JOURNAL OF
ENVIRONMENTAL HYDROLOGY
The Electronic Journal of the International Association for Environmental Hydrology
On the World Wide Web at http://www.hydroweb.com
VOLUME 11 2004

A MODEL FOR SITE SPECIFIC ESTIMATION OF THE AVAILABLE SOIL WATER CONTENT AND THE EVAPOTRANSPIRATION IN FOREST ECOSYSTEMS

Thomas Rötzer[1]
Christoph Dittmar[2]
Wolfram Elling[2]

[1] Department of Ecosystem and Landscape Management, ChairForest Yield Science, Technical University of Munich, Germany
[2] Department of Forest Science and Forestry, Weihenstephan University of Applied Sciences, Germany

A vertical water balance model is presented which calculates a set of different water balance parameters (evapotranspiration, interception, runoff and soil water content) for various land covers and in particular for forest stands as daily values. The model is suitable for site specific calculations as well as for regional and large scale estimation. Climatic input data are readily available from weather services. Texture and structure of soils and rooting depth are assessed from soil profiles, while standardized crop and forest stand information characterize the land cover. The HyMo model was validated with continuously measured soil water content data, as well as with lysimeter data over several years in different forest stands and for different crops. Other validations were done with measured runoff data for two catchment areas. A good agreement between simulated and measured data with deviations that are all smaller than 10% gives evidence for its suitability. Results of water balance calculations for beech and spruce stands in Southern Germany are presented. Additionally, examples show that HyMo is a powerful tool for dendroecological analyses because the retrospective estimation of different water balance parameters is possible.

INTRODUCTION

Stomatal conductance and the water balance of a plant are mainly controlled by weather conditions and the water status of the soil. They exert a strong influence on the growth and development of a plant. Consequently the water balance plays an important role in modeling the growth of forest stands (Bossel,1996, Grote and Pretzsch, 2002), the growth and yield of crops (Ritchie and Otter, 1985, Moulin and Beckie, 1993, Porter, 1993) or the influence of stress factors (Emberson et al., 2000).

The spatial as well as the annual and inter-annual variability of the single water balance parameters can be very great (Rötzer et al., 1997). Hence, an exact estimation of the weather conditions and the water status of a site with its temporal variations is necessary.

Climate data can be acquired by local measurements or from weather services. Measurements of the water balance of specific sites and their temporal variations, however, are difficult and expensive to obtain. Many efforts have been made to estimate water balance parameters using empirical data and model assumptions (Ernstberger, 1987, Running and Coughlan, 1988, Federer, 1992, Golf et al., 1993, Mirschel et al., 1994, Braden ,1995, Menzel, 1997, van Wijk et al., 2001).

The one-dimensional water balance model, HyMo, which calculates daily values of the water balance, was modified for forest ecosystems by taking the investigations of Elling et al., (1990) into account. HyMo can be run with data available from weather services and with a simple characterization of the soil and stand properties. This study presents a description of the model, its validation, and some results and examples of its application in dendroecological investigations.

MODEL DESCRIPTION

The HyMo model computes the water balance for different crops and forest stands, sealed surfaces, water and other land covers continuously as daily values for a given period (Rötzer, 1996, Rötzer et al., 1997). Model input values include climate data and geographical data, as well as soil and stand characteristics (Figure 1).

The required meteorological data, including temperature, precipitation, radiation or sunshine duration, wind speed and humidity, are recorded at almost every climate station. Latitude, longitude,

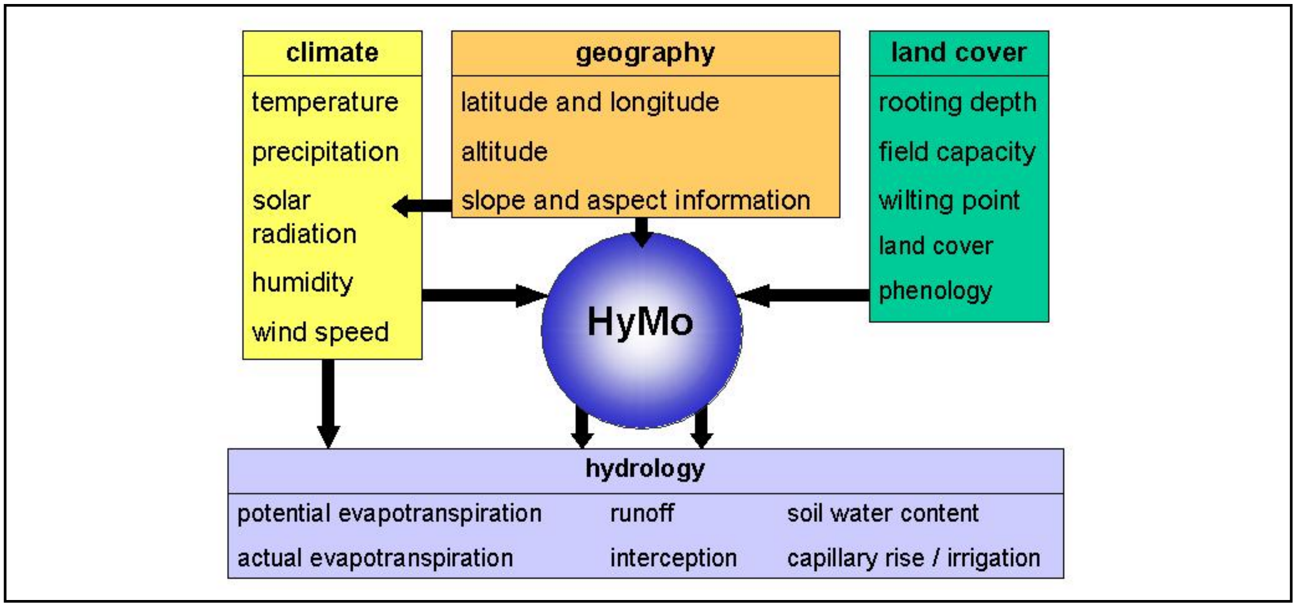

Figure 1. Schematic presentation of the water balance model, HyMo.

and the altitude of the site have to be known, and slope and aspect information are optional input parameters. In terms of land cover information, only the kind of land cover such as crop species (e.g. maize, wheat, barley, potatoes, grass) or standardized forest stands (mature and closed stands of beech and spruce), the timing of the phenological phases, and the rooting depth have to be known.

A simple soil module with one layer is defined by the field capacity, the wilting point and the rooting depth. For forest stands, field capacity and wilting point can be replaced by the maximum available soil water content until rooting depth, which is estimated according to the structure and texture of the soil (Arbeitskreis Standortskartierung, 2003). Using the depth of phreatic water and its distance to the rooting depth, daily capillary rise can be estimated based on the actual soil water content according to the procedures used by Giesel et al. (1972).

A snow module takes snowfall and melting of snow into account by using a degree-day-factor which calculates the daily amount of melting water (Baumgartner and Liebscher, 1990). Basically, the time lag of the precipitation falling as snow and melting at a later time has to be simulated.

