runoff aspect is tested as well. Validation is done not so much the spatial aspect, but merely to see whether the error made by this aspect is not becoming to large. The model is only tested for one dataset which suggests that the runoff model work appropriate although it should be with more data set for a better indication of the error marge.

According to the model the leaf size can be very influencing when it comes to the threshold effect of water stress.

When scenarios were simulated, 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.

FORSPACE simulates transpiration by means of the Penman-Monteith equation. 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 equation calculates a reference evapo-transpiration that has to be multiplied with a crop factor to calculate the real potential evapotranspiration. In the FORSPACE model however deals with a changing vegetation, and FORSPACE simulates the evapotranspiration to change according to the developing vegetation. Also FORSPACE calculates the transpiration for different plant species separately, so the competition is simulated by means of different effect on the radiation use efficiency.

The main conclusion is that the effect of implementing a water balance in the model causes a reduction in the development of the vegetation.

5.3 SWAPS

SWAPS (Ashy *et al.,* 1996) is a one dimensional land surface model comprising an unsaturated soil moisture flow scheme and a one or two layer evaporation-interception scheme. The aim of the model reproduce the water balance and surface energy fluxes accounting for feedback and coupling between processes in the soil, vegetation and the (atmospheric) surface layer. The model is effectively decoupled from the overlying atmosphere in the sense that meteorological variables (such as temperature and humidity) are used to force the model and are not adjusted to fluxed or resistances generated by the model.

SWAPS is based on the SWAP model and has been extended by an atmospheric module based on the energy balance. The interception scheme is based on the model of Rutter where an interception layer is modelled as a reservoir or bucket. A fraction of the precipitation incident above the layer is intercepted and stored in the reservoir. Interception evaporation from water in the reservoir will occur, as will drip if the capacity of the reservoir is exceeded. In SWAPS the latter is the only method of generating drip, unlike the original Rutter model where drip is also generated by a hole in the bucket.

Evaporation is determined using a number of models. The simplest of these is the single big leaf where evaporation from a single layer is calculated using a Penman-Monteith model. For a two layer model evaporation from both an upper and lower layers occurs. A Penman-Monteith model is applied to each layer following the original 'sparse canopy' model of Shuttleworh and Wallace. This assumes that the upper vegetation layer is sparse enough to allow the existence of a mean or in-canopy flow. In this case the latent heat fluxes from each layer are linked by the in-canopy vapour pressure deficit. Two types of two layer model may be used: either the original model or, following Dolman, a modified version of this where the fractional cover of each layer is used to partition the energy fluxes.

In SWAPS the choice of two layer evaporation model is linked to the type of radiation scheme and interception scheme employed. For the original Shuttleworh and Wallace model, in terms of radiation and precipitation the upper layer is pictured as overlying the lower layer. In this case radiation and precipitation reaching the lower layer are determined by an extinction coefficient and free throughfall coefficient respectively. In the case of the modified model of Dolman, incoming fluxes or radiation and precipitation are assumed to be the same for both layers since the layers are pictured as adjacent patches receiving the same loading.

For each layer the surface conductance is needed for the evaporation model. In the case of vegetation, Jarvis proposed a model where the stomatal conductance is controlled by prevailing environmental conditions, modelled in the form of stress functions. Steward modified this to give a surface conductance for a vegetation canopy, and this modified version is used in SWAPS. In the case of a soil layer, an effective soil surface resistance to evaporation is determined based on the soil moisture and soil thermal status.

For a vegetation layer whose interception reservoir is completely full the surface conductance is zero and the latent heat flux from that layer comprises interception evaporation only. This is also assumed to be the case for a soil layer with ponding. For a completely dry vegetation or soil layer the latent heat flux will be transpiration or dry soil evaporation. The latent heat flux from a partially wet vegetation canopy (where the interception reservoir is not full) comprised both transpiration and interception components. These are determined following the original Rutter model. Transpiration is calculated assuming completely dry conditions and interception evaporation assuming completely wet conditions. The actual transpiration is then assumed to be the above dry transpiration reduced by the fraction of the canopy that is actually dry. Similarly the actual interception evaporation is assumed to the above interception evaporation reduced by the fraction canopy that is actually wet.

Soil moisture transport is modelled using the Darcy-Richard's equation where processes such as root uptake and soil evaporation are included as a sink term. The soil moisture calculations are performed using a fully implicit one-dimensional (vertical) finite difference scheme where boundary conditions and initial soil moisture status are required to produce a tri-diagonal set of equations. The upper boundary conditions will be head or flux controlled depending on the prevailing conditions and this is determined within SWAPS. The lower boundary condition is also controlled by a flux or pressure head, specified by the user. In addition the relationships between pressure head, soil moisture content and soil hydraulic conductivity are required. These are given either by specifying a number of parameters that give the functional dependence of these variables following van Genuchten; or by specifying corresponding values of these variables in tabular form.

Soil heat transport is modelled as a conduction process using Fourier's equation. The soil thermal calculations are performed using a fully implicit one-dimensional finite difference scheme with the same vertical discrestistation as the soil moisture calculations. In general these calculations are performed at a longer time step than the soil moisture calculations. Upper and lower boundary conditions are specified by the user giving a tri-diagonal set of equations. In addition soil heat capacity and soil thermal conductivity are required.

Water en energy balance closure

In some models potential evaporation or transpiration is calculated from a Penman-Monteith equation. This is then adjusted, if necessary, to account for soil moisture status and other environmental factors. In SWAPS this is not the case. Soil evaporation and plant transpiration are calculated using respectively an effective soil surface resistance and a vegetation surface resistance in a Penman-Monteith model (evaporation, interception and radiation models). These resistances explicitly account for soil moisture status and other environmental factors. In the case of the vegetation surface resistance this is done using stress functions. Adjustment of the latent heat fluxes calculated using these surface resistances is therefore not required in the same way that it is in models that calculate potential latent heat fluxes. To avoid confusion SWAPS refer to latent heat fluxes calculated using these surface resistances as maximum latent heat fluxes. They are maximum in the sense that they result from the assumption of energy balance closure, using surface resistances that do not account for stored water (i.e. interception or ponding).

