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LONG-TERM WATER BALANCE IN SMALL CATCHMENTS IN THE ATLANTIC FOREST OF SOUTHEAST BRAZIL[1]

BALANÇO HÍDRICO DE LONGO PRAZO EM MICROBACIAS NA MATA ATLÂNTICA NO SUDESTE DO BRASIL[1]

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ABSTRACT - The Atlantic Forest (Mata Atlântica) supplies millions of people with fresh water. Long-term studies of its catchments are essential for an understanding of the hydrological processes involved. A study of the annual water balance maintained in small catchments of the Walter Emmerich Forest Hydrology Laboratory (LHFWE), Serra do Mar State Park, Brazil, was carried out over a period of 20 years (catchment A), 26 years (catchment B) and 30 years (catchment D). The basic hydrological equation $P = Q + ET \pm \Delta S$ was used. Rainfall (P) was measured with tipping bucket rain gauges installed in clearings. Streamflow (Q) was measured in gauging stations equipped with continuous stage recorders. Soil water storage change (ΔS) was considered equal to zero. Evapotranspiration (ET) was calculated by the difference between P and Q. Average annual rainfall of the catchments was high with a mean of 1960 mm and wide interannual variability. The average streamflow was 1432 mm, corresponding to 73% of the rainfall, indicating remarkable water yield in the catchments. The average annual evapotranspiration was 32.2% for catchment A, 24.5% for B and 24.4% for D. These percentages are smaller than those obtained in studies carried out in other tropical forests, including the Atlantic Forest biome.

Keywords: Evapotranspiration; Rainfall; Streamflow; Forest cover.

RESUMO - A Mata Atlântica abastece milhões de pessoas com água de boa qualidade. Estudos de longo prazo de suas microbacias hidrográficas são essenciais para o entendimento dos processos hidrológicos envolvidos. Um estudo do balanço hídrico anual em microbacias do Laboratório de Hidrologia Florestal Walter Emmerich (LHFWE), no Parque Estadual da Serra do Mar, São Paulo, foi realizado durante um período de 20 anos (microbacia A), 26 anos (microbacia B) e 30 anos (microbacia D). Foi utilizada a equação hidrológica fundamental $P = Q + ET \pm \Delta S$. A precipitação (P) foi medida com pluviômetros de básculas instalados em clareiras no interior da floresta. O deflúvio (Q) foi medido em estações fluviométricas equipadas com linígrafos. A variação no armazenamento de água no solo (ΔS) foi considerada igual a zero. A evapotranspiração (ET) foi calculada pela diferença entre P e Q. A precipitação média anual das microbacias foi elevada, com média de 1960 mm e ampla variabilidade interanual. O Deflúvio médio foi de 1432 mm, correspondendo a 73% da precipitação, indicando notável produção de água nas microbacias. A evapotranspiração média anual foi de 32,2% para a microbacia A, 24,5% para a microbacia B e 24,4% para a microbacia D. Esses percentuais são menores do que os obtidos em estudos realizados em outras florestas tropicais, incluindo o bioma Mata Atlântica.

Palavras-chave: Deflúvio; Evapotranspiração; Precipitação; Cobertura florestal.

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1 INTRODUCTION

The Atlantic Forest (Mata Atlântica) is a tropical biome with a hot and humid climate. It once occupied about 15% of Brazil (1,315,460 km2), extending along the Atlantic Coast, originally from Rio Grande do Norte to Rio Grande do Sul, encompassing 17 states. Its dense vegetation has been enormously devastated since the beginning of the colonization of Brazil, mainly from extraction of wood and firewood, as well as increasing rural and urban occupation. Today, it has been reduced to 8.5% of forest remnants above 100 hectares and 12.4% above 3 hectares (Fundação SOS Mata Atlântica, 2018). The Atlantic Forest is fundamental for the maintenance of hydrological processes in catchments that supply millions of people with fresh water (Lino and Dias, 2005).

Small catchments are adequate ecosystems with which to evaluate the impacts of anthropic activity, which may pose serious risks to their equilibrium (Lima, 2010). Understanding water balance is crucial to assessing the role tropical forests play in regulating river water (Mcjannet et al., 2007).