At high altitude sites in mountainous areas the throughfall precipitation sums are distinctly higher than the free precipitation sums (Grunow, 1955, Baumgartner, 1958). Therefore, a fog module that considers fog precipitation is used to simulate throughfall precipitation at high altitude sites (Elling et al., 2001).

By estimating the actual evapotranspiration, the interception, the runoff and, optionally, the capillary rise and the irrigation, the daily change of the soil water content can be calculated:

$$\Delta\Psi = rr - et_a - int - ro - cr + irr \tag{1}$$

with:

$\Delta\Psi$: change in soil water content in mm d^{-1}

rr : precipitation in mm d^{-1}

et_a: actual evapotranspiration in mm d^{-1}

ro: total runoff in mm d^{-1}

int: interception in mm d^{-1}

cr :capillary rise in mm d^{-1}

irr: irrigation in mm d^{-1}

The basis of the evapotranspiration calculation , et_p ,is the Penman equation (Penman, 1948), which includes not only a temperature-humidity term and a ventilation term, but also a radiation term. The energy available for the evapotranspiration as well as the transition of water into the atmosphere can be described as (DVWK, 1996):

$$et_p = \left(s/(s+\gamma)\right)\cdot\left(r_s - r_l\right)/\mathrm{L} + \left(1 - s/(s+\gamma)\right)\cdot e_s \cdot f\left(V_{u\cdot}\right) \tag{2}$$

with:

et_p: potential evapotranspiration in mm d^{-1}

γ: psychrometric constant in hPa K^{-1}

s: slope of the saturation vapor pressure curve in hPa K^{-1}

r_s: short wave radiation balance in W m^{-2}

r_l: long wave radiation balance in W m^{-2}

L: specific evaporation heat in W m^{-2} mm^{-1} d

e_s: saturation deficit in hPa

$f(v_u)$: ventilation function with v_u being the daily wind speed in m s^{-1}

The variable, et_p ,is the potential evapotranspiration of water or of a well watered grassland. To calculate the potential evapotranspiration of a plant, et_p[P], the species and time specific factors that Ernstberger published in 1987 were used:

$$\mathrm{e}t_p[\mathrm{P}] = f_p[\mathrm{t}] \cdot et_p \quad (3)$$

with:

f_p[t]: plant specific factor depending on time t (=day of the year)

et_p[P]: potential evapotranspiration of the plant in mm d^{-1}

Ernstberger's plant specific factors have been adjusted to the developmental stages of the plant in the course of the year (Rötzer, 1996). Figure 2 shows the mean annual course of f_p for beech compared to the static original factors of Ernstberger (1987).

If the annual timings of the phenological phases are unknown, long term means can be used. For the spring phenophases of forest stands the annual beginning of leafing is estimated using a temperature sum model (Rötzer et al., 2004).

The actual evapotranspiration et_a can be derived from the potential evapotranspiration et_p[P] as follows:

$$et_a = r_w \cdot et_p[\mathrm{P}] \quad (4)$$

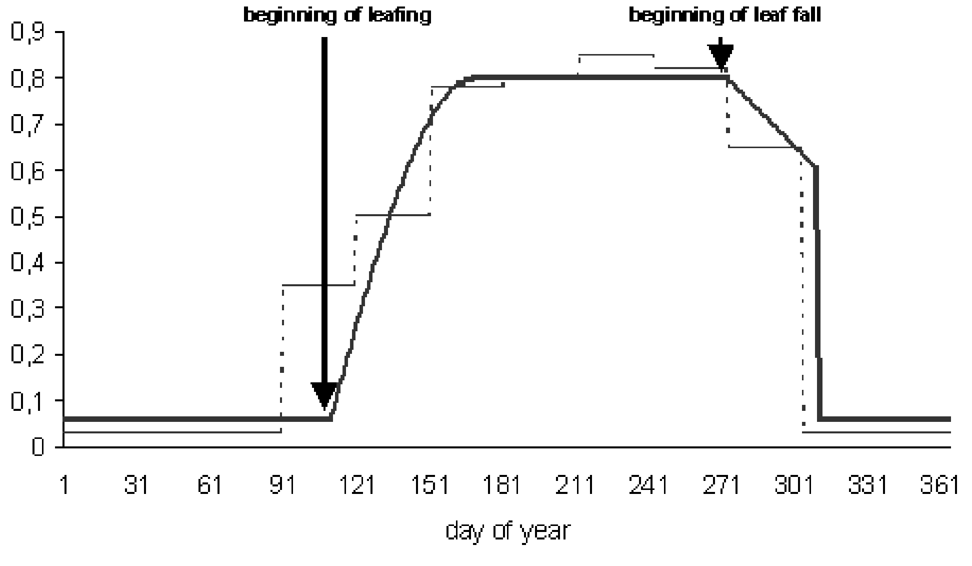

Figure 2. Mean annual course of fp (bold line) for beech compared to the static original factors of Ernstberger (1987, dotted line).

with:

r_w: reduction factor

For crops**,** the actual evapotranspiration, et_a ,is calculated by considering the actual soil water content and the critical leaf water potential as described by Slabbers (1980):

$$r_w = \Psi_{a\%} / \left(\mathrm{a} - \mathrm{b} \cdot \Phi_k / et_p(\mathrm{P})\right) \tag{5}$$

with:

$\Psi_{a\%}$: actual soil water content in vol%

a, b: conversion factors (a=94, b=26)

Φ_k : critical leaf water potential in hPa

According to Equation (4) the actual evapotranspiration of forest stands is calculated by taking the actual and the maximum available soil water content into account and using species specific functions (Elling et al., 1990):

$$r_w = e^{f(w)} / (1 + e^{f(w)}) \tag{6}$$

with:

$f(w)$ species specific function $f(w) = \mathrm{a} + \mathrm{b}{*}w + \mathrm{c}{*}w^2 + \mathrm{d}{*}w^3$

a,b,c,d: species specific constants

w: actual / maximum soil water ratio $\Psi_a / \Psi_{\max}$

If the ratio $\Psi_a / \Psi_{\max}$ is equal or greater than 1, r_w is set as 1, which means that the actual evapotranspiration is equal to the potential evapotranspiration.

While the interception of crops is estimated roughly, the daily interception sums of forest stands have to be specified exactly. By functions depending on time and species (Elling et al., 1990)**,** the daily interception amount of a forest stand is calculated on the basis of the precipitation:

$$int = f_t \cdot (f_{s1} \cdot rr + f_{s2} \cdot \ln(rr+1)) \tag{7}$$

with:

f_t: time dependent factor

f_{s1}, f_{s2}: species specific factors

Runoff occurs if the actual soil water content exceeds the maximum available soil water content (for forest stands) or the field capacity (for crops):

$$ro = \Psi_a / \Psi_{\max} \quad \text{if} \quad \Psi_a > \Psi_{\max} \tag{8}$$

with:

Ψ_a : actual soil water content in mm

$\Psi_{\max}$: maximum available soil water content or field capacity in mm

Moreover, for hydromorphic soil types, runoff can be calculated with a delayed drain off (Dittmar and Kölling, 2002). Concurrently, a fast surface runoff can be simulated for crops in the case of heavy rain (Rötzer, 1996).

