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Simulation of water drainage of a rain forest and forest conversion plots using a soil water model

R. Klinge, J. Schmidt, H. Fölster*

Institute of Soil Science and Forest Nutrition, University of Göttingen Büsgenweg 2, 37077 Göttingen, Germany

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Abstract

The water budgets were estimated for a rain forest plot and two conversion plots (cut and burn) in a rain forest region of eastern Amazonia, Brazil, using a soil water model (SilVlow) to estimate the drainage and soil water storage compartments. A quantification of drainage was required to determine element leaching associated with conversion. The plots were equipped with fast recording tensiometer fields down to 5 m depth. Soil water tension and meteorological data were recorded at 15 min intervals. Monitoring was maintained for 18 months from July 1992 to December 1993.

The special feature of the model is that soil parameter functions (matric potential/ volumetric moisture content and matric potential/ hydraulic conductivity) are introduced in tabular form, and can be changed deliberately during a fitting procedure adjusting simulated to measured matric potential. This fitting requires a vegetation-free period, which was provided by the conversion plots after clear-cutting the forest. For this fitting procedure, high-resolution recording was essential. Actual evapotranspiration in the soil water model is derived from potential (Penman) evaporation using a matric potential-dependent transpiration reduction function. The adjustment of these parameter functions was performed on plots under vegetation, also by fitting.

The annual rainfall of 2479–2706 mm (depending on time interval chosen), fell short of the long-term average of 3000 mm. The forest intercepted 15% of the rain while total evapotranspiration was about 1350 mm. Drainage decreased from 1484–1733 mm at 110 cm to 1130–1331 mm at 500 cm suggesting a water uptake by roots of 350–400 mm from the depth zone 110–500 cm. On the conversion plots that were planted with eucalypts but regularly weeded, drainage at 500 cm depth amounted to >90% of rainfall. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Water budget; Soil water model; Tropical moist forest; Forest conversion

1. Introduction

Rain forest conversion implies a disturbance of the nutrient cycle, which may result in considerable nutrient loss by burning (Mackensen et al., 2000) and leaching. The assessment of leaching loss from the ecosystem requires the simultaneous quantification of water flows into and out of the original forest (control) and the system after conversion. The approach most commonly applied is that of a water catchment balance (for a critical review see Bruijnzeel, 1990). It has the advantage of an easier methodology but the disadvantage that it cannot differentiate between horizontal variations in site conditions and treatments (experimental plots) within

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* Corresponding author. Fax: +49-551-393310.
E-mail address: hfoelst@gwdg.de (H. Fölster).

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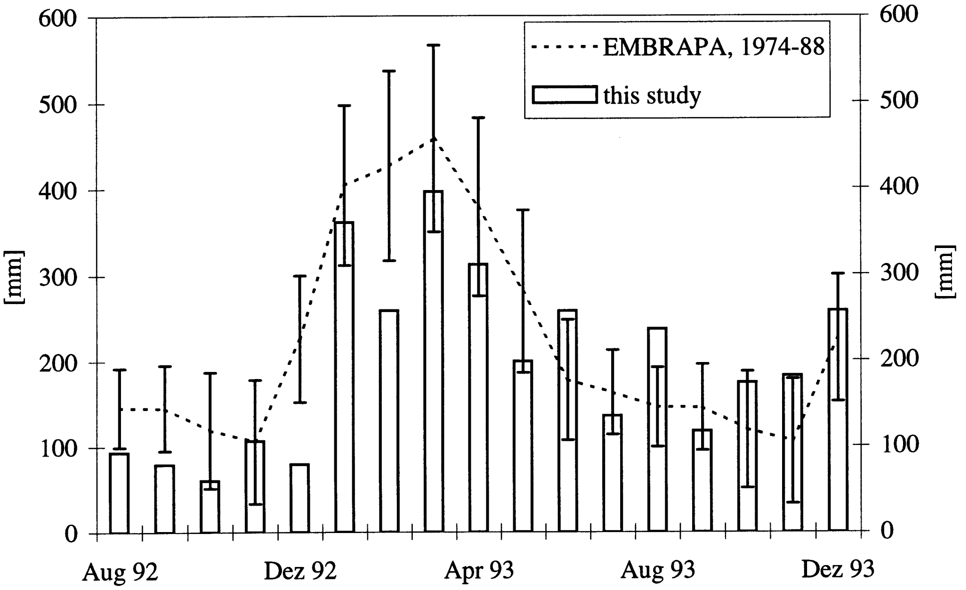

Fig. 1. Average monthly rainfall (and standard deviation) at EMBRAPA weather station compared to monthly rainfall at the experimental site from August 1992 to December 1993.

the same basin, nor between processes in the rooting zone (mineralisation, uptake) and those in the deeper parts of the soil (weathering, exchange) (Bruijnzeel, 1990; Brouwer, 1996; Fölster and Khanna, 1997; Stoorvogel et al., 1997). Because of these handicaps, and because of the physiographic characteristics of our study region — a flat topography without possibility of delineating distinct drainage basins — we used the alternative of a soil water model. Applying a new methodology of fast-recording tensiometer stations (Schmidt et al., 1995), it was possible to achieve a near continuous recording and a considerable improvement of the soil parameter functions relevant under field conditions.

The study was part of a German–Brazilian co-operative research project (SHIFT, Study of Human Impact on Forests and Floodplains in the Tropics) on the sustainability of plantation forestry. Such land-use includes conversion after every rotation. As the envisaged research could not be reconciled with the standard practices of large-scale plantation operations, we simulated the process in a natural forest in which two conversion plots with different residual biomass were established. The field study was carried out between 1992 and 1994 in East Amazonia (Klinge, 1998).

2. Site and methods

2.1. Study site and experimental design

The experimental site was located at the field station of the Federal Cacao Research Institute, 17 km east of Belém-Pará, Brazil. Natural vegetation was a tropical lowland rain forest, partially exploited more than 40 years ago. 542 trees >10 cm DBH, belonging to 162 species, were registered on 750 m^2. With a basal area of 24 m^2 ha^{-1} and an aboveground biomass of 315 t ha^{-1}, this forest falls into the range of Amazonian rain forests (Mackensen et al., 2000). The soil was identified as a deeply weathered Xanthic Ferralsol (FAO-UNESCO-ISRIC, 1990), and according to the Brazilian system as Latossolo amarelo álico, textura media (Vieira and Dos Santos, 1987). An organic surface layer exists but is weakly developed (14 t ha^{-1}).

