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Water Balance in the Brazilian Amazon Basin

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R E S U M O

O objetivo deste trabalho é estudar o balanço hídrico na Bacia Amazônica Brasileira no período de 1982-2012; determinando a vazão referência de cada sub-bacia; determinando a influência dos fenômenos El Niño e La Niña no balanço hídrico; além das diferenças desse balanço ocorridas entre as sub-bacias da margem esquerda e margem direita. A importância desse estudo deve-se ao fato que a Região Amazônia comporta a maior florestal tropical e a maior bacia hidrográfica do mundo, suprindo as necessidades de umidade do resto do pais. Contudo o desmatamento da floresta e a ocorrência de eventos extremos de precipitação modificam o ciclo hidrológico, interferindo na precipitação, vazão e evaporação. Nesse estudo foram utilizadas 224 estações pluviométricas e a vazão de referência em 8 sub-bacias, do rio Solimões, Negro, Trombetas, Jari, Purus, Madeira, Tapajós e Xingu. Assim este estudo encontrou resultados importantes, onde a taxa de evaporação a partir da precipitação teve valores entre 58 e 62% entre as calhas sul e norte, respectivamente, além disso em média a evaporação teve uma tendência positiva ao longo do período estudado mostrando que durante o El Niño essa taxa é maior na margem esquerda e menor na margem direita.
Palavras chaves: eventos extremos, precipitação, vazão e evaporação.

Water Balance in the Brazilian Amazon Basin

A B S T R A C T

The present work aimed at studying the water balance in the Brazilian Amazon Basin in the period from 1982 to 2012; by determining the reference flow of each sub-basin; by determining the influence of El Niño and La Niña phenomena in the water balance; as well as the differences of this balance that occurred between the sub-basins of the left and right banks. The importance of this study is due to the fact that the Region Amazon houses the largest tropical forest and the largest river basin in the world, supplying the humidity needs of the rest of the country. However, deforestation and the occurrence of extreme events of precipitation change the hydrological cycle, affecting the precipitation, flow and evaporation. In this study, 222 rain stations were utilized, as well as the reference flow of 8 sub-basins of rivers Solimoes, Negro, Trombetas, Jari, Purus, Madeira, Tapajós and Xingu. Thus, this study found significant results, where the rate of evaporation resulting from precipitation had values between 58% and 62% between the northern and southern channels,

respectively. Moreover, on average, evaporation had a positive tendency over the studied period showing that during El Niño, this rate is higher in the northern channel and lower in the southern rail.
Key words: extreme events, precipitation, flow and evaporation.

Introduction

According to studies like de Rocha (2004) 70% of the total surface of the Earth, approximately 581 million km2, consists of water, and the oceans are the main sources of water vapor for the global atmosphere. However, the forests, especially the Amazon rainforest, which has great length and biodiversity, also contribute as much water vapor sink to tropical continental regions, playing an important role in the hydrological cycle in these regions.

Brazil has 11.6% of all the world's fresh water and the Amazon region contributes about 70% (Rocha, 2004). Marengo (2006) states that the availability of water in Brazil depends largely on the weather and the type of ground cover, where the plant samples of forests carry water from the soil into the atmosphere. And the energy required (sweating) to turn water into steam may represent 50% of the precipitation.

The variability of precipitation and flow in the Amazon basin are issues of major concern, due to the deforestation of burning, the extremes (drought and flooding) and meteorological phenomena, such as El Nino, causing the dry, forest fires (Fearnside, 2009) and La Niña, which unlike raises rainfall, causing floods, leaving whole riverside populations homeless.

The Brazilian Amazon basin covers the states of Amazonas, Roraima, Acre, Rondônia, part of Mato Grosso, Pará and Amapá, between the 20ºS coordinated 5ºN and 80ºW the 55ºW also part of the hydrography of several other Latin American countries, as the Amazon river rises in the upper Rio Apurimac-Ucayali, in the Andes of southern Peru, over 5,500 meters above sea level and flows into the Atlantic Ocean after passing through Curuçá Lighthouse, Para, through the Marajó Island to the northern archipelago of Bailique. The Amazon Basin encompasses a total of 10 sub-basins and 2,752 rivers (ANA, 2013). This basin is the largest continuous area of world's tropical forest with high levels of rainfall, with large variations in time and space, sustaining extensive biological diversity (Silva Dias et al., 2005). However according to studies by Noble et al.