After the determination of the actual evapotranspiration and the interception as well as the estimation of the runoff and, optionally, capillary rise and irrigation, the change of the soil water content is computed by using the water balance, Equation (1). Because the annual development of a crop or a forest stand is simulated by including the annual timings of the phenological phases, all plant specific parameters such as the albedo in Equation (1), the factor f_p[t] in Equation (3), or the interception factors f_{s1}, f_{s2} in Equation (7) are calculated as depending on the developmental stages of the plant.

Since the short wave radiation balance depends to a great extent on the slope of a site, r_s the evapotranspiration can be determined by taking slope and aspect information into account (Rötzer and Würländer, 1996)

$$r_{s,\text{slope}} = cf(t,\alpha,\varphi)\cdot r_s \tag{9}$$

with:

$cf(t,\alpha,\varphi)$: correction factor depending on t=time, α = aspect information and φ = slope.

Using hourly cloudiness, atmospheric pressure and visibility data of approximately 120 South German climate stations, the time dependent factors $cf(t,\alpha,\varphi)$ have been derived to calculate the actual short wave radiation for a slope on the basis of the value for a plane surface (Rötzer, 1996).

MODEL VALIDATION

In 1996, initial model validation for crops at the Freising site (Southern Germany) showed differences between measured and simulated soil water contents of 7.3% for winter wheat (6 test years), of 8.2% for grass (4 test years) and of 8.3% for maize (6 test years), based on the field capacity of the different soils (Rötzer, 1996).

Another model validation compared measured and modeled runoff sums for two different catchment areas in the southeast of Germany (Würländer, 1997). According to the land cover (agriculture with regional crop rotation, grassland, coniferous, deciduous or mixed forest, sealed surface, water, etc.) for every pixel of a 400 m raster, the water balance was estimated with the HyMo model and summed over the catchment area. While the modeled runoff values for the catchment area of the Regen River showed a deviation of –7.7% from the measured values, the deviation of the values for the catchment area of the Naab River was +5.9%.

Validation of the model in a warm and dry region (northwest of Bavaria) with high et_p-sums and low et_a-sums showed deviations from the measured soil water content between 6% and 9% (basis: field capacity), depending on site, soil and crop (Rötzer, 2001).

Kremb et al. 2000 compared the runoff sums of different water balance models with the measurements of a lysimeter. The mean difference between measured and simulated runoff sums was 4.5% for HyMo.

To test the model output of HyMo for forest stands, the measurements of the soil water content under beech (1994-1997) and spruce (1994-1996) in the forest stand “Höglwald”, northwest of

Munich, were used (Kreutzer and Weiss 1998). For all years a good agreement between measured and modeled soil water contents was found. Averaged over the years 1994-1997 for beech and 1994-1996 for spruce, the deviation of the modeled and measured soil water is 12 mm for both beech and spruce at the "Höglwald" site. On the basis of the maximum available soil water content**,** the deviation of simulated values from the measured ones averages 2.8% for spruce and 4.0% for beech (Table 1).

As an example, Figure 3 shows the measured and modeled soil water contents under spruce for the year 1995 while Figure 4 shows the same parameters under beech for the year 1997. Even throughfall precipitation can be simulated very well by the HyMo model as illustrated in Figure 5, where the measured and simulated values for the period January 1994 to July 1996 are shown.

Table 1. Mean absolute error (MAE) of the simulated and the measured soil water contents under a spruce and a beech stand at the "Höglwald" site for the years 1994-1997 (beech) compared to 1994-1996 (spruce)

forest stand	beech	spruce
MAE in mm	12	12
in % of field capacity	4.0	2.8

SIMULATION OF THE WATER BALANCE AT DIFFERENT FOREST STANDS

Figure 6 shows the annual courses of the water balance parameters for a beech stand at the site "DBKS" in Southern Germany (for the geography of the site see Table 2). The daily values of the precipitation, the potential and actual evapotranspiration, the interception, the runoff, and the soil water content are averaged over the years 1936 to 1997.

After starting at the end of May, the difference between the actual and the potential evapotranspiration increases from day to day. Correspondingly, the soil water content decreases from 270 mm (i.e. field capacity) at the beginning of May to 170 mm in mid September. Until leaf fall in autumn**,** the actual evapotranspiration, et_a, does not equal the potential evapotranspiration, et_p. Similarly, the soil water

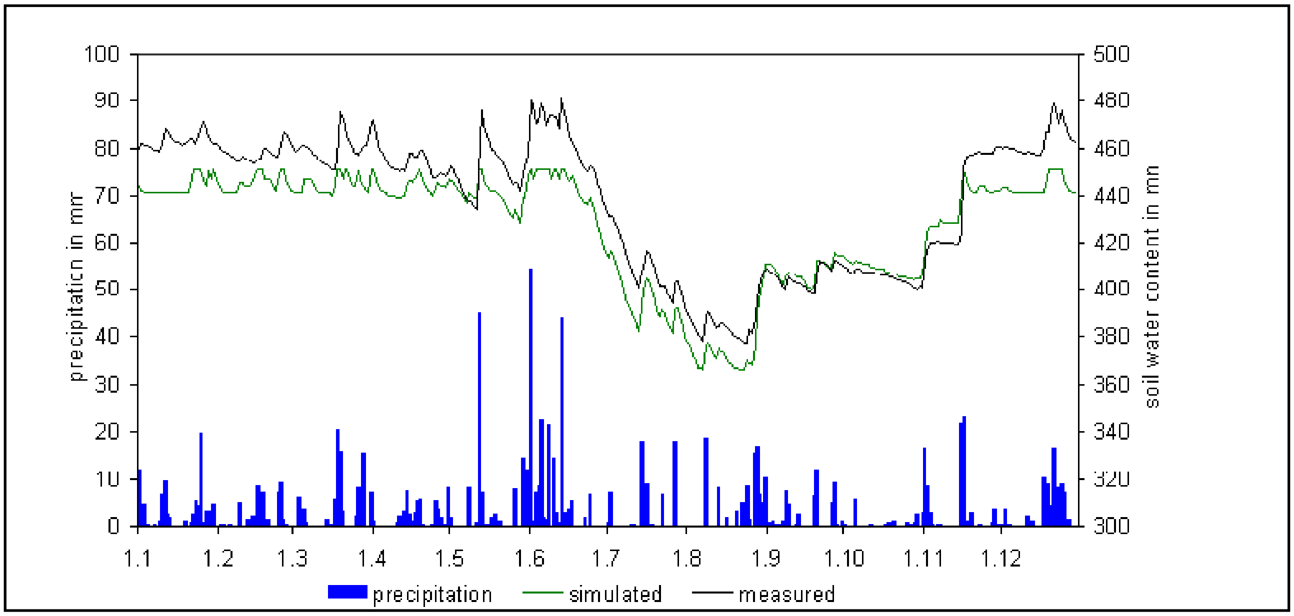

Figure 3. Daily values of the measured and simulated soil water contents (until rooting depth) under a spruce stand at the "Höglwald" site for the year 1995.