The average annual precipitation of 3026 mm (in the Centro de Pesquisa Agropecuária no Trópico Úmido of the Empresa Brasileira de Pesquisa Agropecuária EMBRAPA-CPATU) (EMBRAPA, 1988) shows a seasonal pattern with high rainfall from January to April, moderate rains from May to

September, a low rainfall season (October to November), and a transitional December (Fig. 1). Cumulative precipitation during the year 09/92–08/93 was 2479 mm, which is low compared to the long term average because of lower than average precipitation rates from August to December 92 and in February 93 (Table 1). The mean annual temperature is 26.4°C, and the mean relative humidity is 84% (EMBRAPA, 1988).

Three plots of 2500 m^2 each were established. One plot (A1) remained under forest (control) whereas two others (A2 and A3) were clear-cut in September 92. Stem biomass was removed manually with least disturbance. A residual biomass (leaves, twigs, branches < 7 cm diameter and litter) of 33 t ha^{-1} (A2) and 92 t ha^{-1} (A3) remained behind to dry and was burned in November 92. In February 93, three-month-old *Eucalyptus urophylla* seedlings were planted in both plots. The plots were frequently weeded until August 1993 but only once afterwards. By November 1993, the eucalypts reached a height of 2–3 m and a dry biomass of 0.5–0.8 Mg ha^{-1} dry biomass.

2.2. Field and laboratory measurements

Beginning in August 92, the water input by rainfall was measured in the middle of a clear-cut 50×50 m^2 area next to the experimental site, where the vegetation was kept below 50 cm, with 6 repetitions at a height of 1 m. After conversion and tree planting, 6 further collectors were also installed between the converted plots (in total 12 collectors and one automatic rain gauge with pressure membrane and siphon). Other meteorological instruments were installed on a 6 m mast: temperature and humidity by Thermo-Hygro-Sensor (Pt 100), wind speed by 3-cup-anemometer (Thies), and a Pyradiometer (Thies) for separate global and reflected radiation. In the forest control plot, throughfall (38 fixed collectors) and stem flow (12 adjacent trees with 400 m^2 total crown projection) were collected daily. In each plot, 4 tensiometer blocks were installed with tensiometers at 10, 25, 40 (4 each), 95 (3), 145 and 500 (2 each) cm depths. An automatically recording field station (laptop with switchboard) was used to record the meteorological and tensiometer readings every 15 min. Meteorological readings were averaged values, while the tensiometer readings instantaneous. During the burning of the residual biomass, tensiometer readings were interrupted for 24 h only. All measurements continued during the 18-month period.

On each plot, six undisturbed soil samples (8 cm diameter, 5 cm height: 250 cm^3) in each of 5 depth zones, were collected with a soil sampling kit (Eijkelkamp, Netherlands). The soil samples were secured in a tested transport case and transported to the laboratory of the Institute of Soil Science and Forest Nutrition, University of Göttingen, Germany, to measure the relation between volumetric moisture and matric potential (laboratory pF-curve) with a suction membrane (0–300 hPa, Oparanadi, 1979) and a pressure membrane device (1000–16 000 hPa, Richard and Luthin, 1965). The same samples were used afterwards for textural analysis (Moshrefi, 1983). Parallel measurements of the pF-curves in the laboratory of the CPATU provided similar results.

Hydraulic conductivity was not measured in the laboratory as the transfer of the results to the field provides even more problems than in the case of pF curves (Beese and Wierenga, 1979; Rohdenburg and Diekkrüger, 1984; Stolte et al., 1994). Instead we used initial curves, which were computed according to van Genuchten (1980) using assumed values for saturated conductivity K_s.

2.3. The soil water model

The hydrological model SilVlow has been

Table 1
Annual precipitation in the Belem region (EMBRAPA, 1988) and at the experimental site

Site	Period of record	Mean	Maximum	Minimum
Belem	1974–1988	2993	3598	2315
EMBRAPA Belem	1974–1988	3026	3698	2188
DENPASA Sta.Barbara	1974–1988	3326	4637	2383
This paper	09/92–08/93	2479 (annum)		
This paper	01/93–12/93	2706 (annum)		

developed by Blendinger, Schmidt, Hauhs and Lange (Schmidt et al., 1995). The model calculates one- or two-dimensional water flow in porous media under transient saturated and/or unsaturated conditions. The basis of the model is the Richards equation (Ward and Robinson, 1990). Depending on rainfall (infiltration) and evaporation as boundary conditions, the distribution of water potential, soil water contents as well as water flows within and out of a defined flow compartment are calculated. Sinks (mostly root-water-uptake) and springs are defined. The model describes only laminar flow; swelling and shrinking processes of the soil, hysteresis-effects and surface runoff are neglected.

Starting with the initial conditions and depending on the boundary conditions as well as the defined soil hydraulic properties, the water potentials for each time-step at each nodal point, the resulting water flow over the boundaries of the compartments, and the change of the water contents within the compartments, are calculated. Because of the even terrain and the uniform soil, only the one-dimensional vertical flow of water was simulated.

The special feature of the model is that the initial soil parameter functions (volumetric moisture/matric potential (pF) and matric potential/hydraulic conductivity ($K(h)$) are introduced into the model in tabular form and can be modified by a fitting procedure using the matric potential measurements in 15 min intervals at the 6 depths as a control for a backward calculation (Beven, 1993) of pF- and $K(h)$-functions. By stepwise changing the pF-curves and the $K(h)$-curves, the fitting process was repeated until the simulated and measured matric potentials at the different depths showed optimal adjustment. The high-resolution measurement of the pressure heads is a prerequisite for the fitting as it allows to follow the wetting front caused by individual rain events.

This adjustment of the parameter functions requires a time without root water uptake. In temperate climates, the condition is present in winter. In our study, the condition was given in the converted plots A2 and A3 in the time period without live vegetation (Oct. 92–Dec. 92). Before burning, the soil surface was covered by dead organic debris, after burning the soil was exposed.

Actual transpiration could not be measured. Instead we used potential evapotranspiration calculated according to Penman (1948, short grass cover) and applied a matric potential dependent transpiration reduction function (Feddes et al., 1978) separate for forest and the converted plots. The dependency on matric potential and the vertical distribution of root uptake were also obtained by a fitting procedure between measured and simulated pressure heads, which was applied after the adjustment of the soil parameter functions had been achieved.