The maximum latent heat fluxes may need to be adjusted if there is stored water on a layer, or to maintain the soil water balance. If a layer is wet, some or all of the evaporation from this layer will originate directly from stored water on the layer and the soil evaporation and/or transpiration demand will be less than the maximum flux calculated assuming dry conditions. The total latent heat flux of a layer may compromise interception evaporation, transpiration or dry soil evaporation demand or both. Obviously under dry conditions there is no interception evaporation and the demand equals the maximum latent heat flux.

The actual transpiration or dry soil evaporation component may then be reduced compared to the demand to close the water budget of the soil. In the case of two vegetation layer, the vegetation surface resistances for each layer are calculated based on soil moisture states (and other factors) but without accounting for the presence of the other layer: in this context SWAPS calculated the maximum transpiration of one layer as the transpiration demand of that layer, under dry conditions, when the other layer is not present. Since the two vegetation layer may be competing for the same water the soil moisture may not be able to supply the total transpiration demand and in this situation the actual transpiration will be less than the demand. In the case of an upper vegetation layer and a lower soil layer soil moisture may not be able to supply the transpiration and soil evaporation demand.

When the actual latent heat fluxes (which close the soil water balance) have been calculated, the sensible heat fluxes are recalculated to maintain a closed energy balance. It should be noted that under dry conditions, differences between actual and maximum latent heat fluxes should be small for a two layer model and negligible for a one layer model, if the soil and/or vegetation surface resistance is correctly parameterized.

Evaporation, interception and radiation models

The input parameters are used to define the type of model used. This is done by specifying fractional covers for the upper and lower evaporation-interceptions layers. Setting the fractional cover of the upper layer to zero and the lower layer to unity specifies a one layer model. This single layer may be vegetation, or soil with or without litter. Non-zero fractional cover of both layers is used to specify a two layer or dual source model with upper (i.e. higher) and lower evaporation-interception layers. In this case the upper layer is always assumed to be vegetation, whereas the lower layer may be vegetation, or soil with or without litter.

In the case that the fractional covers of the upper and lower layers add to unity the two layers are pictured as distinct adjacent ‘patches’, each receiving full radiative loading. In this case the available energy is partitioned according to the fractional cover of each layer; and the contribution to the total latent and sensible heat fluxes from each layer is weighted according to the cover of the layer.

One point concerns the aerodynamic behavior of a two layer model. It is assumed that aerodynamic mixing is sufficient to allow the (theoretical) existence of a mean canopy airstream i.e. the upper vegetation layer is ‘sparse’ enough to allow this.

Model limitations

The structure of the model does not allow for soil moisture and micrometeorological calculations to be performed at the same time step. The difference in timing of calculations between the MicroMet and Soil module requires some variables to be calculated at the start of the meteo time step using the latest known soil moisture and temperature profiles. These are then assumed to apply for the current meteo time step i.e. they represent average values for the time step. In situations where the latter is not a good approximation meteo time steps should be decreased.

In the case of a lower soil layer with litter this is effectively a ‘two-and-a-half’ layer model. For this interception evaporation originates from the interception storage reservoir of the litter layer, and soil evaporation (from the ponding layer or within the soil) is also modeled. For a lower vegetation layer soil evaporation is not modeled explicitly although the surface conductance model may implicitly account for soil evaporation.

Soil thermal calculations take not account of a litter or ponding layer. The thermal properties of the litter components (water, air, organic matter) are already available to calculate the thermal properties a litter layer, given the volume fraction of organic matter in the litter as an additional input. A ponding layer can be treated similarly, but in this case the extra component for soil thermal calculations must have a variable depth; and some assumption must be made about precipitation temperature.

SWAPS does not account for the radiative properties of a soil or vegetation layer being modified if the layer is wet; nor does is account for the diurnal variation of radiative properties (in particular the shortwave reflection coefficient).

The Jarvis-Steward surface conductance model is set up so that for a lower vegetation layer the stress functions for humidity deficit and temperature use previous meteo time step in-canopy variables; and the surface conductance is calculated before the stability iteration.

5.4 *SWIF*

The SWIF model (Tiktak and Bouten, 1992) describes vertical water flow and root water uptake in the unsaturated soil zone. The model calculates with the Richards equation. The root water uptake from a layer is calculated from the potential uptake from the layer and a reduction factor. The model simulates preferential uptake from layers with a high saturation fraction. The potential uptake is calculated by distributing the total potential transpiration over all soil layers according to the effective root-length of a layer, expressed as a fraction of the total effective root-length of the soil profile. The actual soil evaporation is calculated according to a empirical relationship. It is assumed that any dry periods end at a day with net precipitation greater than 1 mm d^{-1}.

The depth distribution of water uptake by roots is based on a root-length distribution. Depth distribution of root-length varies with time because the root death occurred in dry soil layers. Although the model does not take explicit account of the variation in depth distribution of root-length, preferential uptake from wet layers is simulated. This lead to a simple empirical way of describing both limited transport of water to roots resulting from reduced contact between root and soil and changing root-length distribution.

