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Forest Ecology and Management 73 (1995) 185–195

Forest Ecology and Management

Real evapotranspiration and transpiration through a tropical rain forest in central Amazonia as estimated by the water balance method

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Accepted 12 September 1994

Abstract

The research was carried out from January 1981 to December 1983, in a small watershed of 1.3 km^2 surface area located at INPA's Ducke Forest Reserve. This watershed is drained by the Barro-Branco stream, and its vegetation cover is characterized by a typical tropical rain forest of the central Amazon region.

In order to estimate its real evapotranspiration, transpiration and other hydrological parameters, the precipitation and the discharge yielded by the Barro-Branco stream were measured during the experimental period.

A mean precipitation of 2209 mm $year^{-1}$ was recorded, from which 67.6% was lost to the atmosphere through evapotranspiration. This result was similar to that calculated by the modified Penman's method (1479.2 mm $year^{-1}$).

If the average rain water interception by the forest canopy is assumed to be 11.3% of the total precipitation amount, as estimated by Gash's model, the transpiration was 1243.7 mm $year^{-1}$, representing 56.3% of the total rainfall observed for the 1981–1983 period.

Keywords: Evapotranspiration; Transpiration; Tropical rain forest; Water balance method; Watershed

1. Introduction

The Brazilian Amazon tropical rain forest covers a significant area, estimated as 3.6×10^6 km^2, corresponding to about 42% of the country.

Despite the speed with which deforestation has occurred in recent decades (Fearnside et al., 1990), this ecosystem can still be considered as being in an initial phase of human exploitation and also as a system in its original state (Salati and Vose, 1984).

A significant change on actual forest cover might cause serious and irreversible disturbances to the region and its environment (Salati, 1985; Shukla et al., 1989).

Salati and Ribeiro (1979) suggested that a large-scale deforestation of the region would,

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SSDI 0378-1127(94)03487-7

among other things, reduce the time that water remains in the Amazon basin. A reduction of only 10–20% in the normal precipitation amount would be sufficient to cause severe alterations in hydrological cycle, with direct consequences on its actual ecological balance (Salati and Marques, 1984).

The Amazon basin at a preliminary estimate functions as a system receiving through precipitation 12×10^{12} m^3 of water per year, of which 5.52×10^{12} m^3 year^{-1} are discharged to the Atlantic Ocean (Villa Nova et al., 1976). The real evapotranspiration resulting from this simple water balance is estimated as 6.48×10^{12} m^3 year^{-1}, corresponding to 54% of the total rainfall.

The main influx of atmospheric water vapor into the Amazon basin comes from the Northern Hemisphere with the easterly trade winds, as described by Salati and Vose (1984) and Molion (1987).

However, as the winds penetrate inland the contribution to the rainfall due to the forest evapotranspiration becomes relatively more important.

It is well known that forest cover plays an important role in the regional water cycle, where about 50% of the precipitation falling in Amazonia is a result of water recycled through evapotranspiration (Marques et al., 1977; Dall' Olio et al., 1979; Salati et al., 1979; Marques et al., 1980; Salati, 1986). This water mass returned to the atmosphere represents a very high vapor rate, with a mean recycling time of about 5.5 days only (Marques et al., 1979).

By using Penman's method adapted to forest conditions, Villa Nova et al. (1976) calculated the average potential evapotranspiration for the whole Amazon basin as being 1460 mm year^{-1} for an annual mean precipitation of 2000 mm, corresponding to a value of 4.0 mm day^{-1}. The actual evapotranspiration was estimated to be 1168 mm year^{-1}, but for many regions of the basin the real and potential values could assume identical values.

Ribeiro and Villa Nova (1979), using Thornthwaite and Mather's method at the Ducke Forest Reserve, estimated a potential evapotranspiration of 1536 mm year^{-1} and an actual one of 1508 mm year^{-1} for an annual mean precipitation of 2478 mm. These authors also observed that the potential evapotranspiration for this reserve is practically equal to the actual value for almost the whole year, except for 3 months when a soil-water deficit occurs.

In general, there is a good agreement among the evapotranspiration results obtained by different methods and researchers, as can be observed in Jordan and Heuveldop (1981), Leopoldo et al. (1982, 1985), Mortatti (1986) and Leopoldo et al. (1993). The main objective of the present work was estimate the actual evapotranspiration and transpiration values from a typical tropical rain forest in central Amazonia, using the water balance method and also to determine other hydrological parameters for this representative watershed.