3. Results

3.1. Soil parameter functions

The soil texture of the three adjoining plots does not differ significantly so that only the average grain size distribution (with standard deviation) is shown as a function of depth (Table 2). Also the initial laboratory pF-curves of the same depth zones showed little and not systematic variation. Therefore, the same pF curves were used for all plots. On the other hand, because of the vertical textural and structural gradient,

Table 2
Mean % and standard deviation ($n = 8$) of grain size fractions (size range in μm) and range of bulk density (g/cm^3)

Depth	Clay <2	Silt 2–20	Silt 20–60	Sand 60–200	Sand 200–600	Sand 600–2 000	Bulk density
0–5	5.4±1.3	3.9±1.3	2.2±0.5	23.3±3.9	59.8±4.4	5.3±1.3	
5–10	11.3±1.1	3.5±0.9	3.9±0.8	27.5±2.7	49.9±3.4	3.8±0.8	1.44–1.56
10–20	15.8±1.0	2.9±0.9	5.0±0.7	27.7±2.0	45.1±2.5	3.5±0.5	1.44–1.58
20–30	18.9±1.2	2.3±0.9	5.6±0.6	27.5±1.6	42.1±1.8	3.5±0.4	1.48–1.58
30–50	20.8±1.3	2.3±1.0	6.0±0.4	27.4±1.6	39.8±1.8	3.8±0.3	1.50–1.57
50–80	23.8±1.4	2.1±1.1	6.2±0.4	26.1±1.4	37.3±1.8	4.5±0.3	1.54–1.63
80–110	24.7±1.4	2.0±1.2	5.9±0.5	25.8±1.5	37.3±1.7	4.4±0.7	1.54–1.63

six parameter functions were used for the whole profile down to 5 m depth. Fig. 2 shows, for three depths, the variability of the measured pF-curves and the respective curves, which finally resulted from the field adjustment and were used in the model throughout. The three curves of the topsoil down to 45 cm differ strongly from those of the subsoil, as total pore capacity in the topsoil reaches 38–41% against 34% in the subsoil. The capacity of large pores (0–50 hPa) is distinctly higher in the topsoil (14%) than in the subsoil (only 4%).

3.2. Soil water inputs and evapotranspiration

In the control A1, the input consists of stem flow and throughfall. Stem flow made up only 0.19% of the rainfall (daily rainfall 0–25 mm: 0.11%, daily rainfall 25–140 mm: 0.21%) and was neglected. Throughfall amounted to about 85% of rainfall with a mean error of 10% following the data given by Lloyd and Marques Filho (1988).

In the conversion plots A2 and A3, precipitation in the open was taken as soil water input. This neglects a certain interception by the organic debris in the first 2 months, and by the planted Eucalypts and weeds in the later part of the recording period (see evaporation below).

Rainfall (A2, A3) or throughfall (A1) is given at the bottom of Figs. 3–5 in mm per 15 min time interval. Daily amounts of water input collected as rainfall or throughfall were allocated to the 15 min recording intervals following the pattern provided by the automatic rainfall recorder. The retardation due to passage through the crown layer was ignored. Throughfall % was calculated for each day.

The soil parameter functions had been adjusted and validated during the vegetation-free period in 1992 on A2 and A3. In the forest control plot, this validated model was applied to develop, again by fitting, the following parameters for the reduction of the (potential) evaporation and the vertical distribution of root uptake:

1. (A1) — an uptake according to potential transpiration on to a matric potential of 700 hPa, with a subsequent linear reduction to 0 at 1200 hPa. The cumulative vertical distribution of uptake was 40% (20 cm), 70% (100 cm), 85% (200 cm), 95% (300 cm), and 100% down to 400 cm.

   On A2 and A3, we assumed zero soil evaporation throughout, and zero transpiration till the 15.5.1993. Till this date, the plots underwent a change: Starting from a debris-covered surface (1), burning produced an exposed soil surface (2) until with planting of the eucalypts, a weak (frequently weeded) plant cover (3) developed. Soil evaporation must have occurred during phase 2, and interception in phase 1 and 3. Their impact was considered small as this period was relatively dry, and had a low frequency of rainfall events. In fact, the 3 phases did not require differential adjustments in the model for optimal agreement between measured and simulated matric potentials. After the 15.5.1993 (see Fig. 5), discrepancies between the two values appeared so that transpiration had to be switched on. The following assumptions of transpiration reduction and distribution of root uptake gave satisfactory agreement between measured and simulated values:
2. (A2 and A3) — an uptake according to potential transpiration on to a matric potential of 300 hPa, and a subsequent linear decline to zero at 600 hPa. The cumulative vertical distribution of uptake was 58% in the 0–20 cm layer, 93% down to 50 cm, and 100% down to 100 cm.

Assuming uniform transpiration reduction and root distribution for the whole period from May to December 1993 is problematic, especially for the period after August 1993 when the ground vegetation gradually developed a denser cover.

3.3. Measured and simulated matric potentials

The readings of the individual tensiometers at corresponding depths in each plot were very close and highly parallel in their time sequences. The readings were not averaged or corrected. During the simulation, two deliberately chosen curves have been used throughout the process while only one curve could be shown in Figs. 3–5 for comparison with the simulated curves.

Fig. 3 shows the measured and simulated matric potential of one of the conversion plots (A3) for 3 depths. We selected a reduced time period of 2 months with moderate intensity and frequency of rainfall events in order to show the degree of fitting between the paired values. As expected, the amplitude