According to Figueroa and Nobre (1990) the Amazon Basin acts as an atmospheric moisture sink, with average annual rainfall of about 2300 mm, ranging from 1600 mm / year to 3000 mm / year in the west, northwest and north coast of the Amazon, presenting two distinct seasons, the dry season (winter and spring HS), with rainfall less than 100 mm / month, and the rainy season (summer and autumn HS) with rainfall exceeding 200 mm / month. Marengo (2006), yet complete, stating that the Amazon Basin contains 70% of the global availability of fresh water, and forming for over a thousand rivers.

Rebouças and Braga (2002) concluded that 56% of the rainwater on the Amazon River, back into the atmosphere by the action of forests, that is, more than 50% of the rainfall comes from the recirculation of water vapor over the Amazon rainforest .

The Amazon River has great regularity in the annual hydrological regime, that is, in the sub-basins which are in precipitation drought regime are offset by sub-basins lying in the flood season, making the annual hydrological regime varies slightly from year to year, as studies Callède et al. (2002), but when it comes to this normal seasonal changes, because according Satyamurty et al. (2013) the rainy season, which runs from November to April, holds 70% of the total annual rainfall and the dry season, which runs from May to October, only holds the remaining 30%.

However, the rainfall in the Amazon Basin is different in the tributaries of the left bank and right bank, for the left margin is influenced by deslocamente the Intertropical Convergence Zone (ITCZ) and the right bank of the South Atlantic Convergence Zone (SACZ) according to the studies of Tomasella et al. (2013).

The moisture balance in the Amazon is one of the important points for the regional hydrological cycle, however to date are difficult to close the water balance in the Amazon, with the errors of the order of 10 to 25% in precipitation, as identified by Rocha (2004), which is at risk from climate change in the Amazon, since the rise in temperature will cause greater evaporation and greater plant transpiration, which will lead to an acceleration of the hydrological cycle (Case, 2006).

The river basins of South America for 30 years (1968-1980) were studied by Garcia and Merchoso (2005), which found that the flow of major rivers had a tendency to increase since the year 1970, which may reflect in large impacts scale on climate change, and periodicities with El Niño (EN). Satyamurty et al. (2013) also obtained results that confirm the studies of Garcia and Merchoso (2005), they found that the water level has increased ten cm / year.

Several studies, such as Zeng (2008), Yoon and Zeng (2010), Marengo et al. (2012) showed that the variability of the hydrological cycle in the Amazon is not due only to the heating and cooling of the eastern Pacific surface, ie, due to the phenomena of El Niño or La Niña, but also to the North and South Atlantic Ocean. Besides addition, Aragon et al. (2007) indicated that droughts in the Amazon are caused by various weather phenomena which cause different impacts in different regions of the Amazon Basin.Zeng et al. (2008) were also on the different influences in the Amazon, water Pacific and Atlantic, as in the rainy season influence Pacific is typically locked and dry season the impact is greatest when influenced by the Atlantic, as occurred in 2005, for the Amazon water ecosystem was more vulnerable, and this small flow rates hit record.

So the purpose of this paper is to study the water balance in the Brazilian Amazon Basin in the 1982-2012 period; determining the flow reference each sub-basin, the influence of El Niño and La Niña in the water balance, beyond the differences that occurred balance between the left and right edge of the sub-basins.

Material and methods

This work was done in the Brazilian Amazon Basin, located in the states of Amazonas, Roraima, Acre, Rondônia, part of Mato Grosso, Pará and Amapá, using flow and precipitation data of the National Water Agency (ANA, 2013) between the years 1982 to 2012. the methodology used is described in detail in the following sections.

2.1 data:

The Amazon region, in its great length, has a considerable density of rainfall and fluviometric networks, but many of these stations datasets have flaws and do not operate in the same period of time, so it was necessary to thorough selection of stations with your criteria above. However the data used in this study are:

a) Monthly precipitation data (in mm) of 224 rainfall stations of the National Water Agency / Geological Survey of Brazil (ANA / CPRM) in the period from 1982 to 2012, totaling 31 years of data.
b) Flow data of 8 fluviometric stations in the main channel of the rivers of the 8 sub-basins, corresponding reference flow and partial and total area (in Km2), as shown in Table 01.
c) History of extreme weather events, drought and floods, El Niño and La Niña, which affected the Brazilian Amazon Basin, in the period from 1982 to 2012, as shown in Table 02.