The evapotranspiration of a uniform forest is calculated with the Penman-Monteith equation. The Penman-Monteith equation contains site-specific parameters which are not available for long periods of time. Therefore, the Makkink reference evapotranspiration for grassland was multiplied by an empirical crop factor to obtain the potential Makkink evapotranspiration. The potential transpiration for dry conditions and the potential soil evaporation are calculated with an empirical crop factor which accounts for stand factors, a canopy gap factor and a reference evapotranspiration for grassland. The canopy gap fraction is obtained from observations in the field, and is low (0.1) as a result of the high LAI of the stand considered. The crop factor is calibrated by comparison the simulated and measured water storage in the rooting zone. The time of replenishment of soil water in autumn is especially sensitive to the value of the crop factor. The best fit to the measured data is found when the crop factor is made dependent on the seasonal course of the LAI. Table 9 shows the parameter values which are used in the simulation of the SWIF model.

Table 9. Parameter values used in the simulation of the SWIF model

Parameter	Value	Unit
Reduction point	-600	cm
Wilting point	-10000	cm
Crop factor	0.85	-
Maximum crop factor	0.95	-
Root density		
0-10 cm depth	0.55	$cm^3\ cm^{-3}$
10-20 cm depth	0.45	$cm^3\ cm^{-3}$
20-40 cm depth	0.25	$cm^3\ cm^{-3}$
40-80 cm depth	0.10	$cm^3\ cm^{-3}$

They found a high correlation between the potential Makkink evapotranspiration and the Penman-Monteith transpiration. This was expected because there was hardly any response of the daily average transpiration to the water vapour deficit. The latter factor is the most important one not accounted for in the Makkink equation.

Both the Penman-Monteith evapotranspiration and the potential Makkink evapotranspiration refer to days without precipitation. On days with precipitation the transpiration is reduced by the evaporative demand of a wet canopy.

The effect of temporal variation of throughfall amounts on soil water dynamics is limited to variations within a year. The highest deviations are found for the deeper soil layers.

According to SWIF when running a scenario with potential Penman-Monteith evapotranspiration and one with potential Makkink evapotranspiration with variable crop factor, the simulated annual total transpiration and soil water fluxes are again almost identical. The only deviation occurs in autumn, when simulated water contents in the deeper soil layer are too low and transpiration too high. The effect of a constant crop factor is also limited to variations within the year. In spring, transpiration is higher and vertical drainage is lower. In autumn, simulated drainage is higher. As a result, simulated water contents in the deeper soil layer are more realistic in the autumn, but deviate slightly from the measurement in spring.

Validation of the model shows that soil water pressure heard are overestimated in autumn and early winter. This discrepancy is related to the value of the crop factor, which is in fact a lumped calibration parameter which not only accounts for the difference between the transpiration of grassland and forest, but also account for fluctuation of forest vitality.

A simulation was run for the period 1960-1990 for a 2.5 ha Douglas fir stand in the central Netherlands. The water table is at a depth greater than 40 m throughout the year. The actual transpiration only deviates from the potential transpiration during dry periods with transpiration reduction. Transpiration reduction occurs when the total amount of evaporated water exceeds the amount of water stored at pressure heads above the reduction point. Apparently, the relationship between rainfall distribution and water storage capacity is such that the actual transpiration is normally kept within narrow bounds.

The model SWIF gave a good description of the mean water content, pressure head and annual transpiration for the stand. However, good estimates of the empirical parameters required to convert synoptic weather data into throughfall and potential evapotranspiration data could not have been made without carrying out a hydrological programme. Thus, to generate long-term througfall and potential evapotranspiration data from synoptic weather data, on site monitoring data must be available for at least two different years (i.e. one year for model parameterization and one year for model validation).
A simulation over the past 30 years showed actual transpiration with small variations over the years (a median value of 363 mm), while variation of throughfall was considerable. Apparently, several feedback mechanism, such as the relationship between rainfall distribution and water storage capacity, keep transpiration within narrow limits. During a median year transpiration reduction by drought was only 4%, but was as high as 31% in the driest years. As serious injury to trees may occur, particularly in these dry years, it is important to estimate their frequency of occurrence. Although total transpiration reduction during average years is small, short periods with considerable drought stress also occur during such year.

5.5 FORHYD

FORHYD (FORest HYDrological package) (Bouten, 1995) was applied to quantify the most important water balance components and soil water dynamics of the Solling spruce. FORHYD contains several modules for simulating hydrological processes in forest, including (a) rainfall interception, canopy wetness and evaporation from the canopy, (b) forest floor hydrology, (c) water flow and route water uptake in the unsaturated soil zone, (d) sap flow in trees, and (e) transpiration. For most processes one can choose between different concepts. The complexity of models can thus be geared to the data availably.
For modelling rainfall interception and throughfall one can choose either a regression function with a threshold value, an empirical curve for low rainfall amounts instead of a single threshold value or a multi-layer cascade model, or a multi-layer cascade model built into a micro-meteorological model. In order to simulate forest floor hydrology one can either use a running water balance model or an empirical evaporation model with evaporation diminishing as a function of time after the last rainfall event. FORHYD calculates soil water flow and root water uptake with the soil water module of SWIF. A transpiration module is available either as the single-big-leaf model based on canopy resistance or a multi-layer micro-meteorological model. Daily transpiration can also be calculated with an empirical module incorporate in SWIF using either Penman open water evaporation, Penman-Monteith or Makkink as reference transpiration.

5.6 *FORGRO*

FORGRO (FORest GROwth, Mohren *et al.*, 1993*)* is a one dimensional process-based model suitable to predict growth of even-aged mono-species stands of trees. It simulates growth processes on a daily basis as a function of the environmental variables: incoming radiation, minimum and maximum temperature, humidity, precipitation and wind speed. Central to FORGRO is the interception of light by the canopy, and the hourly integration of photosynthesis over five shaded and sunlit layers. In FORGRO, photosynthesis is reduced proportionally to the ratio of actual en potential transpiration.