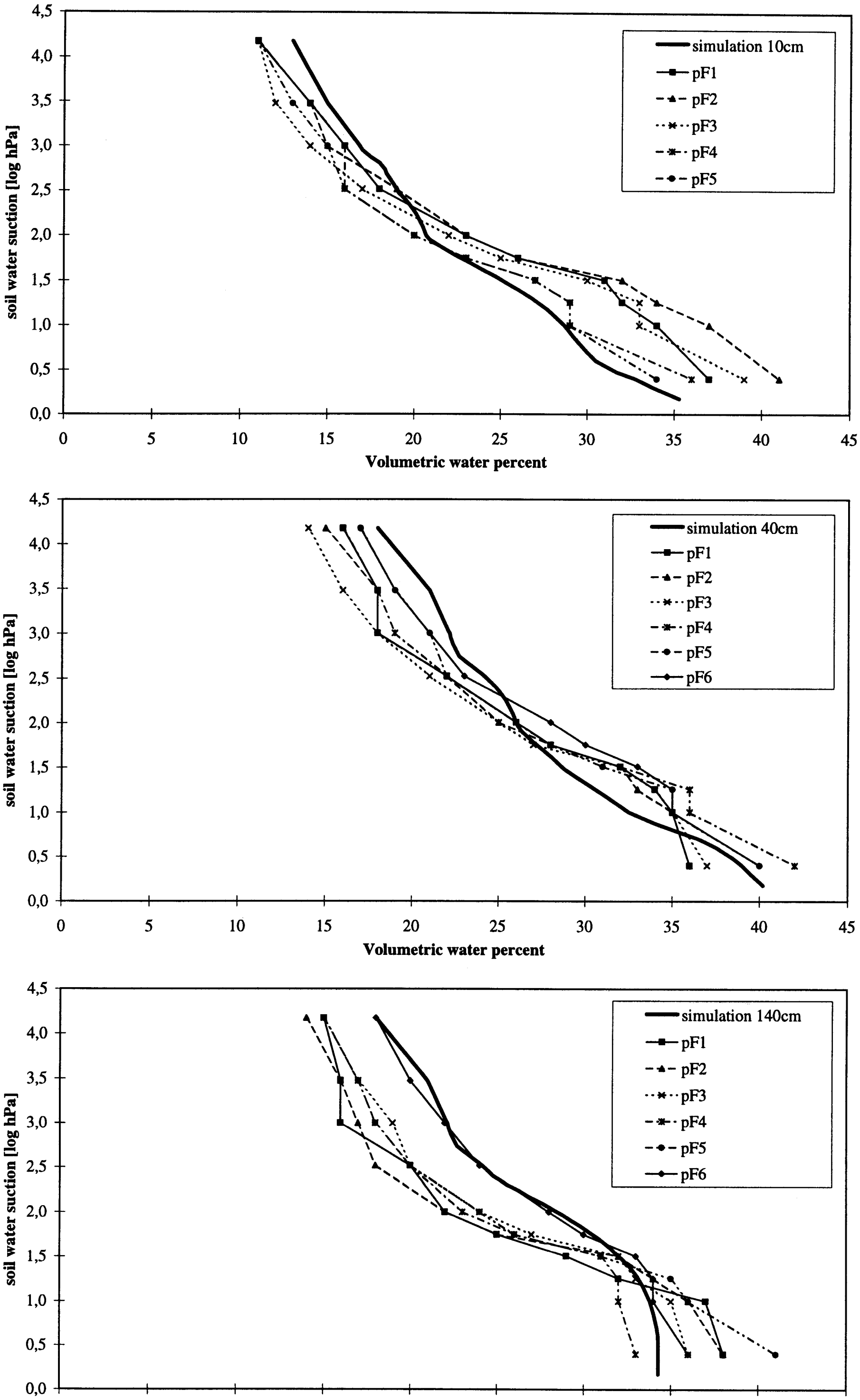

Fig. 2. Laboratory pF-curves (pF 1–5) in three soil depths, and the respective pF-curves used in the simulation.

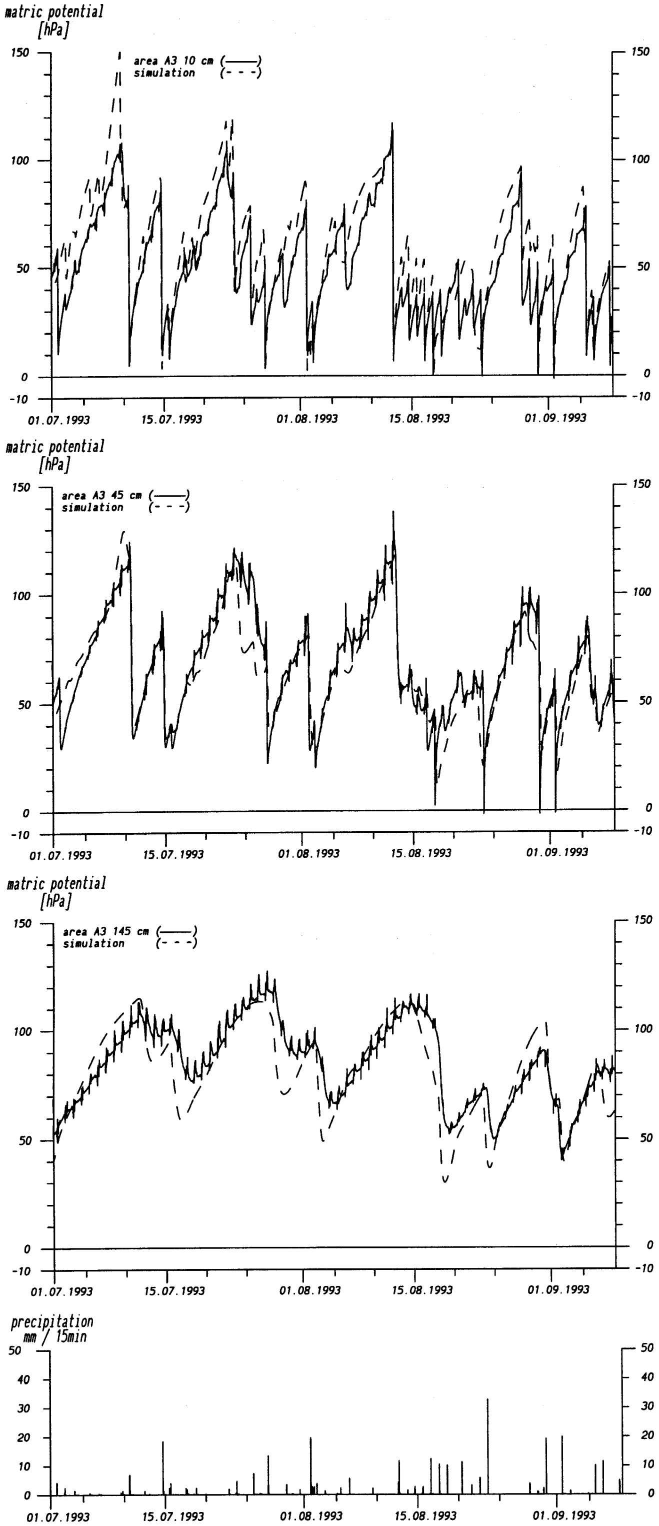

Fig. 3. Measured and simulated matric potential in three depths of conversion plot A3, during 2 months in 1993, and rainfall distribution (mm per 15 min recording intervals).