Table 01 - Real area and reference area of each sub-basin of the Amazon Basin

SUB-BASINS	REFERENCE AREA (Km^2)	REFERENCE STATION	PARTIAL AREA (Km^2)
Jari	57698,7	São Francisco	52767,658
Madeira	1449159,9	Manicoré	1143965,631
Negro	760728,7	Serrinha	308016,623
Purus	410471,8	Canutama	252132,050
Solimões	2107371,8	Itapéua	1814197,999
Tapajós	497166,7	Itaituba	461983,900
Trombetas	129044,2	Garganta	76959,611
Xingu	509545,7	Altamira	3207674,510

Table 02 - Time Event occurrence of El Niño and La Niña between 1982 and 2012

EL NIÑO			LA NIÑA		
WEAK	**MODERATE**	**STRONG**	**WEAK**	**MODERATE**	**STRONG**
2004-2005	1986-1987	1982-1983	1983-1984	1998-1999	1988-1989
2006-2007	1991-1992	1987-1988	1984-1985	2007-2008	1999-2000
	1994-1995	1997-1998	1995-1996		2010-2011
	2002-2003		2000-2001		
	2009-2010		2005-2006		
			2008-2009		
			2011-2012		

Source: Based on the Oceanic Niño Index (Onni) - NOAA, 2015.

Methodology:

Water Balance in the Amazon Basin:

To determine the water balance of the Amazon Basin sub-basins methodological procedures were carried shown in Figure 01.

The water balance was carried out to the north and south rails, later to determine the total water balance of the Amazon Basin as a whole. The analysis was performed with total annual rainfall and the reference flow rate of each sub-basin to 1982 and 2012 to the rainfall and gauged stations used in this study.

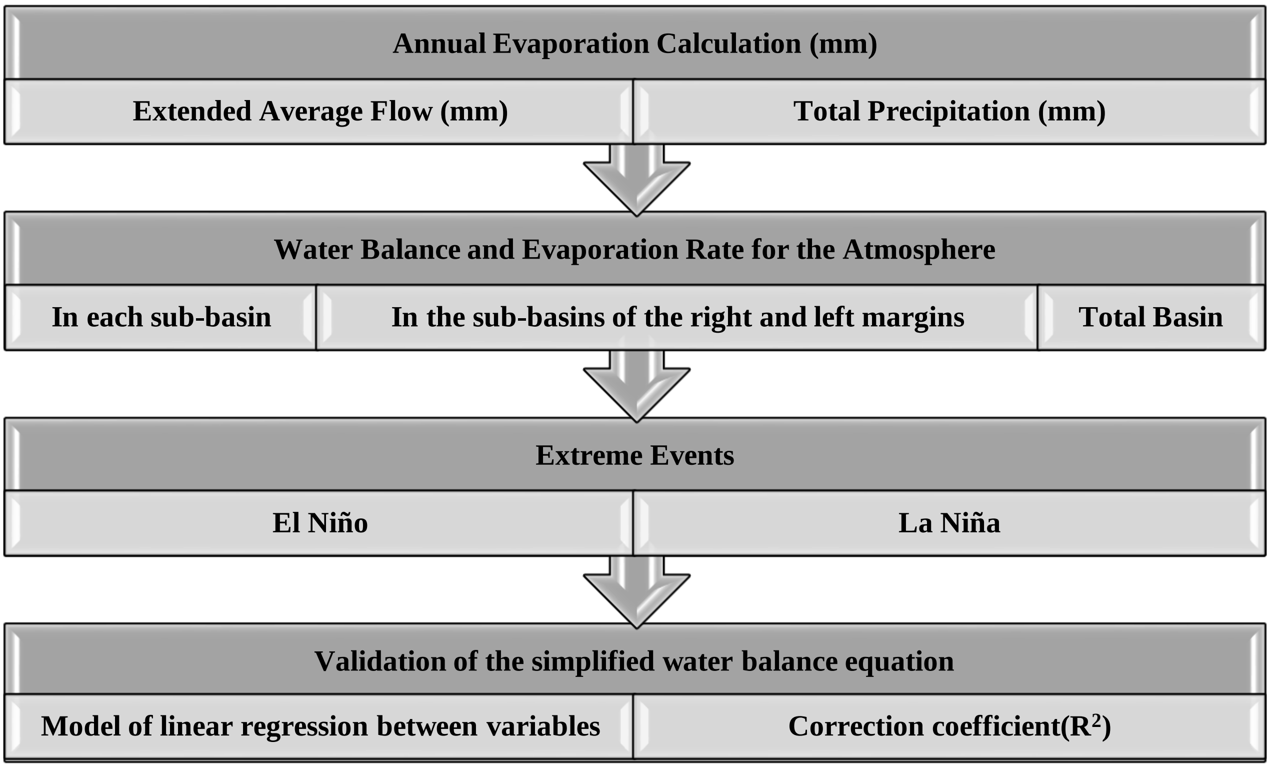

Figure 01 - Organization Chart demonstration of the methodology of the water balance of the Amazon Basin.