2. Methodology

2.1. Description of the experimental watershed

The Barro-Branco watershed in the Ducke Forest Reserve is located about 26 km north of Manaus city at Manaus-Itacoatiara highway. The mean altitude is about 80 m and mean coordinates of the area are 03°08′S and 60°02′W (Fig. 1). The watershed has a small surface area of 1.3 km^2 and it is drained by the Barro-Branco stream (Fig. 2). The topography is gently undulating

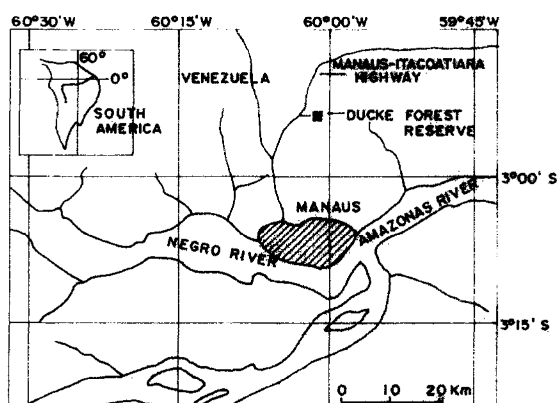

Fig. 1. Localization of the Ducke Forest Reserve.

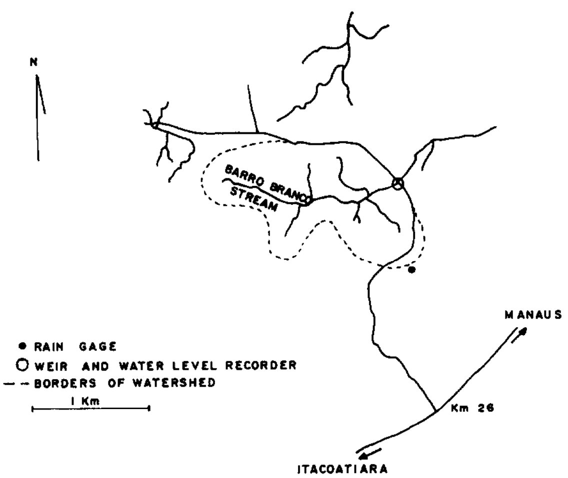

Fig. 2. The Barro-Branco experimental watershed, at Ducke Forest Reserve.

with valleys several tens of meters deep occurring at 300 m intervals. More details about the site can be found in Shuttleworth et al. (1984).

The prevalent soils are classified as yellow latosol, characterized by a clayey texture with light color, and small areas (about 15%) of hydromorphic soil (Viswanadham et al., 1990). Specific information about the soils can be taken from Chauvel (1982).

The average precipitation pattern for the region exhibits a marked seasonal dependence, showing a monthly maximum of 270 mm in March and a minimum of 40 mm in August (Shuttleworth et al., 1984).

The watershed vegetation cover is representative of a typical and undisturbed natural forest of the central Amazonia region, having a surface leaf index close to 5.01 $m^2\ m^{-2}$ (Sellers et al., 1989). Plant density in the watershed can be considered high (up to 3000 stems ha^{-1}, 30–40 m high). However, less than 10% of the plants have girths of 200 mm or more.

2.2. Measurements

The measurements to compute the water budget for the Barro-Branco watershed took place from January 1981 to December 1983.

Precipitation data were obtained by use of a rain gauge installed at the Reserve's meteorological station, located nearby (Fig. 2). The total discharge yielded by the Barro-Branco stream was determined by use of a 0.8-m-wide rectangular weir and a water level recorder at the watershed outlet (Franken and Leopoldo, 1987).

The direct surface runoff (overland flow) was computed by analysis of each storm runoff hydrograph recorded by the water level recorder. This computation was done using the classical hydrological method (Chow, 1964) for separating the direct surface runoff and the baseflow contributions from the total discharge produced by a storm event.

2.3. Water budget model

To determine the water balance, a single and well-known model was applied that takes into account the difference between input of water through precipitation and output through stream (Chow, 1964; Linsley et al., 1975); it can be expressed by the following equation

$$ET = P - (Q_{DS} + Q_{BF}) \pm \Delta S \quad (1)$$

In Eq. (1), P is the rainfall, Q_{DS} represents the direct surface runoff, Q_{BF} corresponds to the baseflow, ΔS is the variation of water stored in the watershed soil and ET is the water lost by evapotranspiration. As can be seen, the $(Q_{DS} + Q_{BF})$ sum represents the total amount of water drained by the watershed (Q_T).

In the case of observations over sufficiently long periods of time, the changes in the soil water storage (ΔS) become negligible and the water balance equation can be rewritten in the following simplified form (Organizacíon Meteorológica Mundial, 1967; Liebscher, 1977)

$$ET = P - Q_T \quad (2)$$

The annual real evapotranspiration (ET) estimated by Eq. (1) was compared with the potential evapotranspiration obtained by Leopoldo et al. (1993) using Penman's method modified to the Amazon forest.