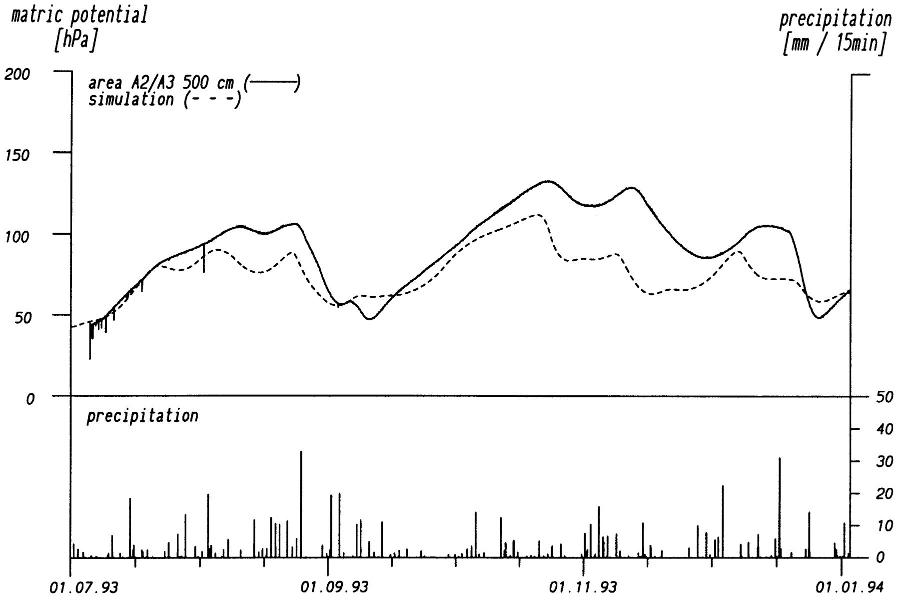

Fig. 4. Measured and simulated matric potential at 500 cm depth of conversion plots A2/A3 during 6 months, and rainfall distribution (mm per 15 min recording interval).

of the matric potential between the drying and the wetting phases is wider in the upper soil (10 and 45 cm) compared to 145 cm. At the latter depth, rainfall events never wetted the soil to values below 50 hPa, and the reactions to events are retarded. This is true even more for 500 cm depth, where the matric potential fluctuates between 50 and 110 hPa (Fig. 4). In general, there is good agreement between measured and simulated curves.

The overall impact of forest on the matric potential is shown in Fig. 5 for the one year recording period after disturbance (Sept.92 until Sept.93) using the measured and simulated matric potential at 10 cm depth of the control (A1). This is compared with corresponding data for one of the conversion plots (A2). The recording period begins with the dry season of 1992. The soil under forest dries up to about 1000 hPa while on the converted plot 220 hPa is the recorded maximum. In the following period of highest rainfall intensity from January to May 1993, the matric potential varies around 50 hPa on both plots. Reduced rainfall during the subsequent and usually less moist part of the rainy season until the middle of September causes the daily maximum to rise to about 150 hPa under forest and to 100 hPa on A2. The following dry season starts with a desiccation peak at the end of September 1993 with 750 hPa under forest and 400 hPa on A2. The differences between the two plots are maintained (not shown) in 25 cm (700 against 170 hpa) and 95 cm (260 and 140 hpa). At 500 cm, the matric potential remains 50 hpa lower in A2 compared to A1 until the increasing rains in December even out this difference.

3.4. Water balance

Because of the very satisfying agreement between measured and simulated matric potentials (Figs. 3–5), the model was used to calculate the water flow passing the lower boundary of the system. Fig. 6 shows the difference of outflow between the control and the converted plots as a function of rainfall distribution. The diagram covers the whole 18-month period (though the A2/A3 curve starts only after clear-cutting). The 3 periods: dry season, the more humid and the less humid part of the rainy season are clearly indicated. The outflow is naturally larger on A2/3, which has no or little vegetation, and it reacts to rainfall events even in the dry season (1992), which is not

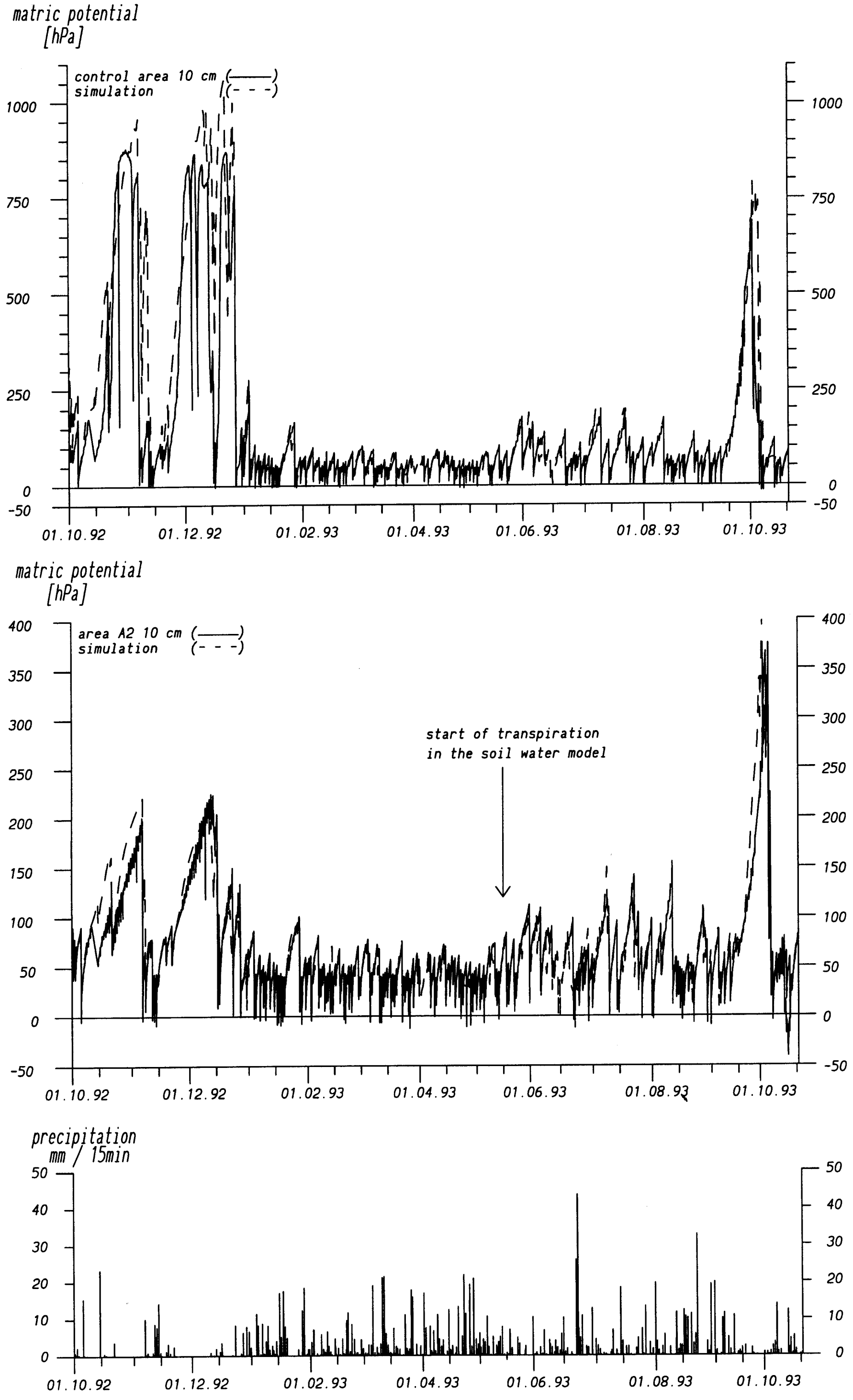

Fig. 5. Measured and simulated matric potential at 10 cm depth of control plot A1 and conversion plot A2 from September 1992 to October 1993, and rainfall distribution (mm per 15 min recording interval).