2.2.1.1. Calculation Annual evaporation (mm)

For the calculation of evaporation was used the model of Water Balance proposed by Bolton (1980) and Iribarne and Godson (1973), according to equation (1) which has emerged from the continuity equation, using the extended flow (in mm) and the total precipitation (in mm).

$$\boldsymbol{Q = P - E} \quad (1)$$

at where,

Q - flow (m3.s-1), converted into mm, by the conversion factor: 31549 * Q (m3.s-1) / area of the sub-basin (km2)

P - is the precipitation (mm)

E - is the evaporation (mm)

The equation (1) is a simplified model of the moisture balance, considering that all other terms are negligible for years, and that only the flow, precipitation and evaporation are important for large basins. This statement can be proven by the methodology by Yanai et. al. (1973).

With the data in Table 02 comparisons were made each year, and the left and right margins with the years of El Niño and La Niña. However, during the years of El Niño evaporation increases due to direct radiation in the region and during La Niña events, cloudiness is higher and thus reduces evaporation.

2.2.1.2. Reference flow in the Amazon river channel:

For the calculation of the reference flow is used only fluviometric stations located in the bed of the main streams of 8 sub-basins as shown in Figure 02 and Table 01. As can be seen in Figure 02, the areas of the sub-basins were not completely filled (white spaces), then it was necessary to determine the extended flow to the main channel of the Amazon River, so that the flow would be representative of the total area of the sub-basin, as shown in Table 01.

Thus, for the determination of the outflows extended in the channel of the Amazon river was used statistical procedure (multiple regression), adopting the largest coefficient of correlation R2 to determine the best type of line to be used.

2.2.1.3 Water balance and rate of evaporation into the atmosphere

The equation (1) is a simplified model of the water balance, whereas all other terms are negligible for periods longer than a month, and that only the flow, precipitation and evaporation are important for large basins. This statement can be proven by the methodology by Yanai et al. (1973).

The evaporation rate was determined from the precipitation, or evaporation rate ($E/_P$) is the amount of evaporation it back to the atmosphere from the precipitable water.

Both the balance as water evaporation rate ($E/_P$) is performed for each sub-basin, to further determine the difference between the left and right margins, and the total balance of the Amazon Basin as a whole.

Extreme events

The extreme events, El Nino and La Nina through the Tables 01 and 02, were analyzed together with the evaporation rate($E/_P$), that is., for each year evaporation rates were compared with the El Nino years and La Nina to identify how such events affect the parameters that make up the water balance of a watershed.

Validation of data

Using the linear regression model was made the comparison by the scattergram and the correlation coefficient between the three variables of water balance, to determine the degree of association between precipitation and flow between precipitation and and evaporation of evaporation and flow, and thus validate the equation (1) for this study.

The Pearson correlation coefficient is a measure of the degree of linear relationship between two quantitative variables. This coefficient varies between the values -1 and 1. The value 0 (zero) means that there is no linear relationship, a value of 1 indicates a perfect linear relationship, and also the value -1 indicates a perfect linear relationship, but reversed, ie when one of the variables increases the other decreases. The closer to 1 or -1, the stronger the linear association between the two variables.

The Pearson correlation coefficient is usually represented by the letter "r", according to equation (2).

$$r = \frac{\sum(x_i-\bar{x}) \cdot (y_i-\bar{y})}{\sqrt{(\sum(x_i-\bar{x})^2) \cdot (\sum (y_i-\bar{y})^2)}} \quad (2)$$

Where x¯= average observed value, "y"¯= mean simulated value and "x" _ "i", "y" _ "i" = observed and predicted values at time i.