5.7 *Topog-IRM*

Topog-IRM (Hatton *et al.*, 1992) is a spatially explicit hydroecological landscape model of water, carbon and energy balance. The model is a combination of a three-dimensional, distributed parameter catchment hydrology model (Topog), with a multi-factor plant growth model (IRM). Topog begins with a digital elevation model of the area to be modelled, and applies a set of topological rules to (a) define a catchment boundary, and (b) calculate a network of landscape elements defined by lines of minimum distance between adjacent contours. The network of elements is arranged around critical topographic features such as peaks, saddles, ridges, drainage lines and stream confluences, the result is a series of adjacent flow strips which diverge or converge according to local terrain. The second key requirement for landscape modelling is expressing the spatial distribution of parameters. Within the Topog framework, basic attributes such as slope, aspect, extraterrestrial radiation and area are calculated for each element. Further, the spatial pattern or soil types, rainfall, vegetation type, biomass and plant nutrients may be imposed upon the simulated catchment.

Infiltration of net rainfall and the vertical redistribution of water in the soil are accomplished through a finite difference numerical solution of the Richards equation for each landscape element. Matrix flow alone is considered for water redistribution in the vertical; preferred pathway flow and hysteresis are not modelled. Overland flow, whether resulting from infiltration excess or surface saturation, is treated explicitly. Following the development of a water table, water is moved latterly according to the saturated hydraulic conductivity and the local hydraulic head. Leakage to the deep groundwater system is treated explicitly. For each soil type in the catchment it is necessary to describe the relationships among water potential, volumetric water content and hydraulic conductivity.

The largest tem in the annual water balance for most land surfaces, after gross rainfall, is evaporation. Thus, the partitioning of the surface energy balance into latent and sensible heat is crucial to models of catchment behaviour. The direct input to the evaporation module is daily meteorological on maximum and minimum temperatures, vapour pressure deficit, precipitation, and direct and diffuse solar radiation incident on the horizontal plane. Recognising that such detailed data are often available for only few location, it is necessary to apply some form of data extrapolation.
Given the direct inputs, the evaporation module calculates daily values for evaporation of water intercepted by the canopy, transpiration and soil evaporation for each element. Each of these processes is related to the extent of the canopy (leaf area index).

The energy available for evaporation is limited to the amount of net radiant energy received by each element, with a consideration of the average daily vapour pressure deficit. The energy balance of each element is thus independent of its neighbours: the horizontal advection of sensible heat is not treated. Direct radiation on a horizontal surface is modified according to the aspect and slope of each element and the time of the year; diffuse radiation is modified by slope only.

Rainfall interception loss is scaled by the daily effective canopy storage per unit LAI. The energy required to evaporate intercepted water is deducted from the available for transpiration.

The amount of net radiant energy received at the soil surface sets an upper boundary condition for evaporation at the uppermost node in the unsaturated zone model. The amount of water evaporated is limited initially by energy and, as the surface dries, by the hydraulic conductivity of the soil.

Daily transpiration is calculated by a 'big leaf' application of the Penman-Monteith formula. Soil heat flux is assumed to approach zero on a daily time step. Surface resistance is assumed to approach zero when the canopy is wet.

The key controls of transpiration are the aerodynamic resistance and the surface resistance terms. For very rough surfaces like forests, the aerodynamic resistance may be treated as small and effectively independent of wind speed and atmospheric stability. The surface resistance, however, will vary widely in time, and is largely a function of the stomatal control of water vapour transport in the canopy. This control reflects the availabilities of light, water, carbon dioxide and nutrients, as modified by temperature and vapour pressure deficits.

Once an estimate of daily transpiration is obtained, that amount of water must be extracted from the finite difference nodes in each landscape element. This total is apportioned vertically on the basis of the relative rooting density and the water potential. The value of relative rooting density is assumed to fall off exponentially to zero at he maximum rooting depth.

Topog-IRM outputs a range of hydro-ecological responses. For each landscape element, the water content and potential at each dept node is calculated, as well as the mean absolute and mean relative water contents for the entire soil column. Daily transpiration, net rainfall, soil evaporation, deep drainage and infiltration excess are available for each element. Catchment-wide mean values of transpiration, soil evaporation, net rainfall, canopy rainfall interception, groundwater recharge, overland flow, subsurface flow, streamflow and total catchment outflow are reported on daily basis and as time series.

5.8 *Forest extended SWIM*

There are a number of integrative models which were developed to simulate eco-hydrological processes at the catchments scale, taking into account human interferences like land use and water management changes. They were developed to simulate all hydrologically relevant processes in river basis like surface runoff, interflow, return flow, impounded storage, plant uptake, groundwater recharge, consumption use and depletion of groundwater by pumping wells (e.g. SWAT (Arnold *et al.*, 1994) and SWIM (Krysanova and Müller-Wohlfeil, 1998). According to Wattenbach *et al., (2005)* dynamic forest growth is generally not considered or it is implemented by a simple parameterisation. As a result, forest related processes such as allocation of biomass, LAI development and root water uptake and related processes like transpiration and interception are usually poorly reproduces and they are not subject to further evaluation. This is problematic because a great number of studies have confirmed the crucial role of forest structure on the hydrology of catchments and landscapes respectively (Wattenbach *et al.,* 2005). In the case of the SWIM model the LAI is one of the most sensitive variables with respect to the discharge and water balance at the basis outlet as well as to groundwater fluctuation.

The inadequate reproduction of forest characteristics in eco-hydrological models is not so crucial if the goal of the model run is to reproduce river discharges at the basis outlet. River flow dynamics integrate all hydrological processes in river catchments, and the influence of a single process is limited. Nevertheless, the local water balance inside basins is impossible without a correct reproduction of the hydrological processes in forests.