the case under forest. Here, drainage at 500 cm approaches zero towards the end of the dry season, while the column between 110 and 500 cm loses about 350–400 mm by root uptake (Table 3). Because of the strongly reduced water store, drainage at 500 cm below surface starts more than a month later compared to the converted plots, and with reduced rate. The rates become similar at the maximum rainfall in March. In the second part of the rainy season (June 1993), fluctuations in drainage are distinctly less and more retarded below forest due to the high root uptake. At the end of the recording period, drainage curves start to converge.

For the quantification of the water balance (Table 3) we used four overlapping periods:

1. firstly the period from 1.9.92, i.e. after the clear-cutting of A2 and A3, to 30.11.1993, in total 15 months. The rainfall of 2951 mm comes close to the annual average of 3026 mm measured at EMBRAPA Belem between 1974 and 1988. This period has been used for the nutrient balance of the conversion impact (Klinge, 1998).
2. secondly three sliding 12-month periods within the overall 15-month period. The rainfall of the experimental year 9/92 to 8/93 with 2479 mm falls short of the average due to a prolonged drier season in 1992. As the same period of 1993 brought more rain, shifting the balance year gradually increases the rain input.

On the control plot A1, the total evapotranspiration of 51–54% of the rainfall consists of 15–16% interception and 35–39% transpiration depending on the time interval chosen. On the converted plots A2 and A3 interception was not measured but assumed to be small because of the low above-ground biomass. Total evapotranspiration for the cleared plots was estimated at 4–6% of incident rainfall while 90% of the rain input leaves the system as drainage below 500 cm with the remaining 4–6% representing changes of soil water storage (Table 3).

4. Discussion

For estimating the water balance in the context of element cycling studies in tropical forest ecosystems, the catchment approach has mostly been preferred to that of soil water model simulation, which was

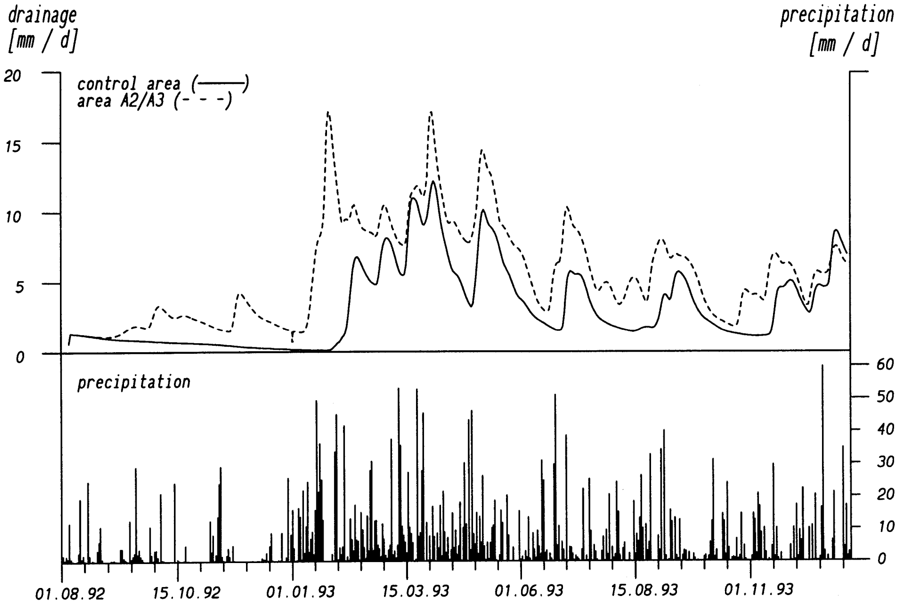

Fig. 6. Daily drainage at 500 cm depth under forest control and on conversion plot A2/A3 from August 1992 to December 1993, and daily rainfall distribution (mm per day).

Table 3
Water balance of forested control (A1) and converted plots (A2, A3): water flows in mm during the balance period after disturbance of conversion plots (1.9.1992–30.11.1993) and three 12-month sliding periods with increasing annual rainfall. ET = evapotranspiration

Control	15 months	12 months		
	1.9.92–30.11.93	1.9.92–31.8.93	1.11.92–31.10.93	1.12.92–30.11.93
Rainfall	2951	2479	2631	2706
Throughfall	2466	2104	2229	2284
Interception	485	375	402	422
Drainage 110 cm	1778	1484	1615	1733
Drainage 500 cm	1394	1130	1250	1331
Uptake 110–500	384	354	365	402
Total ET	1557	1349	1381	1375
% ET of rain	52.8	54.4	52.5	50.8
Conversion				
Rain = throughfall	2951	2479	2631	2706
Drainage 110 cm	2655	2212	2358	2455
Drainage 500 cm	2655	2212	2358	2455
Storage change	149	170	126	104
Total ET	147	97	147	147
% ET of rain	5.0	3.9	5.6	5.4

considered inexact (Bruijnzeel, 1990; Brouwer, 1996). In spite of the fact that the basic requirements for the catchment approach, i.e. homogeneity of vegetation and soil as well as a water tight basin, have often not been met (Bruijnzeel, 1990), this preference may be justified if the water balance is the only object of study. When element flows are involved, however, the situation differs as exchange and weathering processes outside the ecosystem (i.e. beyond the root zone) become important (Brouwer, 1996; Fölster and Khanna, 1997; Stoorvogel et al., 1997). It is also often impossible to carry out experiments using entire catchments as units, although such experiments are frequently required to understand the overall chemical processes in the rooting zone of ecosystems.