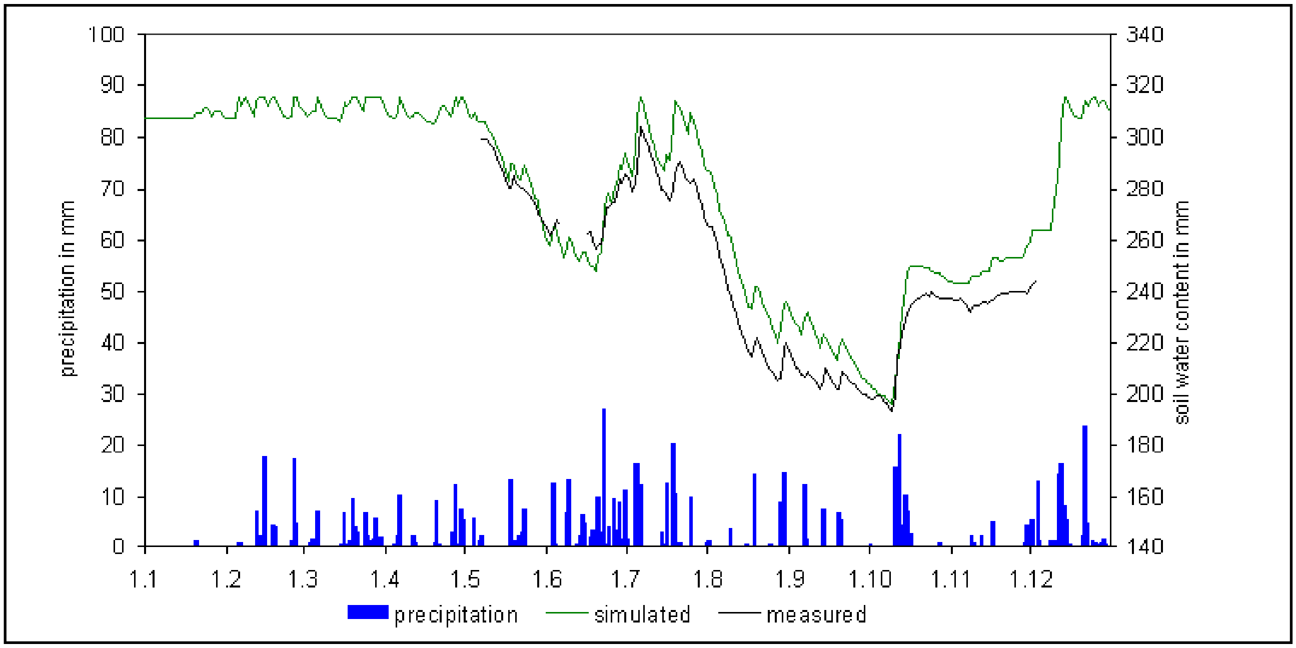

Figure 4. Daily values of the measured and simulated soil water contents (until rooting depth) under a beech stand at the "Höglwald" site for the year 1997.

content does not achieve field capacity until the end of the year. These results confirm former calculations by Rötzer et al. (1997).

The strong dependence of the evapotranspiration on the precipitation sum, particularly in dry regions or in dry years, can also be seen in Table 2. In this table the mean, the maximum and the minimum of the percentage of the evapotranspiration, *et*, which is calculated from the sum of the actual evapotranspiration and the interception, with the precipitation as 100%-basis, is shown. In addition to the geography of the different sites, the mean annual precipitation and evapotranspiration sums are shown. It is obvious that all water balance parameters are dependent on the soil characteristics of the site.

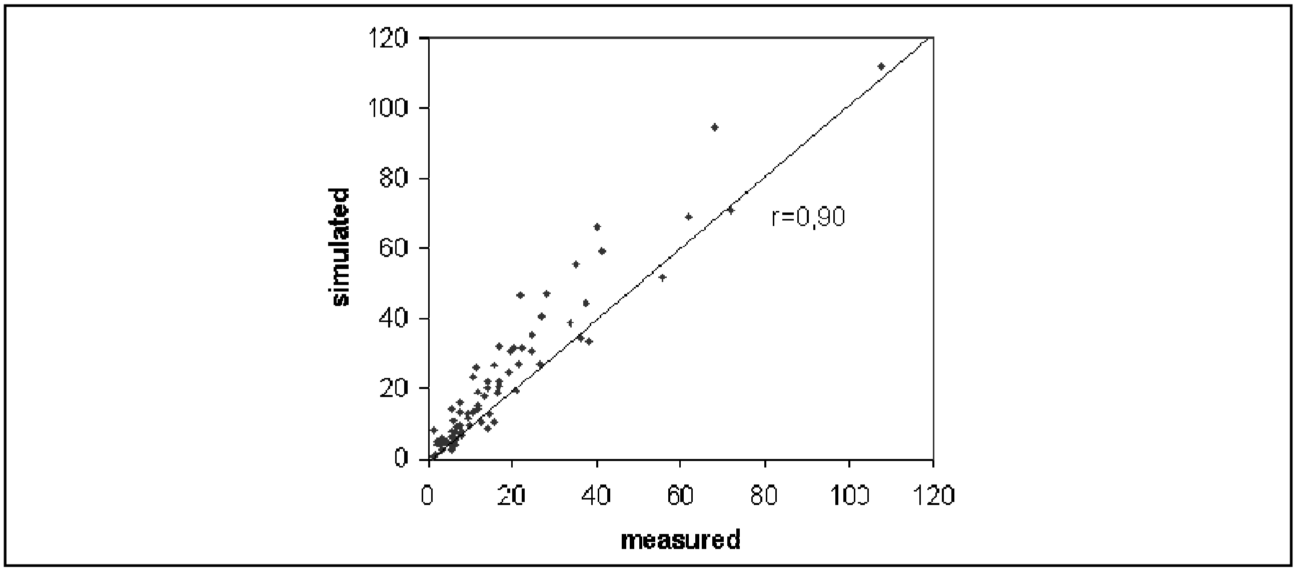

Figure 5. Measured and simulated throughfall precipitation sums under a spruce stand at the "Höglwald" site for the period January 1994 to July 1996.