2.4. Transpiration estimation

By ignoring the loss due to the direct evaporation from the forest soil surface, which has negligible value (Jordan and Heuveldop, 1981; Salati, 1985), the transpiration loss can be estimated as follows

$$T = ET - Ic \tag{3}$$

or by

$$T = P - Ic - Q_T \tag{4}$$

where T is the transpiration and Ic is the rainfall interception by the forest canopy.

The rainfall interception (Ic) was not directly measured, but estimated from results obtained by Lloyd et al. (1988) through Gash's analytical model applied to meteorological measurements made in the Ducke Forest Reserve. Full details of the instrumentation used by these authors are described in Lloyd and Marques Filho (1988).

It is interesting to observe that the results obtained from Gash's model were not significantly different from the measured interception losses (Lloyd et al., 1988).

The mean values of 11.4%, 10.5% and 12.1% of the precipitation were used to estimate the interception losses for 1981, 1982 and 1983, respectively, as resulting from Gash's model applied by Lloyd et al. (1988).

Studies on forest regions have shown that interception loss is a significant component that must be considered when a forest water balance is performed (Franken et al., 1982; Dolman, 1987).

3. Results

The monthly precipitation data recorded at the Ducke Forest Reserve's meteorological station for the period are shown in Table 1.

Table 2 includes the values of total monthly discharges (Q_T) yielded by the Barro-Branco stream and the respective contributions from the direct surface runoff (Q_{DS}) and baseflow (Q_{BF}).

The annual evapotranspiration amounts (ET) produced by the watershed were estimated taking into account the annual values for precipitation and total discharge (Tables 1 and 2) and by using Eq. (1) with a ΔS value of 0.0. The results are shown in Table 3, where the potential evapotranspiration values obtained by the modified Penman method are also included (Leopoldo et al., 1993).

As reported in Van Mullem (1991), the actual storage (Sa) of the rain water during a storm by a watershed can be deduced from the difference between the precipitation (P) and the direct surface runoff (Q_{DS})

$$Sa = P - Q_{DS} \tag{5}$$

This water amount, temporarily retained in the watershed, resulted from the canopy interception, surface storage and also infiltration. The results obtained for this parameter, deduced from values in Tables 1 and 2, can be seen in Table 4, which also includes canopy interception estimates.

The amount of infiltration (If) can be estimated from the difference between Sa and Ic values (Eq. (6)). The parcel of If remaining in the soil (Ss) to satisfy forest transpiration (T) and the soil water storage variation (ΔS) can be deduced by the difference between If and Q_{BF}, as shown in Eq. (7)

$$If = Sa - Ic \tag{6}$$

and

$$Ss = If - Q_{BF} \tag{7}$$

The values computed in Eqs. (6) and (7) are shown in Table 5.

From Eq. (8), which is similar to Eqs. (3) and (4), the total annual watershed transpiration can also be derived if the ΔS value is assumed to be 0.0

$$T \pm \Delta S = If - Q_{BF} \tag{8}$$

The annual transpiration values obtained by the application of one of these equations are reported in Table 6, in addition to those obtained by use of the modified Penman method ($T = ET - Ic$).

Taking into account that the input of water in the watershed soil minus the output value is the

Table 1
Monthly precipitation data (mm) recorded at the Ducke Forest Reserve for the January 1981–December 1983 period

Month	1981	1982	1983	Mean
January	359.7	284.6	27.9	224.1
February	300.6	308.0	67.4	225.3
March	181.5	284.7	287.3	251.2
April	241.5	379.0	230.6	283.7
May	246.7	295.0	237.4	259.7
June	104.3	95.4	123.4	107.7
July	42.4	100.4	97.0	79.9
August	218.4	48.0	82.7	116.4
September	144.2	149.5	122.9	138.9
October	107.4	111.8	159.1	126.1
November	172.6	134.0	75.1	127.2
December	193.0	175.0	438.4	268.8
Annual	2312.3	2365.4	1949.2	2209.0

$CV = 55.17\%$.

Table 2
Monthly total discharge values (Q_T) measured at the Barro-Branco stream and the respective values of the direct surface runoff (Q_{DS}) and baseflow (Q_{BF}) components. All values are expressed in millimeters

Month	1981			1982			1983		
	Q_T	Q_{DS}	Q_{BF}	Q_T	Q_{DS}	Q_{BF}	Q_T	Q_{DS}	Q_{BF}
January	109.82	14.31	95.51	56.79	5.94	50.85	31.59	0.71	30.85
February	99.81	13.65	86.16	98.81	15.59	83.22	29.87	1.16	28.71
March	75.07	6.47	68.60	112.49	10.67	101.82	38.95	6.85	32.10
April	87.94	8.11	79.83	134.77	18.51	116.26	45.00	3.09	41.91
May	87.46	7.97	79.49	129.25	14.80	114.45	52.68	4.31	48.37
June	62.09	2.27	59.82	81.90	1.37	80.53	46.58	5.28	41.30
July	35.27	0.00	35.27	53.53	2.08	51.45	35.66	0.85	34.81
August	54.66	5.69	48.97	52.24	1.03	51.21	29.67	0.70	28.97
September	43.62	2.46	41.16	54.20	4.42	49.78	28.07	2.50	25.57
October	37.94	2.25	35.69	55.13	5.54	49.59	35.25	2.42	32.83
November	35.74	3.40	32.34	34.57	1.99	32.58	25.60	0.82	24.78
December	47.59	3.90	43.69	45.36	3.19	42.17	59.77	12.27	47.50
Annual	780.01	70.48	709.53	909.04	85.13	823.91	458.66	40.96	417.70