A way of improving the soil water simulation approach is to shorten the recording interval for matrix potential. Changing from a daily or weekly interval (Jetten, 1994; Hodnett et al., 1996a) to a 15 min interval has the advantage that individual rain events can be followed, which improves the calibration of soil parameter functions in the soil water model. The fast-recording system used in the present study has proved to work well in the temperate zone (Schmidt, 1992; Schmidt et al., 1995; Schmidt, 1996). The present study marks the first application of the approach in the humid tropics, and it seems to be especially well suited when dealing with the highly dynamic fluctuations of the matric potential associated with the wet tropics, especially in the top soil (e.g. Fig. 5).

In the present study, the stem flow of 0.19% hardly contributed to the soil water input under forest. Together with a consecutive extension by additional 20 trees >7 cm dbh on 500 m^2 (crown projection) in the same forest plot, Silva de Melo, 1999 obtained an overall (1993–1997) stem flow of 0.15%. Similarly low contributions (0.3–2% of rainfall) were reported for other tropical lowland forests both in Amazonia (Franken et al., 1982; Jackson, 1975; Lloyd and Marques Filho, 1988; Ubarana, 1996) and elsewhere (Hutjes et al., 1990). Since only trees >7 cm stem diameter have been used in our study, the real value might be somewhat higher (Jordan, 1978; Raich, 1983) but it would still remain below 1% of rainfall.

The throughfall of 85% of rainfall equals the average found by Bruijnzeel (1990) in a review of 13 studies in tropical lowland forests. The author (see also Brouwer, 1996) was rather critical concerning the length of recording period and the number of collectors. This criticism also applies to our study. However, Araújo Martins (1997) continued our measurements for 12 months in the control plot with 30 additional and systematically (weekly) relocated collectors. She found a throughfall of 85.9% (monthly range 75–91%) for an annual rainfall of 3397 mm, which supports our throughfall estimates.

Quantification of flows in the forest control plot shows a modelled evapotranspiration of 1349–1381 mm corresponding to 53% (50.8–54.4%) of rainfall. This corresponds well with the 50% (of 2684 mm rain), which Shuttleworth (1988) obtained with a micrometeorological measurement approach in Central Amazonia. Bruijnzeel (1990) critically scrutinized results from tropical humid lowlands and arrived at a mean value of 1430 mm, which he judged as high, possibly because of the inclusion of some less tight catchments in the data set. Hölscher et al. (1997), using a micrometeorological method, estimated an evapotranspiration of 1365 mm from a young (2–3 years) secondary bush fallow in their study area in Eastern Amazonia. The lacking difference in evaporation between the present old-growth forest and the bush fallow could be explained by the deep root system (Sommer, 1996) and the high effective leaf area of the bush fallow. As the authors used a micrometeorological approach, the value may include evaporation of dew, not accounted for in precipitation (Hölscher et al., 1997). The authors estimated a water uptake by roots from below 1 m which was close to the amount found in the forested plot of the present study (26–29% of the evapotranspiration). Deep soil water uptake has also been found by Nepstad et al. (1994) under Eastern Amazon forest, and been inferred by Hodnett et al. (1996b) for Central Amazon forests.

Conversion resulted in a considerable increase of drainage. The added drainage of 1100 mm corresponds to the value found by Malmer (1992), which includes surface run-off. This added drainage lies beyond the upper end of the range of values summarised by Bruijnzeel (1990), of water gains due to human interference with tropical forests. One explanation for the low transpiration of 150 mm is, of course, that this value represents active evapotranspiration of only half a year (after 15.5.93), and that in the first part of this period, plots were still intensively weeded. One can assume that ground vegetation has thus been more thoroughly suppressed in our study than in most of the case studies included in the review of Bruijnzeel. Extended to one year under vegetated conditions with simulated transpiration, total transpiration would correspond to about 350 mm. Williams and Melack (1997) estimated an evapotranspiration of 667 mm in a central Amazonian water basin (2754 mm rain), which was converted over 80% of its surface area. However, in this case the converted area was apparently covered by a mixture of crops and bush fallow. On the other hand, our neglect of transpiration and evaporation in the first part of the year, and the assumption of a uniform transpiration reduction function in the second part, certainly results in an overestimate of drainage on the converted plots. But this error will be within the sensitivity range of the model, which admittedly, we cannot quantify.

5. Conclusions

Free adjustment of the soil parameter functions, together with the high-resolution recording of the matric potential, appears to be a great advantage of the SilVlow soil water model. On the converted plots with their changing properties of the vegetation cover, a better control of the upper boundary conditions should be provided.

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References

Araújo Martins, A.R., 1997. Ciclagem hidrológico-quimica: precipitação incidente, precipitação sob dossel e solução do solo, em area de floresta, em Benevides/Pa. Magister thesis, FCAP, Belém, Pará.

Beese, F., Wierenga, P.J., 1979. Zur Bedeutung der qy-Beziehung in bodenhydrologischen Modellen. Mitteilungen der deutschen bodenkundlichen Gesellschaft 29, 101–110.

Beven, K.J., 1993. Prophecy, reality and uncertainty in distributed hydrological modelling. Advances Water Resources 16, 41–51.

Brouwer, L.C., 1996. Nutrient Cycling in Pristine and Logged Tropical Rain Forests, a Study in Guyana. The Tropenbos Foundation, Wageningen, The Netherlands. Tropenbos, Guyana series 1.

Bruijnzeel, L.A., 1990. Hydrology of moist tropical forests and effects of conversion: a state of knowledge review. Unesco International Hydrological Programme.

Boletim Agrometeorológico. EMBRAPA/CPATU, Belém/Pa, Brasil, 1974–1988.

FAO-UNESCO-ISRIC, 1990. Soil map of the world. Revised legend. World Soil Resources report 60.

Feddes, R.A., Kowalik, P., Zaradry, H., 1978. Simulation of Field Water Use and Crop Yield. Center for Agricultural Publishing and Documentation, Wageningen, NL.

Fölster, H., Khanna, P.K., 1997. Dynamics of nutrient supply in plantation soils. In: Nambiar, E.K.S., Brown, A. (Eds.). Management of Soil, Water and Nutrients in Tropical Plantation Forests. Australian Centre for International Agricultural Research, Canberra, Australia, pp. 339–378 ACIAR monograph no.43.

Franken, W., Leopoldo, P.R., Matsui, E., Ribeiro, M.D.G., 1982. Interceptação das precipitações em floresta amazônica de terra firme. Suppl. Acta Amazonica 12, 15–22.

Hodnett, M.G., Oyama, M.D., Tomasella, J., Marques Filho, A.de O., 1996. Comparisons of longterm soil water storage behaviour under pasture and forest in three areas of Amazonia. In: Gash, J.H.C., Nobre, C.A., Roberts, J.M., Victoria, R.L. (Eds.). Amazonian Deforestation and Climate. Wiley, Chichester, pp. 57–77.