Table 2. Annual mean temperature *te*, precipitation sum *rr* and total evapotranspiration sum et (=sum of actual evapotranspiration and interception) as well as the percent of et depending on precipitation for different South German sites (*x*: longitude, *y*: latitude, *z*: altitude, α: aspect information with 0°: north and 180°: south, φ: slope, n number of years)

site	**x**	**y**	**z**	**α**	**φ**	**forest**	**n**	**te**	**rr**	**et**	**%et from rr**		
	[°]	**[°]**	**[m]**	**[°]**	**[°]**	**stand**	**[a]**	**[°C]**	**[mm]**		**mean**	**max**	**min**
WZGV	9.9	49.9	295	247	20	beech	50	9.0	647	382	59	78	40
STSB	9.1	50.5	330	90	2	beech	51	8.5	956	438	46	70	35
DBKS	10.6	49.1	480	0	3	beech	58	7.8	699	453	65	97	52
KCGS	11.5	50.3	530	225	24	beech	51	6.7	1049	468	45	74	34
NWGF	13.5	48.9	1190	225	10	beech	53	4.2	1365	421	31	56	21
NWRW	13.4	49.0	1340	225	10	spruce	53	3.5	1395	479	34	56	23

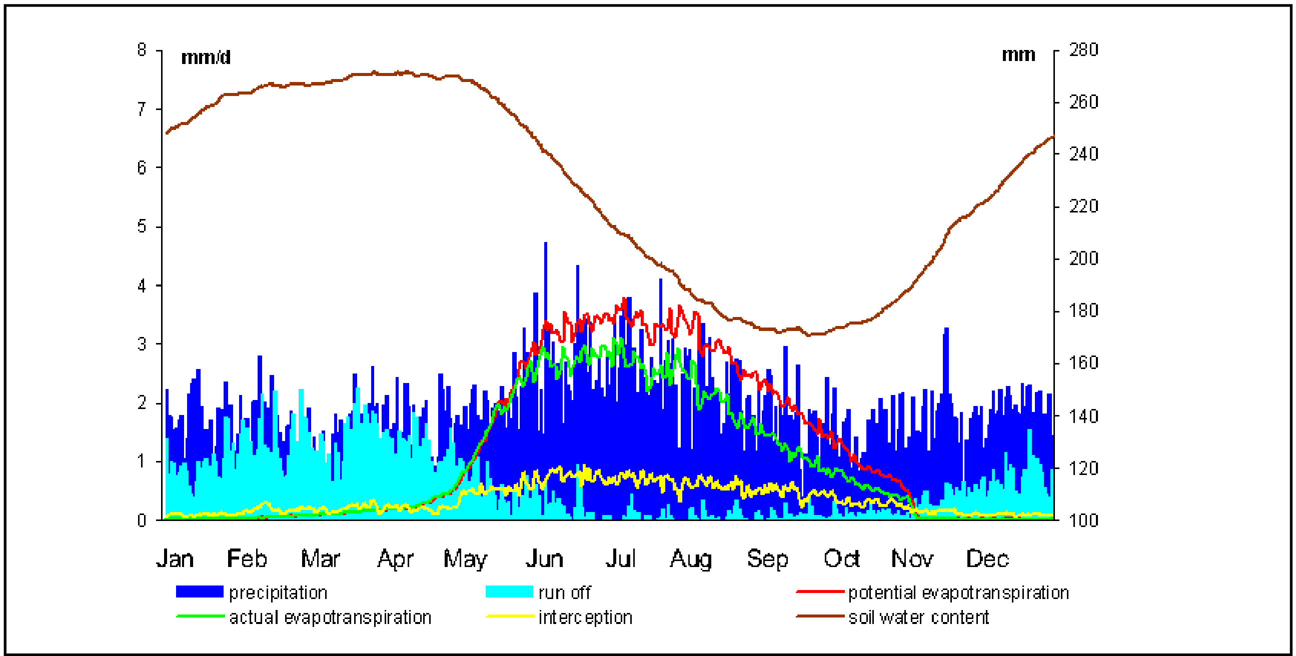

Figure 6. Water balance for a beech stand at the site “DBKS” (geography see Table 2) as daily average of the years 1936 to 1997.

At the site “DBKS”, the percentage ranges from 52% to 97% and averages 65%. These values correspond well with the results of Ladekarl (1998), who calculated the percentage of *et* on the basis of the precipitation at 60% for an oak stand in Denmark. This is somewhat lower than our result for “DBKS” due to a higher precipitation sum of 914 mm at the site in Denmark.

On the other hand the mean percentages of *et* at “KCGS” and “NWGF” - two sites with high precipitation sums - are 45% and 31% respectively, with minimum values of 34% and 21%, and maximum values of 74% and 56%. The dry and warm site “WZGV”, with a mean annual precipitation sum of 647 mm and a mean annual temperature of 9.0 °C shows a mean percentage for the *et* of 59%, whereas at the site “STSB”, which is somewhat cooler (*te*=8.5 °C), but distinctly provided with more precipitation (*rr*=956 mm), the percentage calculates to 46%.

The mean annual percentage values of *et* for a spruce stand at the site “NWRW”, which has a similar climate to “NWGF” (i.e. a low mean temperature and high precipitation), are 34%. One reason for the high evapotranspiration sum of the spruce stand is that - compared to beech stands - spruce stands have higher interception rates. But it also signifies how plant species affect the percentage of et. The highest amount of et_a for a beech stand was calculated for the site “KCGS” with a high mean precipitation sum of 1049 mm and an annual mean temperature of 6.7°C. At this site high precipitation sums are combined with sufficient warmth and radiation supply.

Dittmar and Elling (1999) and Dittmar et al. (2003) found strong site and altitude dependent climate-growth-relationships for spruce and beech. Under dry and warm conditions, which means for Central Europe low altitude sites, radial growth relation to transpiration is frequently restricted by low soil water content. Concurrently, under wet and cool conditions (in Central Europe these are mostly mountainous regions at high altitude sites) low temperature and sunshine duration reduce transpiration, and therefore growth.

WATER BALANCE PARAMETERS FOR DENDROECOLOGICAL INTERPRETATIONS

As the meteorological input data are available from weather service records, HyMo, in combination with site specific information (location, exposition, slope, soil conditions), enables a retrospective estimation of the water balance parameters. Hence, it can be used to improve the analyses and interpretations of growth fluctuations. For illustration two common beech (*Fagus sylvatica* L.) stands with different climatic conditions were selected and their radial growth was compared with the meteorological and hydrological parameters calculated by HyMo. Site 1 is located in the Vogelsberg region (Central Germany, 330 m), while site 2 is situated on the mountain Seeberg near Bayrischzell (Bavarian Alps, Southern Germany) at an altitude of approximately 1190 m. In order to estimate the site specific meteorological data, suitable station data from the German Weather Service were transformed by using regional and time specific factors which describe the dependencies of every meteorological parameter on longitude, latitude and altitude (Rötzer, 2000). Soil characteristics (texture, structure and maximum available soil water content to the rooting depth) were derived from a careful soil profile description (Dittmar and Elling, 2001). Tree-ring measurement and data reduction was done according to Dittmar and Elling (1999).