Since the tropical climate exhibits a high temporal variation of its attributes, it is appropriate that hydrological studies be conducted in the medium to long term since results can vary considerably from year to year (Cicco et al., 2019). Systematic and long-term studies should be performed in small catchments in order to understand the relationships and internal functions involved in the maintenance of these ecosystems (Neal and Clarke, 2007). However, studies in small Atlantic Forest catchments have typically reported on short-term data, rarely exceeding two years of monitoring (Pereira Filho et al., 2002; Cardoso et al., 2006; Voigtlaender, 2007; Groppo, 2010; Mello et al., 2019; Rodrigues et al., 2020).

Three monitored catchments (A, B and D) within the Atlantic Forest, located in the Walter Emmerich Forest Hydrology Laboratory (LHFWE), Serra do Mar State Park, are part of a research project started in the late 1970s. Since then, they have been an outdoor laboratory for detailed studies of water balance processes (Fujieda et al., 1997; Donato et al., 2008; Arcova et al., 2020), water quality and transfer of chemical species (Forti et al., 2007), the hydrological effects of the natural regeneration (Teixeira et al., 2021), as well as hydrological models (Ranzini et al., 2004, 2007), in order to provide data supporting the establishment of adequate planning for land use in this region.

This paper summarizes and discusses the results from annual long-term water balance obtained in catchments A, B and D.

2 MATERIAL AND METHODS

2.1 Site Description

Experimental catchments A (37.5 ha), B (38.7 ha) and D (56.0 ha) are part of LHFWE located at Cunha Station, Serra do Mar State Park (PESM) (São Paulo state). It is near the headwaters of the Paraibuna River, which forms the Paraíba do Sul River (Figure 1).

The present vegetation is denominated Dense Ombrophilous Montane Forest (Atlantic Forest); however, it has suffered from intense logging since the early 1950s, and only hilltops and some stretches of valley bottom have been preserved. With the transformation of the area into a conservation unit (PESM) (SÃO PAULO, 1977), the vegetation has been undergoing a process of natural regeneration. The bedrock consists of gneisses and crystalline schist of the Precambrian age and is generally classified as impermeable with the presence of Crystalline Aquifer with low and very variable productivity conditioned to the presence of open fractures. The topography is characterized by bulging tops, steep slopes and altitude ranging from 1050 to 1220 m. Oxysols (FAO-System) comprise the dominant soil coverage with Gleyic Cambisols close to the creeks. It is chemically poor, acidic, with coarse texture, high porosity and good permeability.

The average annual rainfall (1980 to 2017) is 1950 mm. The mean annual air temperature is 17.0ºC, and the average maximum and minimum air temperatures are 21.6ºC and 6.7ºC in winter and 26.4ºC and 15.6ºC in summer, respectively. Köppen’s system classifies the climate as Cwb type. Details of the region and characteristics of the catchments are in Teixeira et al. (2021).