$CV_{Q_T} = 49.31\%$; $CV_{Q_{DS}} = 89.47\%$; $CV_{Q_{DB}} = 46.66\%$.

variation of the soil water storage (ΔS), it follows that

$$\Delta S = If - Q_{BF} - T \qquad (9)$$

For ΔS estimates it was assumed that the monthly potential transpiration values, deduced from the differences between the monthly potential evapotranspiration values and the canopy interception losses, were close to the actual values.

In Table 7 are reproduced the potential evapotranspiration values as computed by Leopoldo et al. (1993) for the Barro-Branco watershed, the potential transpiration estimated using Eq. (3) and also the ΔS results derived from Eq. (9).

Considering the mean values measured and

Table 3
Annual evapotranspiration (ET) values estimated using the water balance and modified Penman methods

Year	Water balance (actual)		Modified Penman method (potential)	
	ET (mm)	ET/P (%)	ET (mm)	ET/P (%)
1981	1532.3	66.3	1392.0	60.2
1982	1456.4	61.6	1495.7	63.2
1983	1490.5	76.5	1549.9	79.5
Mean	1493.1	67.6	1479.2	67.0

$CV_{actual}=2.08\%$; $CV_{pot.}=4.43\%$.

Table 4
Values deduced for the actual storage of precipitation (Sa) and the canopy interception (Ic), expressed in millimeters

Month	1981		1982		1983	
	Sa	Ic	Sa	Ic	Sa	Ic
January	345.39	41.01	278.66	29.88	2.19	3.38
February	286.95	34.27	292.41	32.34	66.24	8.16
March	175.03	20.69	274.03	29.89	280.45	34.76
April	233.39	27.53	360.49	39.80	227.51	27.90
May	238.73	28.12	280.20	30.98	233.09	28.73
June	102.03	11.89	94.03	10.02	118.12	14.93
July	42.40	4.83	98.32	10.54	96.15	11.74
August	212.71	24.90	46.97	5.04	82.00	10.01
September	141.74	16.44	145.08	15.70	120.40	14.87
October	105.15	12.24	106.26	11.74	156.68	19.25
November	169.20	19.68	132.01	14.07	74.28	9.09
December	189.10	22.00	171.81	18.38	426.13	53.05
Annual	2241.82	263.60	2280.27	248.38	1908.24	235.87

$CV_{Sa}=55.34\%$; $CV_{Ic}=55.27\%$.

estimated for the entire experimental period, a summary of the water balance for the Barro-Branco watershed is shown in Table 8. This table also includes the respective mean percentages of each parameter in relation to the rainfall.

From a correlation between rainfall (P) and actual storage of precipitation (Sa), the following linear regression, with an R^2 of 0.9993 and a standard deviation of 2.3908, was calculated

$$(P-Q_{DS})=0.9560P+2.6188 \quad (10)$$

This regression curve produces a precipitation value of about 60.0 mm month^{-1} for 0.0 mm of overland flow (Q_{DS}), which means that this amount of rainfall would be necessary for direct surface runoff to occur.

Taking into account Eq. (11), which gives the linear regression curve for precipitation (P) versus soil water storage (ΔS) values ($R^2=0.9376$), it could be deduced that a monthly precipitation of 183 mm would be necessary in order to have no change in the ΔS value

$$\Delta S=0.92P-168.25 \quad (11)$$

Therefore, from a monthly rainfall of 183 mm, about 157 mm of rain water would be infiltrated (If) in the forest soil as estimated by the following linear regression curve ($R^2=0.9994$)

Table 5
Amounts of water infiltrated (If) and retained (Ss) in the forest soil, given in millimeters

Month	1981		1982		1983	
	If	*Ss*	*If*	*Ss*	*If*	*Ss*
January	304.38	208.87	248.78	197.93	23.81	−7.04
February	252.68	163.52	260.07	176.85	58.08	29.37
March	154.34	85.74	244.14	142.32	245.69	213.59
April	205.86	126.03	320.69	204.43	199.61	157.70
May	210.61	131.12	249.22	134.77	204.36	155.99
June	90.14	30.32	84.01	3.48	103.19	61.89
July	37.57	2.30	87.78	36.33	84.41	49.60
August	187.81	138.84	41.93	−9.28	71.99	43.02
September	125.30	84.14	129.38	79.60	105.53	79.96
October	92.91	57.22	94.52	44.93	137.43	104.60
November	149.52	117.18	117.94	85.36	65.19	40.41
December	167.10	123.41	153.43	111.26	373.08	325.58
Annual	1978.22	1268.69	2031.89	1207.98	1672.37	1254.67

CV_{If}= 54.41%; CV_{Ss}= 70.55%.