Wattenbach *et al.* (2005) developed a model approach that considers forest specific eco-hydrological characteristics in time and space. They approach is an as much as simplified forest growth description integrated in the eco-hydrological model SWIM. The key variable is the LAI because it is linked to age and stand density. They assumed that it is possible to simulate transpiration and interception based on a realistic LAI development.

They used the eco-hydrological model SWIM for the implementation because if its suitability from simulating the annual growth of a wide range of crops and natural vegetation types in Central Europe and their hydrological interactions under current and climate change conditions. In addition it is a SWAT sibling, which opens the opportunity to use the new module within this model too. The SWIM model integrates hydrology, vegetation, erosion, and nutrient dynamics at the watershed scale and was developed to simulate hydrology and water quality in meso-scale and lager river basins (100-10.000 km^2)

The forest module

The central element of the forest module is the use of an allometric relation for the ratio of leaf biomass to total biomass. Additionally, Wattenbach *et al.* (2005) simplified this approach by assuming that the age-dependent relation is independent of the environmental conditions.

To initiate the forest stands of a catchment, any hydrotope is defined by a uniform forest stand with an initial total aboveground biomass and age value. The daily potential maximum LAI for each stand is calculated based on total aboveground biomass. The minimum LAI fir Scots pine depends on the number of needle generations on the tree and is set to two third of maximum LAI assuming three needle generations as an average value in summer and the loss of one during autumn. For oak the minimum LAI is set to zero.

Management actions like thinning or harvest as well as natural biomass losses like litter fall and mortality are modelled as a reduction in aboveground biomass which forces a change in LAI by changing maximum LAI.

The start of the growing season is simulated by using a empirical phenological model. The model is based on the assumption that an increasing number of chill days in winter reduces the temperature sum that is required as stimulus in spring.

The simulation of interception is done by a modified version of the Menzel approach that was tested for a broad range of vegetation types. The basic advantage is its ability to simulate the different characteristics of deciduous and coniferous tree species with a distinct number of parameters on a daily time step. For the description of the interception of precipitation the maximum storage capacity is calculated on a daily basis. The maximum storage capacity is only filled during a rain event with a clearly higher amount of rain. The reason is that an increased saturation of the canopy leads to increase in the part of rain that is only temporally stored and later drops-trough or occurs as stem flow.

The potential evapotranspiration is provided by the relevant SWIM modules. If the potential evapotranspiration is less than the actual canopy storage, the residue is added to the storage of the next day. Once the water in the canopy is removed, the remaining evaporative water demand is partitioned between transpiration and evaporation from the soil.

The water stress factor is estimated as the quotient of the sum of the actual water in the soil profile and the uptake from groundwater available for actual transpiration and the potential transpiration. The root water uptake is estimated based on the SWAT2000 approach (Neitsch *et al.*, 2001). As a modification for forest, it is postulated that the root distribution is not necessarily correlated with root water uptake. Thus potential water use for each soil layer can be equal to the potential transpiration. This allows compensation of low water supply in the upper layers by uptake from deeper layers down to the maximum root depth of 2 meter.
The potential daily uptake for each soil layer is computed based on the tree available soil water content, starting from the uppermost layer down to the layer of the maximum root dept. If the total soil water content is one layer falls below 75% of the tree available water content, the uptake is reduced exponentially. If the actual water uptake from one layer is lower than the potential water uptake the residue can be taken from the next deeper layer until the atmospheric water demand is satisfied of the total available water of the soil profile is used.
If the sum of available soil water is lower than the tree water demand the model allows the uptake from groundwater if the actual groundwater level is within the rooting zone of 2 meter. The ground vegetation and litter layer is only represented as additional interception storage where the processes of storage and evaporation take place. Wattenbach *et al.* (2005) assumed a storage capacity of 2 mm for a pine forest and 0.5 mm for deciduous forest.

Comparison of the simulated data of the forest extended SWIM model with measured data showed a mean underestimated of the soil water content. This may indicate a problem in reproduction of the depth allocation of the water uptake. There is still a high degree of uncertainly because of the simple multilayer storage approach used in the SWIM model.

A model sensitivity study showed the influence of the phenology on the landscape water balance. Wattenbach *et al.* (2005) assumed that an extension of the vegetation season in Europe by 6-10 days as a response to the climate change, will likely lead to a real world effect on the water balance which should be investigated.

In general the forest module is able to simulate Scots pine and partly common oak growth and hydrological properties as well as discharge from the basin outlet and the landscape water balance within the SWIM framework. A reasonable description of forest growth (LAI and phenology) and forest related hydrological processes (interception, transpiration and root water uptake) is crucial in catchment modelling, because changes in land use as well as climate change will also change the forest distribution and tree composition. This will affect the regional water balance.

Because of the strong similarities between SWIM and the SWAT model, the module should be applicable within the SWAT model too.

5.9 SWAT

The conceptual semi-distributed model SWAT (Soil and Water Assessment Tool) (Arnold *et al.*, 1994) has been developed to predict the impact of management on water balance, erosion and transport of nutrients and pesticides in meso- to macroscale basins. Major model components include: weather, hydrology, soil, temperature, plant growth, nutrients, pesticides and land management. The smallest spatial sub-units resolved by the model are hydrotopes (hydrological response units) which are assumed to be homogeneous with respect to their hydrological properties. In each of the hydrotopes, water balance is represented by several storage volumes: canopy storage, snow, soil profile, shallow aquifer and deep aquifer. The soil profile can be subdivided into multiple layers. Soil water processes include infiltration, evaporation, plant uptake, lateral flow and percolation to lower layers. Percolation from the bottom of the soil profile recharges the shallow aquifer. Other shallow aquifer components include evaporation, pumping withdrawals and seepage to the deep aquifer.