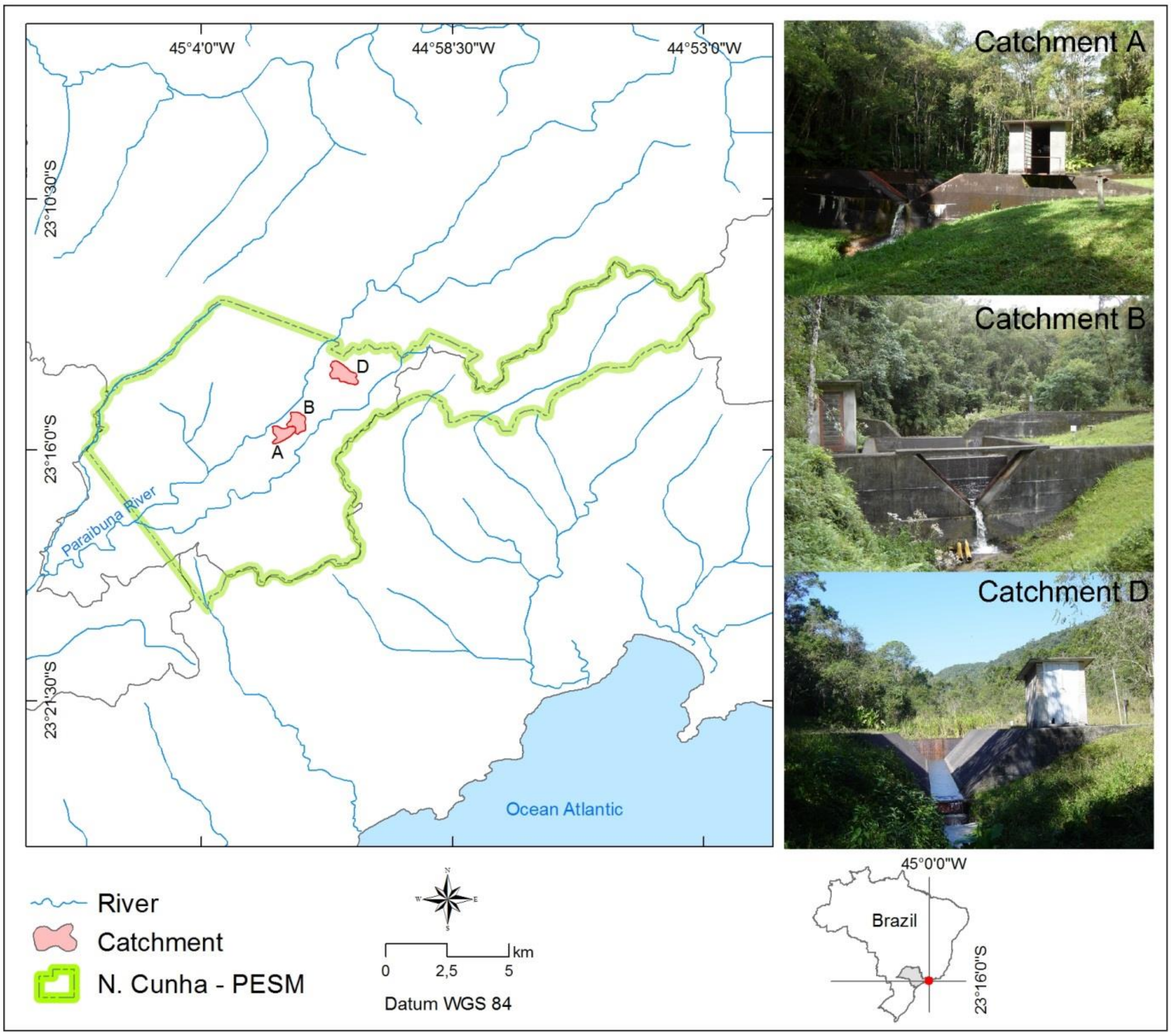

Figure 1. Location of the Laboratory of Forest Hydrology Walter Emmerich, Serra do Mar State Park, São Paulo - Brazil, catchments A, B and D, and their gauging stations.

Figura 1. Localização do Laboratório de Hidrologia Florestal Walter Emmerich, Parque Estadual da Serra do Mar, São Paulo - Brasil, microbacias A, B e D, e suas estações fluviométricas.

2.2 Water Balance

The annual water balance in catchments A, B and D was determined using the basic hydrological equation 1.

$$P=Q+ET\pm\Delta S \quad (1)$$

Where P is annual rainfall, Q is annual streamflow, ET is annual evapotranspiration and ΔS is the annual variation in soil water storage. During long periods, ΔS becomes very small relative to the magnitude of P and Q. ET is the difference between P and Q. The hydrological year begins in October, which is when water storage in the catchments reaches the lowest value (Fujieda et al., 1997). Rainfall was measured with tipping bucket rain gauges with a capacity of 0.5 mm, and these were installed in clearings: two in catchment A, three in catchment B and four in catchment D. The actual rainfall within each the catchment was calculated by the arithmetic mean method. Streamflow was measured with a stilling pond equipped with a continuous stage recorder (Figure 1). Details of catchment facilities and equipment are found in Teixeira et al. (2021).

Monitoring catchment A was initiated in 1992, catchment B in 1986 and catchment D in 1982. For this study, data collected up to 2012 were used.

3 RESULTS AND DISCUSSION

Table 1 shows the results of the annual water balance components for the three catchments.

Table 1. Rainfall (P), streamflow (Q) and evapotranspiration (ET) in mm and standard error (SE) of the mean with a 95% probability of confidence for catchments A, B and D.

Tabela 1. Precipitação (P), deflúvio (Q) e evapotranspiração (ET) em mm e erro padrão da média (SE) com 95% de probabilidade para as microbacias A, B e D.