Table 6
Annual results of transpiration (T) as estimated by the water balance and modified Penman methods

Year	Water balance		Modified Penman method[a]	
	T	T/P (%)	T	T/P (%)
1981	1268.69	54.9	1128.40	48.8
1982	1207.98	51.1	1247.32	52.7
1983	1254.67	64.3	1314.03	67.4
Mean	1243.78	56.3	1229.92	55.7

[a] $T=ET-Ic$; ET estimated by the modified Penman method.
CV_{WB}=2.08%; CV_{PEN}=6.24%.

Table 7
Monthly potential evapotranspiration (ET), potential transpiration (T) and variation in the soil water storage (ΔS) values, given in millimeters

Month	1981			1982			1983		
	ET	T	ΔS	ET	T	ΔS	ET	T	ΔS
January	94.2	53.19	155.68	104.5	76.62	121.31	151.0	147.62	−154.66
February	89.9	55.63	107.89	100.2	67.86	108.99	142.8	134.62	−105.27
March	117.8	97.11	−11.37	115.0	85.11	57.21	136.7	101.94	111.65
April	94.5	66.97	59.06	107.7	67.90	136.53	117.0	89.10	68.60
May	120.9	92.78	38.34	118.4	87.42	47.35	143.5	144.77	41.22
June	120.9	109.01	−78.69	120.0	109.98	−106.50	117.0	102.07	−40.18
July	124.3	119.47	−117.17	138.9	128.36	−92.03	146.3	134.56	−84.96
August	133.9	109.00	29.84	155.0	149.96	−159.24	140.1	130.09	−87.07
September	121.5	105.06	−20.92	148.5	132.80	−53.20	138.6	123.73	−43.77
October	145.7	133.46	−76.24	151.0	139.26	−94.33	114.7	95.45	9.15
November	113.7	94.02	23.16	130.5	116.43	−31.07	108.0	98.91	−58.50
December	114.7	92.70	30.71	106.0	87.62	23.64	94.2	41.15	284.43
Annual	1392.0	1128.40	140.29	1495.7	1247.32	−39.34	1549.9	1314.03	−59.36

CV_{ET}= 14.73%; CV_T=26.90%.

Table 8
Mean values estimated for the water balance components at the Barro-Branco watershed, in central Amazonia

Parameter	Amount (mm)	%
Rainfall (P)	2209.0	100.0
Actual storage (Sa)	2143.4	97.0
Infiltration (If)	1894.2	85.7
Soil water retention (Ss)	1243.8	56.3
Water storage variation (ΔS)	±41.6	1.9
Actual evapotranspiration (ET)	1493.1	67.6
Actual transpiration (T)	1243.8	56.3
Interception loss (Ic)	249.3	11.3
Direct surface runoff (Q_{DS})	65.5	3.0
Baseflow (Q_{BF})	650.4	29.4

$$If = 0.8437P + 2.3776 \quad (12)$$

However, for an infiltration of 146 mm no baseflow would be yielded, as deduced from Eq. (13), that gives the linear regression curve for If versus $(If - Q_{BF})$ values with an R^2 of 0.9225 and a standard deviation of 20.61

$$(If - Q_{BF}) = 0.8217If - 26.08 \quad (13)$$

Then, the value of 146 mm found in Eq. (13) can be taken as being the maximum water quantity that the forest soil could retain.

4. Discussion and conclusions

As a whole, the results show that the Amazonian tropical rain forest could be taken as a gigantic water reservoir responsible for a particular water recycling mechanism.

The high percentage of locally derived water from rainfall in the central Amazon region indicates that careful consideration should be given to possible consequences resulting from destruction of large forest areas, since forests are more efficient at water storage of rainfall and returning water to the atmosphere than other types of vegetation or even bare soils (Jordan and Heuveldop, 1981; Leopoldo et al., 1993).

From Sa values (Table 4), conclusions can be drawn about the importance of the forest on rainfall water temporarily retained by the ecosystem. The amount of water retained has direct effects on the water residence time of the watershed, discharge peaks, nutrient losses, soil erosion and floods.

The Sa values represented a very large portion of the total precipitation, corresponding to a mean percentage of 97%; only 3% of the rainfall was lost directly during storm events through surface runoff (Table 2).