Because of the low soil water capacity and the low precipitation sums during the summer months**,** tree-ring widths of beech trees at the “Vogelsberg” site (Site 1) are closely related to the soil water content (Figure 7a). In contrast, beech trees growing at the high altitude site in the northern Alps (Site 2) show negative relationships between water supply and radial growth (Dittmar and Elling 1999). Warmth and radiation are the main growth limiting factors at these sites. Accordingly, in most years a close relationship between temperature and global radiation (Figure 7b) and ring widths was found.

Distinct differences are found in the water balances of the two sites during a dry and warm vegetation period in 1976 (Figure 8). As early as May the actual evapotranspiration dropped below the potential at Site 1, after the mid of June even strongly below the long-term average (Figure 8a). Consequently, beech trees at Site 1 show only very small ring widths (for one tree even a missing ring, Figure 7a). At Site 2, however, the values of the actual evapotranspiration for the summer months of 1976 were clearly above the average values (Figure 8b). Only for short periods during July the actual evapotranspiration dropped below the potential evapotranspiration. Because of the favorable weather conditions at this altitude, radial growth of beech at Site 2 was not reduced in 1976 compared to 1975 (Figure 7b). This confirms the observation that the repeatedly observed growth depressions of beech at the end of the 1970s in high altitude sites at the northern border of the Alps cannot be explained by water deficiency (Elling and Dittmar 2003).

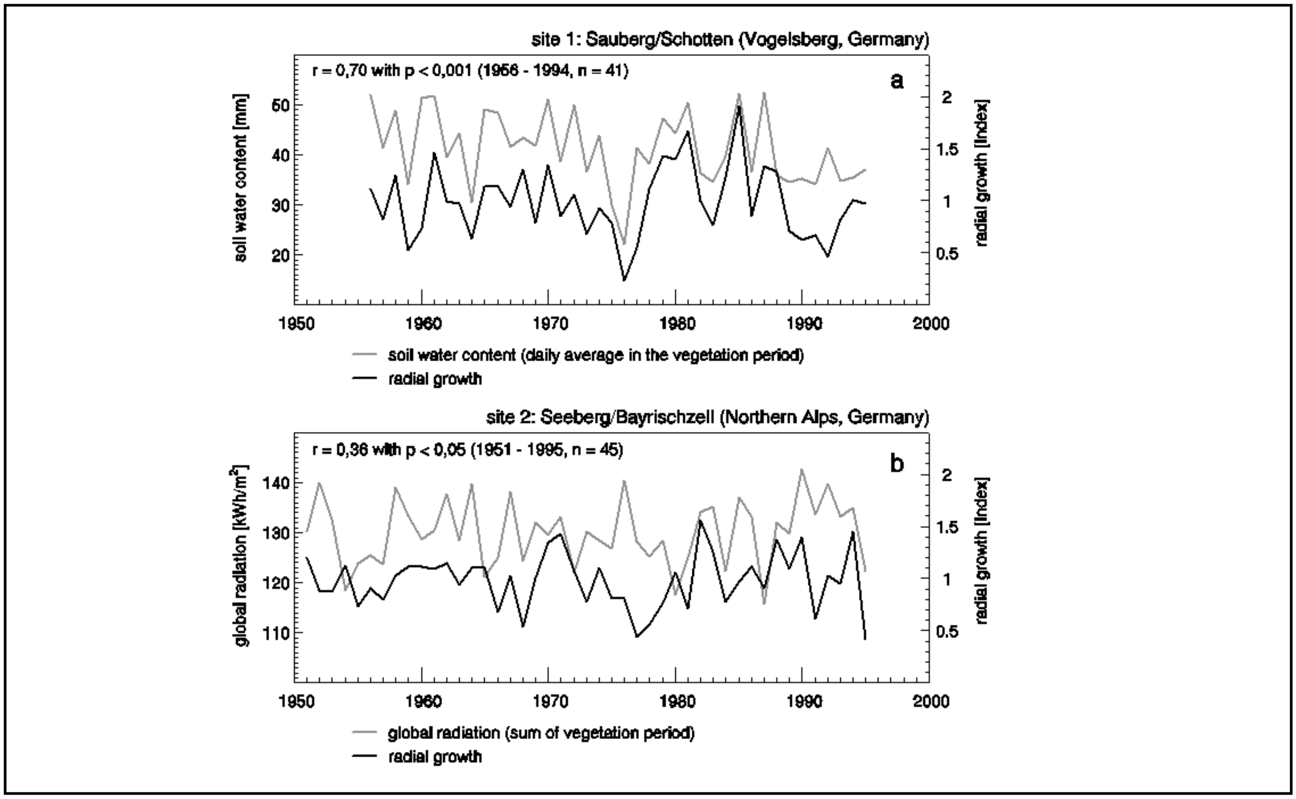

Figure 7 Relations between meteorological and hydrological parameters and the average radial growth of two beech stands.