Water Year	Catchment A			Catchment B			Catchment D		
	P	Q	ET	P	Q	ET	P	Q	ET
	mm.year^{-1}								
1983							2568.9	1827.1	741.8
1984							1841.8	1346.3	495.5
1985							3061.7	2721.5	340.2
1986							2356.8	1183.0	1173.7
1987				2287.9	1862.1	425.8	2552.0	1969.8	582.2
1988				2052.3	1468.0	584.2	2124.8	1592.3	532.5
1989				2201.0	1514.1	686.9	2334.4	1521.6	812.8
1990				1738.8	1194.6	544.2	1824.2	1199.6	624.6
1991				2089.1	1609.6	479.5	2198.7	1798.5	400.1
1992				1753.9	1163.3	590.6	1778.9	1247.1	531.8
1993	1886.3	1323.3	562.9	1843.4	1710.7	132.7	2030.7	1357.9	672.8
1994	1775.5	1170.7	604.8	1774.5	1309.4	465.1	2059.0	1437.1	621.9
1995	1945.0	1429.0	516.0	1902.9	1470.4	432.5	2155.7	1570.1	585.6
1996	2505.0	2328.7	176.3	2428.6	2319.7	108.9	2375.2	1730.9	644.3
1997	1377.1	859.9	517.2	1490.1	929.0	561.1	1777.7	783.4	994.2
1998	1857.6	1085.5	772.1	1701.6	1220.8	480.8	2114.4	1218.9	895.5
1999	1823.4	1241.7	581.7	1552.5	1341.6	210.9	2098.1	1457.8	640.3
2000	1961.6	1444.0	517.6	1823.4	1669.6	153.8	2173.4	1551.9	621.5
2001	1594.5	842.3	752.2	1508.1	930.4	577.7	1668.1	920.3	747.8
2002	1578.3	838.9	739.4	1437.3	835.1	602.2	1665.1	1263.6	401.5
2003	1632.5	878.6	753.9	1501.8	957.6	544.1	1742.4	1681.7	60.8
2004	1983.0	1084.1	898.9	1887.3	1328.1	559.2	2102.9	1968.1	134.9
2005	2086.4	1458.8	627.6	2188.0	1691.9	496.1	2316.4	2218.3	98.1
2006	1732.8	1197.6	535.2	1703.4	1360.9	342.5	1850.6	1705.1	145.5
2007	1738.5	1009.6	728.9	1723.7	1113.6	610.1	1797.0	1299.7	497.3
2008	1838.5	1089.1	749.4	1888.5	1136.2	752.3	1829.3	1501.1	328.2
2009	2117.5	1236.3	881.2	2148.9	1458.9	690.0	2217.5	1733.6	483.8
2010	2518.8	2243.9	274.9	2491.0	2358.0	133.1	2802.4	2661.6	140.8
2011	2131.4	1835.9	295.6	2102.1	1946.3	155.8	2452.3	2264.9	187.5
2012	1568.1	928.1	640.0	1584.8	941.4	643.3	1719.8	1366.0	353.8
Mean	**1882.6**	**1276.3**	**606.3**	**1877.1**	**1417.0**	**460.1**	**2119.7**	**1603.3**	**516.4**
SE	**±128.1**	**±187.5**	**±84.6**	**±113.5**	**±154.9**	**±74.9**	**±123.7**	**±160.1**	**±97.0**
% of P	**100.0**	**67.8**	**32.2**	**100.0**	**75.5**	**24.5**	**100.0**	**75.6**	**24.4**

3.1 Rainfall

Annual rainfall in the three catchments is high with a mean of 1959.8 mm. The Cunha catchments constitute part of the so-called "eastern regional unit of rainfall typology" proposed for the São Paulo territory, which includes the interior border of Serra do Mar, the annual rainfall rates of which are between 1800 mm and 2000 mm (Sant'Anna Neto, 1995). The annual average of the catchments exceeded the average rainfall in the Paraíba do Sul River basin (1988 and 2014) by more than 600 mm with a final total of 1390 mm (Gomes et al., 2021). The mean of 1959.8 mm is higher than the value of 1782.0 mm in the historical series from 1957 to 2003 from the Lídice rainfall station (Rio Claro-RJ), which is located mid-valley in the Paraíba do Sul River basin in Rio de Janeiro state (Costa et al., 2012). The Cunha and Lídice localities typically experience the effects of humidity from the sea and orography of Serra do Mar, both factors affecting the significant rainfall indexes documented in this region (Nery et al., 2000).

The range of values indicates an extensive interannual variability, or annual fluctuation, of rainfall in the catchments. The smallest rainfall recorded was 1377.1 mm in catchment A, and the largest was 3061.7 mm in catchment D. Essentially, such fluctuations occur as a result of differences in supply and activity of the polar masses. The years of intense polar activity imply high rainfall in the state of São Paulo, while the weakening of these areas, which can be attributed to intertropical systems, accounts for the less rainy years (Fundação Florestal, 2009). The amplitude of the annual rainfall of the LHFWE catchments agrees with that predicted for Serra do Mar, i.e., values between 1300 mm and 2800 mm (Soares et al., 2008).