For crop area conditions or even large watersheds, higher direct surface runoff values than those reported here for the Barro-Branco watershed are normally observed. The DAEE (1977), for example, deduced a mean overland flow of 13.6% from an average annual precipitation of 1450 mm for the Paraiba do Sul watershed, which has a surface area of 13 605 km^2 at the State of São Paulo's southeastern region. This result shows that large crop areas beside an intensive urban development, which is the landscape of the watershed taken as example, can change significantly the direct surface runoff value when compared with forest conditions.

Therefore, on a specific condition of a small agricultural watershed, with an efficient soil conservation system and a highly permeable soil, a low overland flow of 3.4% was obtained by Da Silva and Leopoldo (1988). This result can be considered of the same magnitude for the Barro-Branco watershed.

As estimated by Eq. (10), a monthly precipitation close to 60 mm would be necessary for direct surface runoff to occur, which could be considered too large when compared with other types of vegetation cover. However, it reflects the great temporary storage capacity of the Amazon ecosystem.

Unfortunately, no similar research has been conducted at the Central Amazon level, so comparison with other results is not possible.

The evapotranspiration estimates derived using the water balance and modified Penman methods (Table 3) show that actual and potential evapotranspiration can be considered as being of the same magnitude for the region. Close results and similar observations were also reported by Ribeiro and Villa Nova (1979), when evapotranspiration of 4.1 mm day^{-1} was obtained at the same site.

Using the eddy correlation method for micrometeorological data from Ducke Reserve, a daily evapotranspiration rate close to 4.0 mm can also be deduced (Alvalá, 1993).

In general, there is a good agreement among evapotranspiration estimates obtained by different methods, not only for the central region but also for the Amazon basin as a whole (Villa Nova et al., 1976; Marques et al., 1980; Salati and Marques, 1984).

It is interesting to observe that evapotranspiration values obtained for tropical rain forests of other regions of the world do not differ greatly from Amazon forest estimates. From an evapotranspiration study on a tropical rain forest in Java, evapotranspiration was calculated as 1481 mm $year^{-1}$, representing 52% of the total precipitation (2851 mm $year^{-1}$) (Calder et al., 1986). The measurements of rain and net rainfall indicated that the interception losses were 21% of the gross rainfall and the transpiration component accounted for 886 mm $year^{-1}$, or 2.6 mm day^{-1}, corresponding to only 31% of the total rainfall (Calder et al., 1986).

Although the evapotranspiration results from these two different sites can be regarded as of similar magnitude, the transpiration values for the Amazon tropical rain forest are larger (Jordan and Heuveldop, 1981; Leopoldo et al., 1982).

The transpiration rate determined by Jordan and Heuveldop (1981) was 2186 mm $year^{-1}$, estimated using the tritium method. This value corresponds to 59.6% of the average yearly precipitation observed.

However, the authors have assumed that the transpiration value was better calculated when the Class A pan values corrected for interception losses were used, since the tritium method may overestimate transpiration during several months. From this second method, Jordan and Heuveldop (1981) obtained an annual transpiration of 1720 mm only, representing about 47% of a mean rainfall of 3664 mm $year^{-1}$. The studies reported by these authors were carried out on the Amazonian tropical rain forest, located near San Carlos, Venezuela (01°56′N, 67°03′W).

From a water balance at Modelo experimental watershed (60 km north of Manaus), 48.5% transpiration was estimated by Leopoldo et al. (1982). As reported by the latter authors, the annual precipitation amounted to 2089 mm and the transpiration rate was estimated as 1014 mm $year^{-1}$ (2.8 mm day^{-1}). Certainly, this transpiration rate could be considered a low value when compared with the value of 4.7 mm day^{-1} computed by Jordan and Heuveldop (1981).

Therefore, it is interesting to pay attention to the fact that when the transpiration component is estimated using the water balance method, the resulting value depends on the value assumed for the interception loss. The latter becomes a very significant parameter when Eqs. (3) or (4) are applied.

Leopoldo et al. (1982) found a yearly transpiration of 1014 mm using an interception loss value of 25.6% of the total rainfall (Franken et al., 1982). However, this value could be considered excessively high compared with the 5% reported by Jordan and Heuveldop (1981) or 11.3% derived using Gash's model (Shuttleworth et al., 1984).

If a mean interception loss of 11.3% is assumed, which could be considered closer to the central Amazon region conditions, the results obtained at the Modelo experimental watershed would be estimated as being an annual transpiration rate of 1312 mm, or 62.8% of the yearly rainfall and corresponding to a daily rate of 3.6 mm.