SWAT incorporated three methods to calculate the potential evapotranspiration: the Penman-Monteith method, the Priestley-Taylor method and the Hargreaves method. The three methods included in SWAT vary in the amount of required inputs. The Penman-Monteith method requires solar radiation, air temperature, relative humidity and wind speed. The Priestley-Taylor method requires solar radiation, air temperature and relative humidity. The Hargreaves method requires air temperature only.

Once total potential evapotranspiration is determined, actual evaporation must be calculated. SWAT first evaporates any rainfall intercepted by the plant canopy. Next, SWAT calculates the maximum amount of transpiration and the maximum amount of soil evaporation. The actual amount of evaporation from the soil is then calculated.

Any free water present in the canopy is readily available for removal by evapotranspiration. SWAT removes as much water as possible from canopy storage when calculating actual evaporation. SWAT allows the maximum amount of water that can be held in canopy storage to vary from day to day as a function of the leaf area index. Once any free water in the canopy has been evaporated, the remaining evaporative water demand is partitioned between the vegetation and soil.

The amount of soil evaporation will be impacted by the degree of shading. The maximum amount of soil evaporation is reduced during periods of high plant water use.

The crop model in SWAT is a simplification of the EPIC crop model. Growth can only occur when the daily mean temperature exceeds a plant–specific base temperature. The temperature excess, counted in 'heat units', is accumulated over the time. The phenological development of the plants is controlled by comparing the actually accumulated heat units to the predefined heat units sum required for maturity of the plant. The leaf area index is simulated as a function of heat units and varies between plant-specific potential minimum and maximum values. SWAT categorizes plants into seven different types: warm season annual legume, cold season annual legume, perennial legume, warm season annual, cold season annual, perennial and trees. The differences between trees and different plant types, as modelled by SWAT, are as follows:

- Root depth always equal to the maximum allowed for the tree species and soil
- Partitions new growth between leaves/needles (30%) and woody growth (70%). At the end of each growing season, biomass in the leaf fraction is converted to residue.

Calculation of root depth varies according to plant type. SWAT assumes perennials and trees have roots down to the maximum rooting depth defined for the soil throughout the growing season. The amount of water uptake that occurs on a given day is a function of the amount of water required by the plant for transpiration and the amount of water available in the soil. As the water content of the soil decreases, the water in the soil is held more and more tightly by the soil particles and it becomes increasingly difficult for the plant to extract water from the soil. To reflect the decrease in the efficiency of the plant in extracting water form dryer soils, the potential water uptake is modified.
Water stress is simulated by comparing the actual and the potential plant transpiration.

Eckhardt *et al*. (2003) simulated land use change effects for different plant species with the following parameters used in SWAT:

Table 10. Parameters used in SWAT (Eckhardt et al., 2003)

Parameter	Coniferous forest	Deciduous forest	Pasture
Maximum leaf area index	4.5-14.5	5.0-12.0	1.5-9.0
Minimum leaf area index	2.5-9.5	1.0-2.0	1.0-2.0
Maximum interception capacity (mm)	2.5-6.5	2.5-4.5	1.0-3.0
Maximum stomatal conductance (mm/s)	0.5-4.0	1.0-3.0	2.0-10.0
Maximum plant height (m)	18.0-32.0	16.0-30.0	0.4-1.5
Maximum rooting depth (m)	1.5-2.5	1.5-1.8	0.7-0.9
Albedo	0.10-0.13	0.19-0.26	0.20-0.28

5.10 FutureView

The FutureView method is completely based on the SWAP (Soil, Water, Atmosphere and Plant) model with an active connection to a database. FutureView makes use of hydrological response units, which are defined as homogeneous areas with respect to their hydrological properties like target water level, freeboard, soil, drainage resistances etc. Each hydrological response unit is one SWAP column. With the FutureView method it is possible to get a better insight in the spatial distribution of different hydrological processes. An outline of the different steps in FutureView can be seen in Figure 1.

SWAP simulates transport of water, solutes and heat in unsaturated and saturated top soils. Transport processes at field scale level and during whole growing seasons are considered. System boundaries at the top are defined by the soil surface with or without a crop and the atmospheric conditions. The lateral boundary simulates the interaction with surface water systems. The bottom boundary is located in the unsaturated zone or in the upper part of the groundwater and describes the interaction with regional groundwater. The first version of SWAP is developed by Feddes *et al.* (1979) and since then various improvements are incorporated. The theory of the processes simulated by SWAP is extensively described by Van Dam (2003).

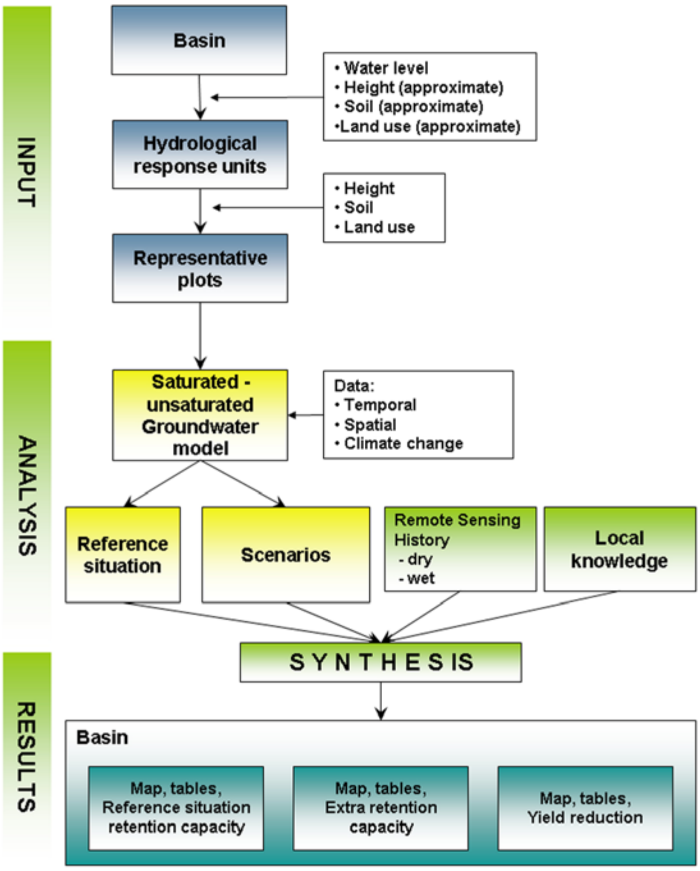

Figure 1. Outline of FutureView.