Compared to the results of water balance studies in other locations in the Atlantic Forest biome, average annual rainfall of catchments A, B and D was lower than the highest recorded rates, i.e., 2503 mm in Serra da Mantiqueira (Mello et al., 2019) and 2359.5 mm in the Serra do Mar (Groppo, 2010). The annual rainfall that comes closest to that of the Cunha catchments was obtained in the Pedras River basin in Paraná (Cunha et al., 2011). For the time series from 1985 to 2009, average annual rainfall was 1893.3 mm, a difference of just 66.5 mm relative to that for Rio das Pedras-PR basin.

3.2 Streamfall

The streamflow of the catchments, which is generated when stored water in different parts of catchments connects and forms a steady flow, presented considerable variation over the years of monitoring (Table 1). However, a similar pattern was observed between the series (Figure 2). The total streamflow was generally larger in catchment D, which is consistent with its greater rainfall.

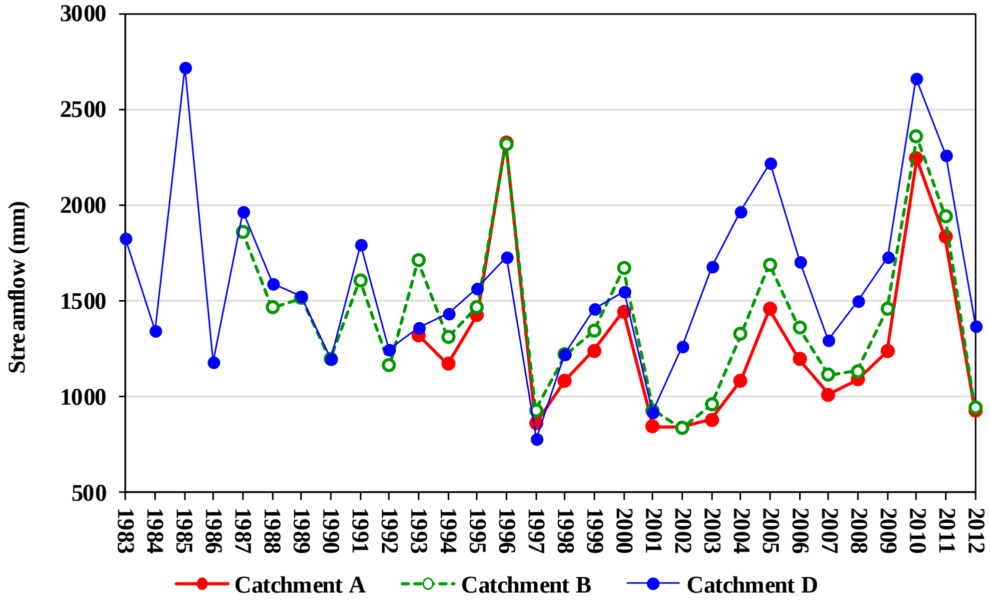

Figure 2. Time series of annual streamflows in catchments A, B and D.

Figura 2. Séries temporais do deflúvio anual das microbacias A, B e D.

The average annual streamflow of catchments A, B and D (1432.2 mm) corresponded to 73% of the rainfall. This is larger than that recorded in other catchments in the Atlantic Forest biome, even though these records of streamflow show a higher rainfall than those in Cunha. In Serra da Mantiqueira, the average streamflow, over the two-year experimental period was 871 mm (35% of the rainfall) (Mello et al., 2019). In São Luiz do Paraitinga, Serra do Mar, the average streamflow was 1302 mm (55% of rainfall), also for an experimental period of two years (Groppo, 2010).

The high flow rates in LHFWE catchments result from the combination of high surface infiltration and high permeability inside the soil. On the slopes of catchment D, for example, the infiltration capacity was determined to be 18 mm h-1 and is rarely surpassed by the intensity of rainfall, which tends to be less than 10 mm h-1 (Ranzini et al., 2004). The mean porosity and the saturated hydraulic conductivity of the hillslope are 51.4% and 10-3 cm/s (36 mm h-1), respectively (Fujieda et al., 1997). Thus, most of the rain that crosses the forest cover, and the litter infiltrates moves to the lower portions of the soil and the regolith and is stored there, constituting the main source of supply for the streamflow.