This daily rate would be in accordance to the values shown in Table 6, where a mean annual transpiration of 1243.8 mm is shown. This amount represents 56.3% of the total mean precipitation observed during 1981–1983, corresponding to 3.4 mm day^{-1}. It is also similar to values indirectly deduced from Ribeiro and Villa Nova (1979), Franken and Leopoldo (1987) and Mortatti (1986).

From these considerations, in the central Amazon region a transpiration rate higher than 3.0 mm day^{-1} can be expected.

The values in Table 5 show that the amounts of rainfall water entering the forest soil by infiltration are also high when compared with some other hydrological conditions, showing that this component represented 85.7% of the total rainfall.

Using tritium as a tracer, Araguás-Araguás et al. (1993) found an infiltration rate lower than that shown in Table 8. Their experiment was also carried out at the Ducke Forest Reserve, where tritium was injected on two different areas: undisturbed forest and cleared zone. Results from the tritium method showed that the effective yearly infiltration rate in the forest soil was substantially lower than in the cleared area, with values of 1465 mm and 1840 mm, corresponding to 60% and 75%, respectively, of a total annual rainfall of 2455 mm.

Therefore, the results obtained by Araguás-Araguás et al. (1993) could be underestimated since the transpiration flux reached only 40% of the total annual rainfall observed; this value could be considered significantly low for the region.

The water balance method proved to be a very effective way to investigate the water distribution in small watersheds under tropical conditions of central Amazonia once the ΔS value was found to be only 1.9% of the total rainfall observed in the 3 year period (Table 8).

Despite some deviations from results obtained by other authors or methods, the data obtained indicated the order of magnitude and importance of the water balance components to the central Amazon ecosystem.

These results show that if the large-scale clearance of the Amazon ecosystem for pasture and annual crops is continued, a significant change in its water cycle can be expected, with direct consequences for biogeochemical cycles.

References

Alvalá, R.C. dos S., 1993. Estudo da partição de energia em terrenos complexos (áreas desflorestadas e florestadas). Tese de Doutoramento, I.N.P.E., 151 pp.

Araguás-Araguás, L., Rozanski, K., Plata Bedmar, A., Vital, A.R.T., Tancredi, A.C. and Franken, W., 1993. Downward movement of soil moisture in the central Amazon region traced by means of hydrogen isotopes. Intern. Rep., International Energy Atomic Agency, Vienna, 24 pp.

Calder, I.R., Wright, I.R. and Murdiyarso, D., 1986. A study of evaporation from tropical rain forest—West Java. J. Hydrol., 89: 13–31.

Chauvel, A., 1982. Os latossolos amarelos álicos argilosos dentro dos ecossistemas das bacias experimentais do INPA e da região vizinha. Acta Amazon., 12: 47–60.

Chow, Ven T., 1964. Handbook of Applied Hydrology. McGraw Hill, New York, 1466 pp.

DAEE, 1977. Estudo de águas subterrâneas: região administrativa 3, São José dos Campos. DAEE, São Paulo, 160 pp.

Dall'Olio, A., Salati, E., Azevedo, T.C. and Matsui, E., 1979. Modelo de fracionamento isotópico da água na Bacia Amazônica. Acta Amazon., 9: 675–687.

Da Silva, A.R. and Leopoldo, P.R., 1988. Escoamento superficial e subterrâneo em bacias hidrográficas sob utilização agrícola. Rev. Energia Agric., 3: 31–36.

Dolman, A.J., 1987. Summer and winter rainfall interception in an oak forest. Predictions with an analytical and numerical simulation model. J. Hydrol., 90: 1–9.

Fearnside, P.M., Tardin, T.A. and Meira Filho, L.G., 1990. Deforestation rate in Brazilian Amazon. INPE, São José dos Campos, Brazil, 8 pp.

Franken, W.K. and Leopoldo, P.R., 1987. Relações entre fluxos de água subterrânea e superficial em bacia hidrografica caracterizada por cobertura florestal amazônica. Acta Amazon., 16/17: 253–262.

Franken, W.K., Leopoldo, P.R., Matsui, E. and Ribeiro, M.N.G., 1982. Interceptação das precipitações em floresta amazônica de terra firme. Acta Amazon., 12: 15–22.

Jordan, C.F. and Heuveldop, J., 1981. The water budget of amazonian rain forest. Acta Amazon., 11: 87–92.

Leopoldo, P.R., Franken, W.K., Matsui, E. and Salati, E., 1982. Estimativa de evapotranspiração de floresta amazônica de terra firme. Acta Amazon., 12: 23–28.

Leopoldo, P.R., Fanken, W.K. and Matsui, E., 1985. Hydrological aspects of the tropical rain forest in the Central Amazon. In: J. Hemming (Editor), Change in the Amazon Basin: Man's Impact on Forest and Rivers. Manchester University Press, Manchester, pp. 90–107.