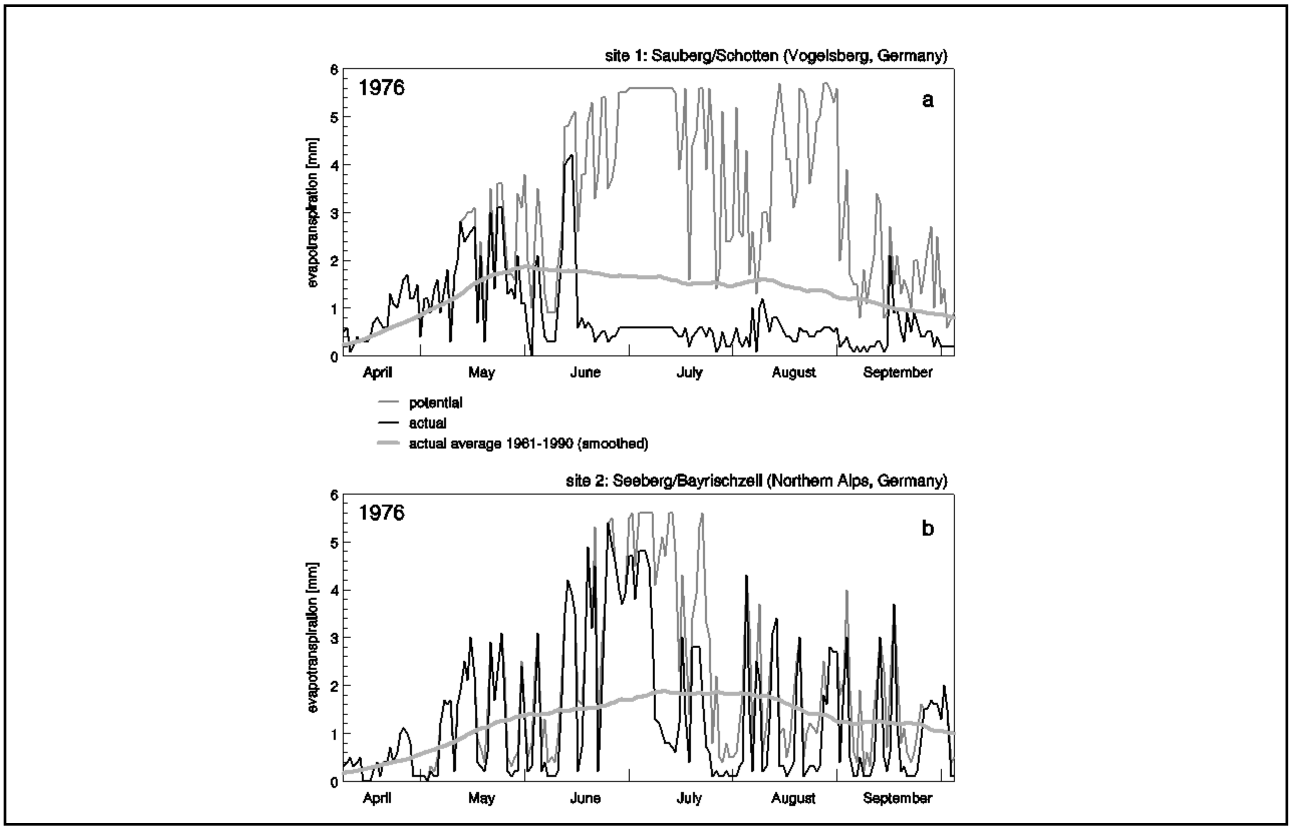

Figure 8. Potential and actual evapotranspiration for the two beech stands during the dry and warm vegetation period 1976 in comparison with the means of the years 1961-1990.

CONCLUSIONS

Compared to other water balance models (e.g. Braden 1995, Gusev and Nasonova 2003) HyMo is a simply structured model with only a few easily available input parameters. If the model validation results are compared with those of other water balance models (e.g. Mirschel et al. 1994, Disse 1997, Ladekarl, 1998, Gusev and Nasova, 2003), HyMo produces satisfactory results. For all validations, the deviations of the simulated values from the measured ones were less than 10%.

While van Wijk et al. (2001) give values for the explained variance of 0.81 for the measured and simulated transpiration, the explained variance for the soil water content obtained by the HyMo model ranges from 0.83 to 0.90 for crops, is 0.87 for the spruce stand, and 0.88 for the beech stand at the "Höglwald" site.

The results of the water balance for different forest sites in Southern Germany offer a wide range of evapotranspiration values (Table 2). The range of these regional and land cover dependent differences can also be found in the Hydrological Atlas of Germany (HAD 2001) when the long term means are compared. In combination with tree-ring data, interactions between water supply and growth can be analyzed. As shown by the examples above, HyMo provides valuable data for dendroecological analyses.

The HyMo model presented in this paper offers a proven and practicable tool to estimate the water balance parameters of various land covers, in particular of forest stands for different time scales. As all required input parameters are available at most climate stations, site specific as well as large-scale calculations are possible. Despite the good validation results the model can still be further improved. For example the deviations between simulated and measured values of the throughfall precipitation are high in some cases (see Figure 5). These differences could be avoided by the inclusion of stand density parameters to improve estimation of interception.

ACKNOWLEDGMENTS

The investigation was funded by the German Ministry for Education and Research (BMBF) and the Bavarian Ministry for Food, Agriculture and Forestry (BayStMELF). The authors thank the Technical University Munich, Chair of Forest nutrition and Water Balance, for providing data of the "Höglwald" sites and the German Weather Service (DWD) for the climate data. We thank Frank M. Chmielewski (Humboldt University Berlin) and B. Schultze (Bavarian State Institute of Forestry) for a critical review of the manuscript.

REFERENCES

Arbeitskreis Standortskartierung; (2003). Forstliche Standortsaufnahme. 6. Auflage, IW-Verlag, München.

Baumgartner, A.; (1958). "Nebel und Nebelniederschlag als Standortfaktoren am Großen Falkenstein, Bayerischer Wald (fog and fog precipitation as site factors at the Großer Falkenstein, Bavarian Forest)". Forstw. Cbl. 77, pp.257-272.

Baumgartner, A. and H.J. Liebscher; (1990). "Lehrbuch der Hydrologie. Band 1: Allgemeine Hydrologie (manual hydrology. Bd.1: general hydrology)". Gebrüder Bornträger, Berlin-Stuttgart.

Bossel, H.; (1996). "TREEDYN 3 forest simulation model". Ecol. Modell. 90, pp.187-227.

Braden, H.; (1995). "The model AMBETI. A detailed description of a soil-plant-atmosphere model". Berichte des Deutschen Wetterdienstes 195, 117pp, Offenbach a.M.

Disse, M.; (1997). "Flächendetaillierte Modellierung der Verdunstung und der Grundwasserneubildung (modeling evapotranspiration and ground water recharge)". Wasser & Boden 49, 43-48.

Dittmar, C. and W. Elling; (1999). "Jahrringbreite von Fichte und Buche in Abhängigkeit von Witterung und Höhenlage (radial growth of Norway spruce and European beech in relation to weather and altitude)". Forstw. Cbl. 118, pp.251-270.

Dittmar, C. and W. Elling; (2001). "Der Einfluß von biotischen und abiotischen Umweltfaktoren auf die Jahrringbreiten der wichtigsten Waldbaumarten (influence of biotic and abiotic environmental factors on the tree-ring growths of the most important forest trees)". Final report of a project funded by the German Ministry of Education and Research, 125 pp.

Dittmar, C., W. Zech and W. Elling; (2003). "Growth variations of Common beech (Fagus sylvatica L.) under different climatic and environmental conditions in Europe – A dendroecological study". Forest Ecology and Management 173 (1-3): 63 - 78.

Dittmar, C. and C. Kölling; (2002). "Verbesserte Wasserhaushaltsansprache von Waldstandorten an ausgewählten Beispielen der Bodenprofildatenbank der LWF (improved characterisation of the water status of forest sites at selected examples of the soil profile data base of the LWF)". Final report of a project funded by the Bavarian Ministry of Nutrition, Agriculture and Forestry, 36 pp.

DVWK (Deutscher Verband für Wasserwirtschaft und Kulturbau); (1996). "Ermittlung der Verdunstung von Land- und Wasserflächen". DVWK-Merkblätter zur Wasserwirtschaft 238, 135 pp.

Elling, W. and C. Dittmar; (2003). "Neuartige Zuwachsdepressionen bei Buchen". Allgemeine Forstzeitung Der Wald 58, 1, pp. 42 – 45.

Elling, W., H. Häckel and G. Ohmayer; (1990). "Schätzung der aktuell nutzbaren Wasserspeicherung (ANWS) des Wurzelraumes von Waldbeständen mit Hilfe eines Simulationsmodells (estimating the actual available water content in the root zone of forest stands using a simulation model)". Forstw. Cbl. 109, pp.210-219.