Although the streamflow regime of LHFWE catchments is typical of places with regular distribution of rainfall throughout the year, the rainfall regime is not. In general, rains supplant the streamflow between September and March. In the less humid months of May to August, the opposite occurs (Figure 3). The smallest monthly streamflow occurs in August, albeit still high, averaging 70 mm. This indicates that the catchments have a large storage capacity, causing the stream to be fed by base flow originated by rains that occurred during the rainy season (Fujieda et al., 1997).

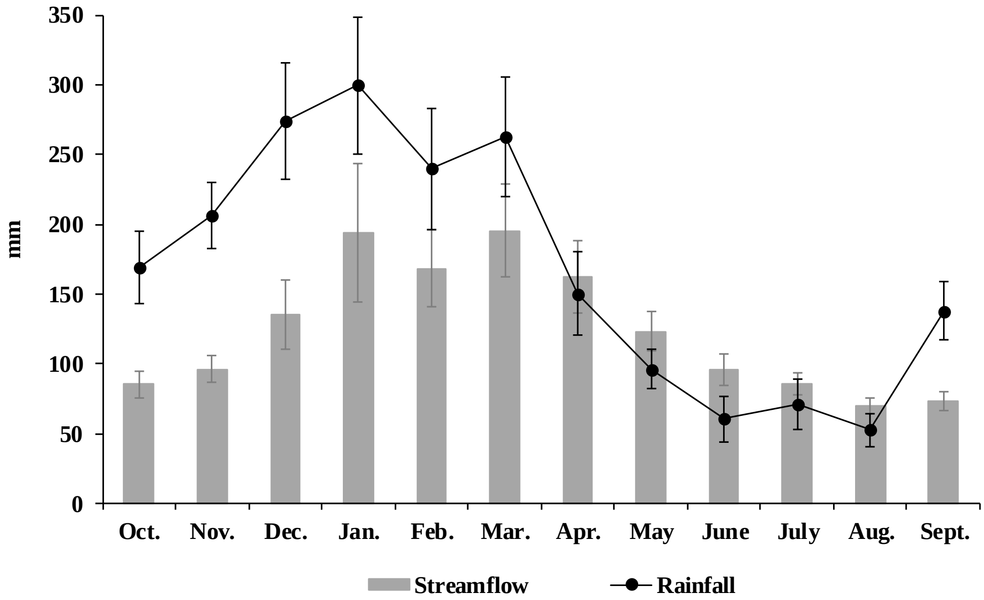

Figure 3. Average monthly rainfall and streamflows calculated from the average of the three catchments, A, B and D. The error bars show the standard error of the mean with a confidence interval of 95% probability.

Figura 3. Precipitação e deflúvio médios mensais calculados a partir da média das microbacias A, B e D. As linhas verticais são o erro padrão da média, com intervalo de confiança de 95% de probabilidade.

3.3 Evapotranspiration

A large extension of evapotranspiration values was observed (Table 1). In catchment A, the average was 606 mm, 460 mm in catchment B, and 516 mm in catchment D. As a percentage of rainfall, mean evapotranspiration was 32.2%, 24.5% and 24.4%, respectively.

The evapotranspiration percentages for catchments B and D were slightly lower than those recorded by Fujieda et al. (1997). For data series from catchment B (1986 to 1992) and from catchment D (1983 to 1992), the authors recorded values of 29% of evapotranspiration in relation to rainfall. On the other hand, the average percentage of the twenty-year series of catchment A was equal to that of the eight-year series of data evaluated by Anido (2002), that is, 30%, and lower than that obtained in the subsequent five years when evapotranspiration was 697 mm, corresponding to 39% of the annual rainfall (Donato et al., 2008).

An appropriate estimate of evapotranspiration can be obtained from the measurement of several years' worth of rainfall and streamflow, attenuating variations in soil water storage. In order to demonstrate the importance of having a long period of observation, the years 1983 to 1986 for catchment D were selected (Table 1 and Figure 4). In the first two years, evapotranspiration was close to the average for the thirty-year series (29% and 27%). However, in 1985, the rainfall was atypical (3061.7 mm) in that it was concentrated in the first three months (1839.3 mm). This rainfall caused a large volume of streamflow, in turn causing a considerable part of the water to rapidly exit the catchment, reducing evapotranspiration losses. Consequently, in 1986, evapotranspiration was high (50%). When considering these four years, the average evapotranspiration was 28.0%, a representative value for the total period.