Leopoldo, P.R., Chaves, J.G. and Franken, W.K., 1993. Solar energy budgets in Central Amazonian ecosystems: a comparison between natural forest and bare soil areas. For. Ecol. Manage., 59: 313–328.

Liebscher, H.J., 1977. Water balance studies in the experimental basins of Upper Harz mountains. Hydrol. Sci. Bull., 22: 283–296.

Linsley, Jr., R.K., Kohler, M.A. and Paulhus, J.L.H., 1975. Applied Hydrology, 3th edn. McGraw-Hill, New York, 689 pp.

Lloyd, C.R. and Marques Filho, A. de O., 1988. Spatial variability of throughfall and stemflow measurements in Amazonian rainforest. Agric. For. Meteorol., 42: 63–73.

Lloyd, C.R., Gash, J.H.C., Shuttleworth, W.J. and Marques Filho, A. de O., 1988. The measurement and modelling of rainfall interception by Amazonian rainforest. Agric. For. Meteorol., 43: 277–294.

Marques, J., Santos, J.M., Villa Nova, N.A. and Salati, E., 1977. Precipitable water and vapour flux between Belém and Manaus. Acta Amazon., 7: 355-362.

Marques, J., Santos, J.M. and Salati, E., 1979. O armazenamento atmosférico de vapor d' água sobre a região Amazônica. Acta Amazon., 9: 715–721.

Marques, J., Santos, J.M. and Salati, E., 1980. Cálculo da evapotranspiração real na bacia Amazônica através do método aerológico. Acta Amazon., 10: 357–361.

Molion, L.C.B., 1987. Climatologia dinâmica da região Amazônica: mecanismos de precipitação. Rev. Bras. Meteorol., 2: 107–117.

Mortatti, J., 1986. Caracterização biogeoquímica dos principais rios do Estado de Rondônia. Tese de Doutorado, ESALQ, Piracicaba, p. 118.

Organizacíon Meteorológica Mundial, 1967. Guia de Practicas Hidrometeorologicas, 1a Edición. Publ. 168.TP.82, Secretaría de la Ginebra, Suiza.

Ribeiro, M.N.G. and Villa Nova, N.A., 1979. Estudo climatológico da reserva florestal Ducke. III. Evapotranspiração. Acta Amazon., 9: 305–309.

Salati, E., 1985. A floresta e as águas. Ciência Hoje, 3: 58–64.

Salati, E., 1986. Climatology and hydrology of Amazonia. In: G.T. Prance and T.M. Lovejoy (Editors), Amazonia. Pergamon Press, Oxford, pp. 267–276.

Salati, E. and Marques, J., 1984. Climatology of the Amazon region. In: H. Sioli (Editor), The Amazon Limnology and Landscape Ecology of a Mighty Tropical River and its Basin. Dr. Junk, Dordrecht, pp. 85–126.

Salati, E. and Ribeiro, M.N.G., 1979. Floresta e clima. Acta Amazon., 9: 15–22.

Salati, E. and Vose, P.B., 1984. Amazon basin: a system in equilibrium. Science, 255: 129–138.

Salati, E., Dall' Olio, A., Matsui, E. and Gat, J.R., 1979. Recycling of water in the Amazon basin: an isotopic study. Water Resourc. Res., 15: 1250–1258.

Sellers, P.J., Shuttleworth, W.J., Dorman, J.L., Dalcher, A. and Roberts, J.M., 1989. Calibrating the simple biosphere model for Amazonian tropical forest using field and remote sensing data. Part I: average calibration with field data. J. Appl. Meteorol., 28: 727–759.

Shukla, J., Nobre, C. and Sellers, P., 1989. Amazon deforestation and climate change. Science, 247: 1322–1325.

Shuttleworth, W.J., Gash, J.H.C., Lloyd, C.R., Moore,C.J., Roberts, J., Marques Filho, A.O., Fisch, G., Silva Filho, V. de P., Ribeiro, M.N.G., Molion, L.G.B., Abreu Sá, L.D., Nobre, C.A., Cabral, O.M.R., Patel, S.R. and Moraes, J.C., 1984. Eddy correlation measurements of energy partition for Amazonian forest. Q. J. R. Meteorol. Soc., 110: 1143–1162.

Van Mullem, J.A., 1991. Runoff and peak discharges using Green–Ampt infiltration model. J. Hydraul. Eng., 117: 354–370.

Villa Nova, N.A., Salati, E. and Matsui, E., 1976. Evapotranspiração na bacia Amazônica. Acta Amazon., 6: 215–228.

Viswanadham, Y., Molion, L.C.B., Manzi, A.O., Sá, L.D.A., Silva Filho, V.P., André, R.G.B., Nogueira, J.L.M. and Santos, R.C., 1990. Micrometeorological measurements in Amazonian forest during GTE/ABLE 2A Mission. J. Geophys. Res., 95 (D9): 13669–13682.