Hodnett, M.G., Tomasella, J., Marques Filho, A.de O., Oyama, M.D., 1996. Deep soil water uptake by forest and pasture in Central Amazonia: predictions from long term daily rainfall data using a simple water balance model. In: Gash, J.H.C., Nobre, C.A., Roberts, J.M., Victoria, R.L. (Eds.). Amazonian Deforestation and Climate. Wiley, Chichester, pp. 79–99.

Hölscher, D., Sa, T.D.A., Bastos, T.X., Denich, M., 1997. Evaporation from young secondary vegetation in eastern Amazonia. Journal of Hydrology 193 (1-4), 293–305.

Hutjes, R.W.A., Wierda, A., Veen, A.W.L., 1990. Rainfall interception in the Tai forest Ivory Coast. Application of 2 simulation models to a humid tropical system. Journal of Hydrology 114 (34), 259–275.

Jackson, I.J., 1975. Relationship between rainfall parameters and interception by tropical forest. Journal of Hydrology 24, 215–238.

Jetten, V.G., 1994. Modelling the Effects of Logging on the Water Balance of a Tropical Rain Forest. A Study in Guyana. The Tropenbos Foundation, Wageningen, The Netherlands, p. 196 Tropenbos Series 6.

Jordan, C.F., 1978. Stem flow and nutrient transfer in a tropical rain forest. Oikos 31, 257–263.

Klinge, R., 1998. Wasser- und Nährstoffdynamik im Boden und Bestand beim Aufbau einer Holzplantage im östlichen Amazonasgebiet. Göttinger Beiträge zur Land- und Forstwirtschaft in den Tropen und Subtropen, 122.

Lloyd, C.R., Marques Filho, A.de D, 1988. Spatial variability of throughfall and stemflow measurements in Amazonian rainforest. Agricultural and Forest Meteorology 42, 63–73.

Mackensen, J., Tillery-Stevens, M., Klinge, R., Fölster, H., 2000. Site parameters, species composition, phytomass structure and element stores of a Terra-firme forest in East-Amazonia, Brazil. Plant Ecology 151, 101–119.

Malmer, A., 1992. Water yield changes after clearfelling tropical rainforest and establishment of forest plantation in Sabah, Malaysia. Journal of Hydrology 134, 77–94.

Moshrefi, N., 1983. Ein neues Verfahren der Schlämmanalyse für die Bestimmung der Korngrößenzusammensetzung. Mitteilungen der Deutschen Bodenkundlichen Gesellschaft 38, 115–118.

Nepstad, D.C., de Carvalho, C.R., Davidson, E.A., Jipp, P.H., Lefebre, P.A., Negreiros, G.H., da Silva, E.D., Stone, T.A., Trumbore, S.E., Viera, S., 1994. The role of deep roots in the hydrological and carbon cycles of Amazonian forests and pastures. Nature 372, 666–669.

Oparanadi, O.A., 1979. A comparison of some methods for determining the hydraulic conductivity of unsaturated soils in the low suction range. Göttinger Bodenkundliche Berichte, 57.

Penman, H.L., 1948. Natural evaporation from open water, bare soil and grass. Proceedings of the Royal Society (London) 193, 120–146.

Raich, J.W., 1983. Throughfall and stemflow in mature and year old wet tropical forest. Tropical Ecology 24 (2), 234–243.

Richard, F., Luthin, J., 1965. Zur Untersuchung der Wasserbewegung in Hangböden mit unvollkommener Durchlässigkeit. Mitteilungen der Eidgenössischen Anstalten für Forstliches Versuchswesen 41 (6), 305–367.

Rohdenburg, H., Diekkrüger, B., 1984. Zur Beschreibung von Hystereseschleifen bei der Bodenwassermodellierung. Landschaftsökologisches Messen und Auswerten, Braunschweig 1 (1), 61–66.

Schmidt, J.P., 1992. Die Beziehung der hydromorphologischen Merkmale zum Wasserhaushalt auf drei Waldstandorten im Hunsrück. Berichte des Forschungszentrums Waldökosysteme, Reihe a (95). 11–49

Schmidt, J.P., Blendinger, C., Lange, H., 1995. SilVlow: Eine Modelldokumentation. In: Hörmann, G. und Schmidt, J.P. (Eds.), Dokumentation von Wasserhaushaltsmodellen; Berichte des Forschungszentrums Waldökosysteme, Reihe b, 42: p. 71–83.

Schmidt, S., 1996. Zusammenhang von Wasser- und Stoffhaushalt in der Langen Bramke, Vergleich unterschiedlicher zeitlicher und räumlicher Maβstäbe. Dissertation am Geographischen Institut, Universität Göttingen.

Shuttleworth, W.J., 1988. Evaporation from Amazonian rainforest. Proceedings of the Royal Society (London) 233, 321–346.

Silva de Melo, V,. 1999. Contribuicão da água escorrida pelo caule à chuva efetiva em floresta primária explorada na Amazonia Oriental. Magister thesis, FCAP, Para.

Sommer, R., 1996. Kohlenstoffvorräte in Böden unter intensiv genutzten Sekundärwaldflächen im östlichen Amazonasgebiet. Grad.thesis, University of Göttingen, Germany.

Stolte, J., Freijer, J.I., Bouten, W., Dirksen, C., Halbertsma, J., 1994. Comparison of six methods to determine unsaturated hydraulic conductivity. Soil Science Society of America Journal 58 (6), 1596–1603.

Stoorvogel, J.J., Janssen, B.H., van Breemen, N., 1997. The nutrient budgets of a watershed and its forest ecosystem in the Tai national park in Cote d'Ivoire. Biogeochemistry 37, 159–177.

Ubarana, V.N., 1996. Observations and modelling of rainfall interception at two experimental sites in Amazonia. In: Gash, J.H.C., Nobre, C.A., Roberts, J.M., Victoria, R.L. (Eds.). Amazonian Deforestation and Climate. Wiley, Chichester, pp. 151–162.

van Genuchten, M.Th., 1980. A closed form equation for predicting hydraulic conductivity in unsaturated soils. Soil Science Society of America Journal 44, 892–898.

Vieira, L.S., Dos Santos, P.C.T.C., 1987. Amazônia seus solos e outros recursos naturais. Editora Agronômica Ceres ltda, São Paulo.

Ward, R.C., Robinson, M., 1990. Principles of Hydrology. 3rd edMcGraw-Hill, New York.

Williams, M.R., Melack, J.M., 1997. Solute export from forested and partially deforested catchments in the central Amazon. Biogeochemistry 38 (1), 67–102.