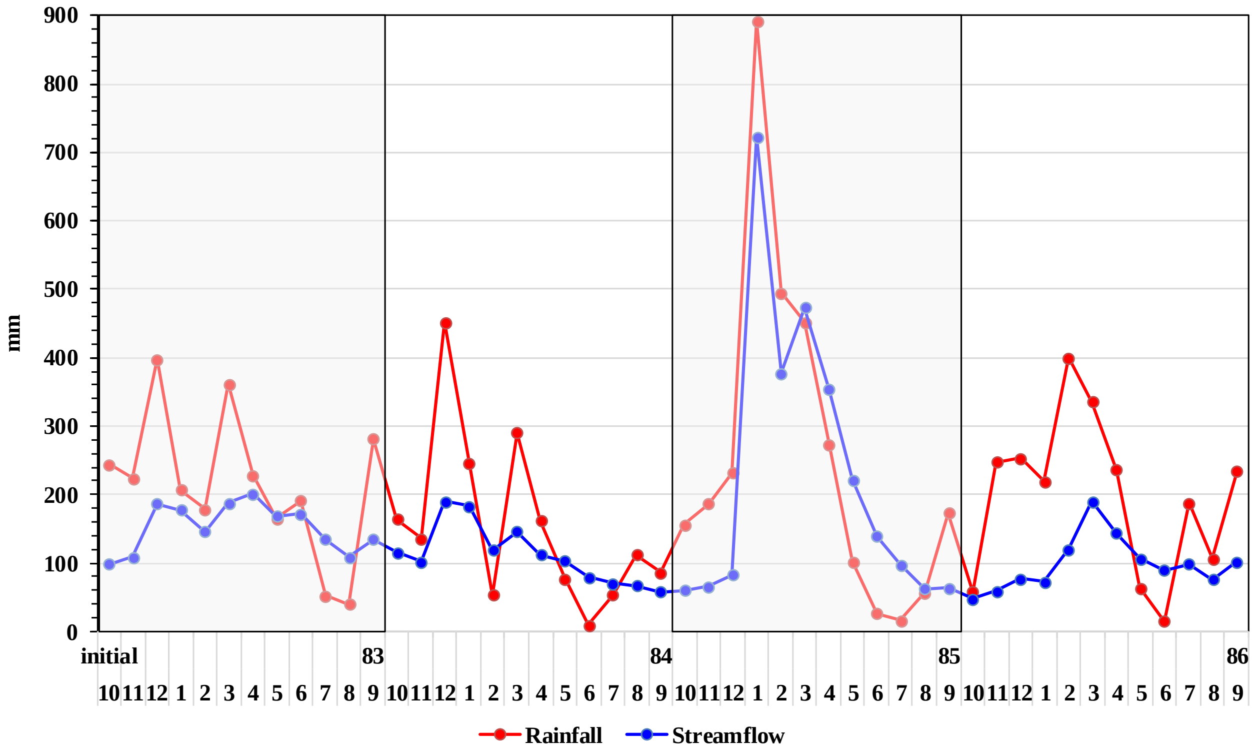

Figure 4. Monthly variation of rainfall and streamflow of catchment D for water years 1983 to 1986.

Figura 4. Variação mensal da precipitação e do deflúvio da microbacia D para os anos hídricos de 1983 a 1986.

To compare the results obtained here, Table 2 presents annual evapotranspiration values in tropical and subtropical forests of the world. Cunha catchments had average evapotranspiration percentages midway between those of catchments with nebular forest (12% to 15%) and other catchments (35% to 81%). The LHFWE is located in a region strongly influenced by mountain fogs (Arcova et al., 2016). The occurrence of this meteorological phenomenon in the domains of the three catchments should contribute to low levels of radiation in the forest during these events and, consequently, to low transpiration. Hutley et al. (1997) reported on a catchment in Australia where the relative humidity remained at 100% for twenty-four hours on a foggy day with a resultant 40% reduction in the transpiration rate. Although the Cunha catchments suffer the influence of fog, this effect should be smaller from a hydrological point of view than that in the catchments of nebular regions, which are normally at higher altitudes.

Table 2. Annual evapotranspiration in tropical and subtropical forests, including the Atlantic Forest.

Tabela 2. Evapotranspiração anual em florestas tropicais e subtropicais, incluindo a Mata Atlântica.