Elling, W., C. Dittmar, M. Meschederu, K. Pfaffelmoser, H. Pretzsch, T. Rötzer and H. Utschig; (2001). "Prüfung statistischer Zusammenhänge zwischen Zuwachsgang/Schädigungsmerkmalen der Fichte und Witterungseinflüssen sowie der Belaubung durch schwefelhaltige Immissionen und der Bezug zu Standortsfaktoren innerhalb von Bayern (investigation of the influence of the weather and the stress by sulphur immissions on the development of increment/decline symptoms of Norway spruce and the relation to site factors in Bavaria)". Final report of a project funded by the Bavarian State Ministry for Agriculture and Forestry, 110 pp.

Emberson, L.D., M.R. Ashmore, H.M. Cambridge, D. Simpson and J.P. Tuovinen; (2000). "Modeling stomatal ozone flux across Europe". Environ. Poll. 109, pp.403-413.

Ernstberger, H.; (1987). "Einfluss der Landnutzung auf Verdunstung und Wasserbilanz (influence of the land use on evapotranspiration and water balance)". Ph.D. Thesis University of Giessen, Giessen, Germany.

Federer, C.A.; (1992). "Brook90: A simulation model for evapotranspiration, soil water and stream flow". USDA Forest Service, Northeastern Forest Experiment Station, Durham NH, USA.

Giesel, W., M. Renger and O. Strebel; (1972). "Berechnung des kapillaren Aufstiegs aus dem Grundwasser in den Wurzelraum unter sttionären Bedingungen". Z. Pflanzener. Bodenkunde 132, pp.17-29.

Golf, W., K. Luckner and A. Münch; (1993). "Berechnung der Waldverdunstung im Wasserhaushaltsmodell AKWA (calculation of the evapotranspiration of forest stands using the water balance model AKWA)". Meteorol. Z. 2/3, pp.99-107.

Grote, R. and H. Pretzsch; (2002). "A model for individual tree development based on physiological processes". Plant. Biol. 4, pp.167-180.

Grunow, J.; (1955). "Der Niederschlag im Bergwald (precipitation in mountainous forests). Forstw. Cbl. 74, 21-36.

Gusev, Y.M. and O.N. Nasova; (2003). "The simulation of heat and water exchange in the boreal spruce forest by the land-surface model SWAP". J. Hydrology 280, pp.162-191.

HAD; (2001). "Hydrologischer Atlas von Deutschland". Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit, Berlin.

Kremb, S., T. Rötzer and H. Schaupp; (2000). "Berechnung des Sickerwasseranfalls nach verschiedenen Wasserhaushaltsmodellen (water seepages calculated using different water balance models)". Boden & Wasser 52/4, pp.26-30.

Kreutzer, K. and W. Weiss; (1998). "The Höglwald field experiments – aims, concept and basic data". Plant and

Soil 199, pp.1-10.

Ladekarl, U.L.; (1998). “Estimation of the components of soil water balance in a Danish oak stand from measurements of soil moisture using TDR”. For. Ecol. Manage. 104, pp.227-238.

Menzel, L.; (1997). “Modellierung der Evapotranspiration im System Boden-Wasser-Pflanze (modeling of the evapotranspiration in the soil-plant-atmosphere interface)”. Ph.D. Thesis ETH Zurich, Switzerland.

Mirschel, W., K. Wenkel and R. Koitzsch; (1994). “Simulation of Soil Water Evapotranspiration using die model BOWET and data sets from Krummbach und Eisenbach, two research catchments in North Germany”. Ecol. Modell. 81, pp.53-69.

Moulin, A.P. and H.J. Beckie; (1993). “Evaluation of the CERES and EPIC models for predicting spring wheat grain yield over time”. Ca. J. Plant. Sci. 73, pp.713-719.

Penman, H.L.; (1948). “Natural evaporation from open water, bare soil and grass” . Proc. Roy. Met. Soc. A193, pp.120-145.

Porter, J.R.; (1993). “AFRCWHEAT2: A model of the growth and development of wheat incorporating responses to water and nitrogen”. Europ. J. Agronomy 2, pp.69-82

Ritchie, J.T. and S. Otter; (1985). “Description and Performance of CERES-Wheat: a User-oriented Wheat Yield Model”. US Department of Agriculture, ARS, 38, pp.159-175.

Rötzer, T. and R. Würländer; (1996). “A new kind of water balance maps for different crops and soil types with regard to slope and aspect information”. – Proceedings of the 14th Congress of Biometeorology, Ljubljana, Slovenia, Vol. 2, pp.112-120.

Rötzer, T.; (1996). “Neuartige Karten der Phänologie und des Wasserhaushalts von Bayern unter Berücksichtigung möglicher künftiger Klimaverhältnisse (a new kind of phenology and water balance maps of Bavaria in regard to possible future climate change)“. Ph.D. Thesis Technical University München, Freising, Germany.

Rötzer, T., H. Häckel and R. Würländer; (1997). “Der Agrar- und Umweltklimatologische Atlas von Bayern. (The environmental and agroclimatological atlas of Bavaria)”. Deutscher Wetterdienst Weihenstephan, Zolling (CD-ROM).

Rötzer, T.; (2000). “Bestimmung von Transferfunktionen zur Berechnung der Witterung von Waldstandorten (transformation of meteorological data on specific geographical sites)“. Final report on a project of the University of Applied Sciences Weihenstephan, Department of Forests and Forestry, Freising, 55 pp.

Rötzer, T.; (2001). “Berechnung des Wasserhaushalts von 19 Standorten der Bayerischen Landesanstalt für Bodenkultur und Pflanzenbau für definierte Fruchtfolgen und Bodenarten (1980-1996) (calculation of the water balance of 19 sites for defined crop rotations and soil types (1980-1996))“. Final report on a project of the Bavarian State Institute for Agriculture, Freising, 32 pp.

Rötzer, T., R. Grote and H. Pretzsch, (2004). “The timing of bud burst and its effect on tree growth”. Int. J. of Biomet. 48, pp. 109-118.

Running, S.W. and J.C. Coughlan; (1988). “A general model of forest ecosystem processes for regional application. I.: Hydrological balance, canopy gas exchange and primary production processes”. Ecol. Modell. 42, pp.125-154.

Slabbers, P.J.; (1980). “Practical prediction of actual evapotranspiration”. Irr.Sci. 1, pp.185-196.

Van Wijk, M.T., S.C. Dekker, W. Bouten, W. Kohsiek and G.M.J. Mohren; (2001). “Simulation of carbon and water budgets of a Douglas-fir forest”. Forest Ecol. Manage. 145, pp.229-241.

Würländer, R.; (1997). “Validierung der hydrologischen Bilanz in Teileinzugsgebieten des Untersuchungsgebietes Naab-Regen (validation of the hydrological balance for the river catchments Naab-Regen)“. Final report on a project of the Bavarian State Office for Water Management, Munich, 17 pp.

ADDRESS FOR CORRESPONDENCE
Thomas Rötzer
Department of Ecosystem and Landscape Management, Chair of Forest Yield Science
Technical University of Munich
Am Hochanger 13
D-85350 Freising
Germany

E-mail: Thomas.Roetzer@web.de