Crop growth can be simulated by the code WOFOST 6.0 (Hijmans et al., 1994). The cropping pattern may consist of maximal three crops per agricultural year.

WOFOST calculates the radiation energy absorbed by the canopy as function of incoming radiation and crop leaf area. Using the absorbed radiation and taking into account photosynthetic leaf characteristics, the potential gross photosynthesis is calculated. The latter is reduced due to water and/or salinity stress, as quantified by the relative transpiration, and yields the actual gross photosynthesis. Part of the carbohydrates (CH_2O) produced are used to provide energy for the maintenance of the existing live biomass (maintenance respiration). The remaining carbohydrates are converted into structural matter. In this conversion, some of the weight is lost as growth respiration. The dry matter produced is partitioned among roots, leaves, stems and storage organs, using partitioning factors that are a function of the crop phenological development stage. The fraction partitioned to the leaves, determines leaf area development and hence the dynamics of light interception. The dry weights of the plant organs are obtained by integrating their growth rates over time. During the development of the crop, part of living biomass dies due to senescence.

If simulation of crop growth is not needed, the user might just prescribe leaf area index, crop height, rooting depth, and root density distribution as a function of development stage.

To gain insight in the sensitivity of the results of the model SWAP to changes on some of its input parameters, a global sensitivity analysis was performed with this model by Wesseling and Kroes (1998). Generation of parameter values and the analysis were carried out with the statistical package Usage (Jansen and Withagen, 1997) for different crop-soil combinations. The analysis was carried out with a range of meteorological years, which included average and extreme meteorological data. Input parameters were selected that are associated with a number of processes in the SWAP-model: soil physics, evapotranspiration, drainage, regional hydrology. For each input-parameter a distribution type, its average, variance, minimum and maximum value were selected using existing databases and expert-judgement. The analysis focussed on results as cumulative terms of the water balance and groundwater level. Some conclusions drawn from this analysis are:

- Boundary conditions (both upper and lower) are of crucial importance when applying the model SWAP.
- For all soil-crop combinations the soil and crop evaporation were strongly depending on the function describing the Leaf Area Index (LAI).
- Drainage, simulated as lateral discharge, is very sensitive to the surface water levels.
- High groundwater levels are strongly related to surface water levels; low groundwater levels depend on a combination of LAI, soil physical parameters and surface water levels; the average groundwater level is mainly determined by the level in the primary drainage system.
- At low values for the saturated hydraulic conductivity the model SWAP did not succeed in finishing the simulations within one hour cpu-time; this occurred for peat at values below 0.1 cm d-1. and for clay at values below 0.06 cm d-1. At these low values the Richards equation could not be solved within the specified cpu-time.

SWAP is developed for calculations with daily meteorological input data. Exceptions are e.g. studies with surface water runoff, for which the user may provide actual, short time rainfall intensities. In general, model results should be analysed on a daily base. For many cases this will be sufficient; for analyses using more detailed and complete meteorological data other models such as SWAPS (see section 5.3) (Ashby *et al.,* 1996) are recommended.

6 Conclusion/Recommendation

	Models									
Subject	Gap models	FORSPACE*	SWAPS	SWIF	FORHYD	FORGRO	Topog-IRM	Forest extended SWIM	SWAT	FutureView
1D/3D	1D	3D	1D	1D	1D	1D	3D	3D	3D	3D
Soil component	±	+	++	+	++	+	++	++	++	++
Wet stress	-	-	-	-	-	+	-	-	-	
Dry stress	±	+	+	+	+	-	+	+	+	+
Vegetation dynamic/static	dynamic	dynamic	static	static	static	dynamic	static	dynamic	static	static
Available	?	yes	yes	?	?	yes	?	?	yes	yes

- = not included, ± = included in some model, + = included, ++ = detailed included, ? = unknown

[*] = FORSPACE with the optionally water balance module

[Om aan de doelstellingen van het GeoBos project te voldoen kan het best gemodelleerd worden met een 3D model. Het ruimtelijke aspect in FORSPACE is nog onvoldoende getest en zit er maar marginaal in, FORSPACE simuleert met tijdstappen van maanden, die te groot zijn voor deze studie. Het is niet bekend of de modellen Topog-IRM en de forest extended SWIM beschikbaar zijn. De bosmodule van SWIM is te uitgebreid voor de doelstellingen van deze studie. FutureView is een ruimtelijk model, waarbij de boscomponent er niet duidelijk inzit. SWAT is ruimtelijk toepasbaar met de mogelijkheid om bosgebieden te modelleren. Voor de opzet van deze studie kan het best gewerkt worden met SWAT]

[opmerkingen Eddy Moors;