Location	P (mm)	ET (mm)	ET(%)	
Tropical and subtropical forests around the world				**References**
Floresta Amazônica-BR	2075	1675	80.7	Bruijnzeel (1990)
Sierra Nevada-COL	2316	308	13.3	
Mt. Data-PH	3382	392	11.6	
Kimakia-KEN	2307	1156	50.1	
Mbeya-TZA	1924	1381	71.8	
Ciwidey-IDN	3306	1170	35.4	
Cerrado-BRA	1221	823	67.4	Oliveira (2014)
Floresta de baixa altitude-AUS	2171	1171	53.9	Mcjannet et al. (2006)
Floresta de elevada altitude-AUS	7190	1074	14.9	
Floresta Tropical Úmida-MYS	1720	1182	68.7	Lion et al. (2017)
Atlantic Forest (Mata Atlântica)				**References**
Telêmaco Borba-PR	1218	994	81.6	Voigtlaender (2007)
Guarapuava-PR	1893.3	960.4	51.1	Cunha et al. (2011)
São Paulo-SP	1290.5	1004.9	77.9	Pereira Filho et al. (2002)
São Luiz do Paraitinga-SP	2359.5	1302.5	55.2	Groppo (2010)
Bocaina de Minas Gerais-MG	2503	1190	47.5	Mello et al. (2019)
Aracruz-ES	1375	1350	98.2	Almeida and Soares (2003)
São Miguel do Anta-MG	1078.4	899.5	83.4	Rodrigues et al. (2020)
Nova Friburgo-RJ	2163	1923	88.9	Cardoso et al. (2006)

Evapotranspiration values from other studies in the Atlantic Forest are also in Table 2. As for tropical and subtropical forests, the variation is wide with a minimum of 900 mm and a maximum of 1923 mm. Catchments A, B and D have an average evapotranspiration percentage of 27%, lower than the values reported in the literature. Cunha catchments are located in an environment of dense montane rainforest (secondary), altitude of approximately 1000 m, and high incidence of fog, but despite its proximity to São Luis do Paraitinga of about 30 km, considerable difference was shown between catchments. Also using mass water balance, Groppo (2010) estimated evapotranspiration at 1035 mm (60% of rainfall) in 2008 and at 1570 mm (52% of rainfall) in 2009. In the hydrological years 2008 and 2009, evapotranspiration in catchments A, B and D was equivalent to 21%, 40% and 41% and 22%, 32% and 42% of the rainfall, respectively. If the "calendar year" is considered, as done by Groppo (2010), the values are 17.1%, 39.8% and 40.3% in 2008 and 22.9%, 33.2% and 43.5% in 2009, respectively. In both situations, the average percentage difference between São Luis do Paraitinga catchment and the catchments of LHFWE was 23%. One of the possible causes of the mismatch between the results of the two studies is related to interception losses by the crowns. In São Luis do Paraitinga, this process corresponds, on average, to 33% of annual rainfall (Groppo, 2010), while in Cunha catchments it is, on average, 19% (Arcova et al., 2020). Evapotranspiration in the forest consists of the crown interception component and the transpiration component. In the climatic conditions of São Luis do Paraitinga and Cunha, a regime of not very intense rains, continuous and frequent rains, interception may constitute the largest share of total water consumption by the forest (Arcova et al., 2003). As in the A, B and D catchments, the interception is smaller than that in the São Luis do Paraitinga catchment. Therefore, it should result in the lowest verified evapotranspiration rates.

4 CONCLUSIONS

The monitoring of rainfall and streamflow in the experimental catchments of LHFWE is, to date, the longest conducted in the Brazilian Atlantic Forest Domain, extending for thirty years in catchment D, twenty-six years in B and twenty years in catchment A. Synthesizing the results of this annual long-term water balance shows that the average annual rainfall of the catchments was 1960 mm, with a wide interannual variability. The annual streamflow presented considerable variation during the studied period, but with a similar pattern between the catchments. The average streamflow of the catchments was 1432.2 mm and corresponded to 73% of the rainfall. The mean evapotranspiration of the three catchments ranged from 460.1 to 606.3 mm, corresponding to 24.4% to 32.2% of the rainfall. These are lower percentages than those obtained in most studies reporting on catchments in tropical and subtropical forests, except those of higher altitude nebular forests. They are also smaller than those obtained in studies in the Atlantic Forest biome (Mata Atlântica). Continuity of research at LHFWE is extremely important for the generation of information to help formulate public policies aimed at managing and restoring this ecosystem, which constitutes a remarkable water source.

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