- Eerst 1D model voor de parameteranalyse en daarna een 'eenvoudiger' 3D model. SWAPS kan gebruikt worden. SWAPS gaat uit van vrije drainage, de grondwaterstand zit diep.
- Natschade is een moeilijke component, wortels gaan dood, grote kans op windworp, je kan natschade meenemen als O_2 gebrek, waardoor een reductie is op de verdamping. Er is echter maar weinig bekend over deze reductiefactor
- Nederland weinig gegevens over droogte/natschade
- Modelleren over een langere tijd moet je een aantal aannames doen; blijft alles hetzelfde of treedt vergrassing en open plekken op, neem je competitie mee tussen de verschillende bomen, modelleer je ook de ondergroei. De verdamping van de ondergroei is bij een gesloten bladerdek ongeveer 10% van de totale verdamping, maar op open plekke neemt het percentage toe
- Bij 3D model, welke tijdsperiode, uur of dag? Op uur basis bepaalt de straling, luchtvochtigheid etc de huidmondjes op dagbasis is alleen het bodemvocht beperkend voor de huidmondjes
- Aan de rand van een bos heb je een hogere transpiratie en interceptieverdamping omdat daar de bladeren tot aan de grond kunnen groeien en de wind kan zorgen voor extra verdamping. Op een groot bosgebied is deze hogere verdamping en transpiratie te verwaarlozen ten op zichte van de totale verdamping, maar als het gebied uit kleine bosgebieden bestaat, is deze extra verdamping wel belangrijk.

- Om SWAPS te gebruiken, contact opnemen met Herbert ter Maat
- Voor Simgro is ook een boscomponent ontwikkeld voor de langbroekerwetering, meer info bij Ab Veldhuizen]

7 Literature

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8 Appendix

Additional information about SWAPS

General order of calculations

For a given meteorological (‘meteo’) time step, forcing data are used to determine the heat fluxes. First, latent, sensible and (if necessary) soil heat fluxes are calculated using soil and/or vegetation surface resistance which depend on the forcing data, and the latest known soil moisture status. If there is stored water on a layer (interception or ponding) the surface resistance of that layer is set to zero and the fluxes are calculated for wet conditions. These calculations are performed by the MicroMet module. The Soil module performs soil moisture calculations at a time step which may be less than the meteo time step. The transpiration and/or soil evaporation calculated by MicroMet is then used in the soil moisture calculations, where the flux rates are assumed to be constant for all soil time steps within a given meteo time step. However, in order to maintain a closed water balance in the soil, the transpiration and/or soil evaporation may be further adjusted for each soil time step within the meteo time step. Finally the latent heat fluxes form the Soil module are integrated over all soil time steps within a given meteo sensible heat fluxes are then calculated by SensHCalc as a residual of the energy balance using the actual latent heat fluxes.

Brief outline of the model components

The model comprises a main program that call various modules with specific tasks. Those modules dealing with calculations other than data processing are summerised as follows:

Timer - time synchronization between Soil and MicroMet modules
Soil - soil moisture calculations including:
    - RootExtr - distribution of root uptake of water and possible adjustment of transpiration
    - ReducEvap - possible adjustment of soil evaporation
SoilTerm - calculation of soil thermal properties
MicroMet - evaporation, transpiration and interception calculations comprising:
    - RSoilCalc - soil surface resistance calculations
    - JarStew - vegetation surface resistance calculations
    - GSoil - soil heat flux calculations
    - Radiation - calculation of the radiative parts of the surface energy balances
    - Storage - calculation thermal energy stored in the canopy
    - Ev1Lay/Ev2Lay - one/two evaporation-interception calculations
SensHCalc - sensible heat calculations and energy balance closure

Timer

The Timer module is used to synchronise Soil and MicroMet calculations because these are not necessarily performed at the same time step.

Soil

The Soil module is based on soil moisture calculations in the SWAP model. Root uptake and soil evaporation calculations are performed respectively by the modules RootExtr and ReducEvap. These modules are not the same as those used in SWAP. The RootExtr module partitions the extraction of water by roots over the soil profile, and if necessary limits root extraction (transpiration) to maintain water balance closure. Similarly the ReducEvap module assigns soil evaporation to a particular depth in the soil profile. The SWAPS version of HeadCalc has additional calculations for assigning the supply of soil evaporation to compartments and possibly restricting it.

SoilTherm

The SoilTherm module calculates soil thermal properties from the soil moisture contents calculated in the Soil module. These properties are necessary to calculate the soil temperatures, and the soil heat flux part of the surface energy balance.

MicroMet

Surface energy balances are formulated for each evaporation-interception layer to obtain the available energy that drives the latent and sensible heat fluxes. The available energy comprises radiative, soil heat flux and possibly stored thermal components calculated in respectively the modules Radiation, GSoil and Storage. The partitioning of the available energy into latent and sensible heat fluxes depends on certain environmental (soil and atmospheric) variables. In particular these variables influence the soil and vegetation surface resistances to evaporation which have a strong influence on energy partitioning. Soil and vegetation surface resistances are calculated in RSoilCalc and JarStew respectively. These resistances are further modified in Ev1lay or Ev2Lay if there is stored water on the evaporation-interception layers. Given the surface resistance and the available energy for each layer SWAPS can calculate the latent and sensible heat fluxes. MicroMet produces transpiration and soil evaporation demand, and interception or ponding evaporation. If the transpiration demand cannot be supplied by the soil moisture the RootExtr module will modify actual transpiration. Similarly if the soil evaporation demand cannot be supplied by the soil moisture the actual soil evaporation will be modified in the ReducEvap and HeadCalc modules. Note that the RootExtrm ReducEvap and HeadCalc modules form part of the Soil module which may not run at the same time step as the MicroMet module.

SensHCalc

This module calculates sensible heat fluxes as a residual of the energy balance of each layer using the actual latent heat fluxes. This ensures that both the energy and water balances are closed. The total sensible heat flux is required to determine atmospheric stability for latent heat flux calculations. If the actual latent heat fluxes have been adjusted compared to the demand or the maximum, then the total sensible heat flux produces by SensHCalc will be different.