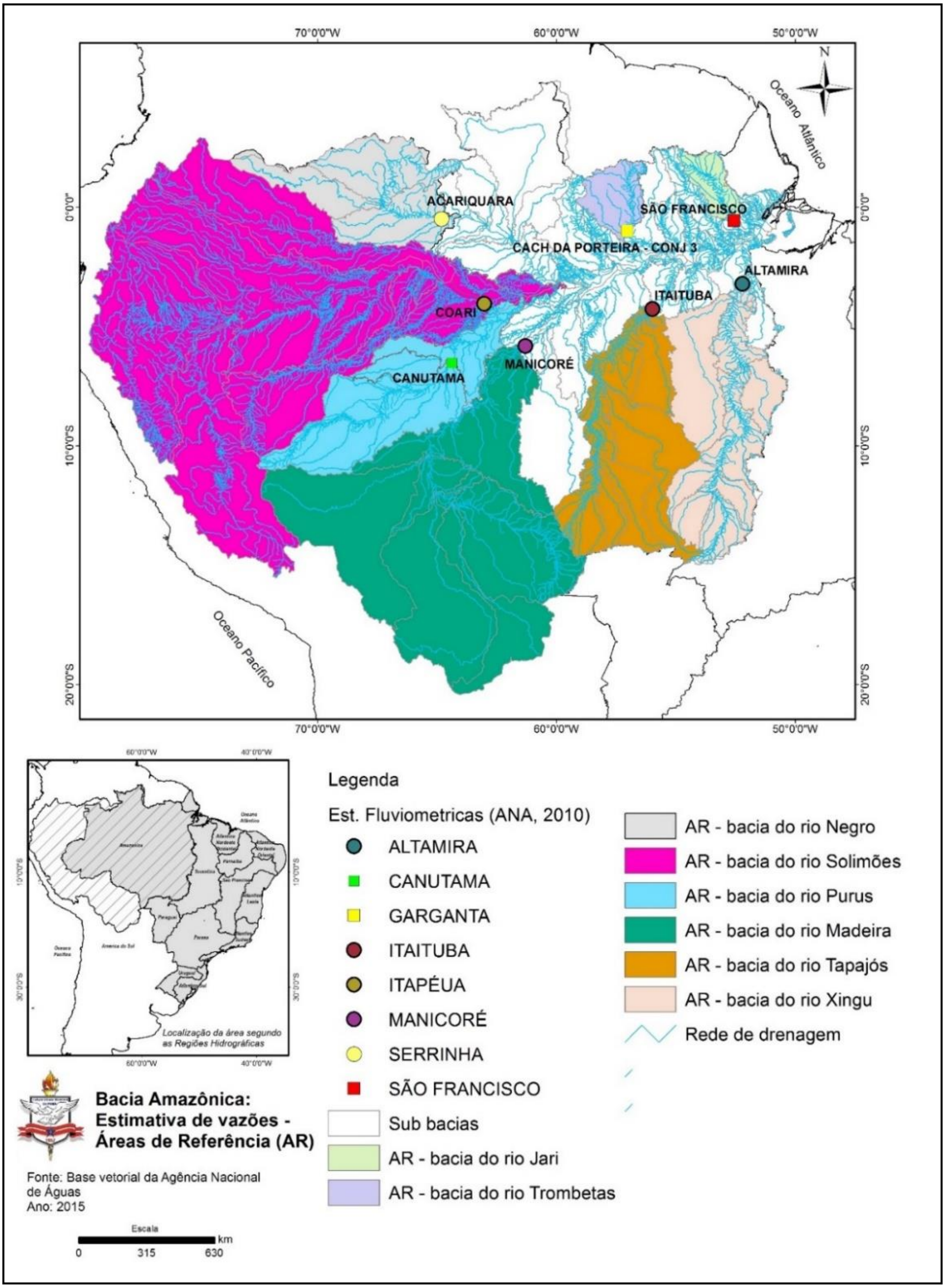

Figure 02: reference area (AR) of each sub-basin from the Amazon basin.

The square of the Pearson correlation coefficient is called the coefficient of determination or simply "r²". It is a measure of the proportion of the variability in a variable which is explained by the variability of the other, in the range 0 to 1 (0 to 100%). The simulation results are considered good for values greater than or equal to 0.75, satisfactory to between 0.75 to 0.36 and unsatisfactory to below 0.36 (Van Liew; Garbrecht, 2003).

Results and discussion

Figure 03 and Table 03 show the water balance in the Amazon river basin, whereas the 8 sub-basins, Solimoens, Punis Wood Tapajos Xingú, Black, trumpets, and Jari, and it was found that the Solimões basin precipitation and the flow are the highest, with climatological average between 1982 and 2012, approximately 2400 mm and 1400 mm, respectively.

When it comes to the right edge of the sub-basins, Punis Wood Tapajós and Xingu realizes the same relationship between precipitation and flow, but in all of them evaporation was higher than the flow rate ranging from 960 to evaporation of 1250 mm and 720 to 870 mm flow rate. Already in the left margin of the sub-basins, only the Negro sub-basin had higher flow, agreeing with the Ga studiesrcia and Mechoso (2005) and Satyamurty et al. (2013), who reported a flow increase over the years.Figure 03 and Table 03 also show that precipitation in the Amazon River basin exceeds evaporation around 42%, or 58% of the precipitation back to the atmosphere in the form of evaporation, according to several studies, as Rebougas and Braga (2002) and Marengo, et al. (2001), which reported that 56% of rainwater back into the atmosphere, Rock (2004), Ferreira (1987), Salati et al. (1979), Marques (1978) and Molion (1975) that 50% of precipitation is transformed into evaporation and Nizhizawa and Loike (1992), stating that 53% of the rain returns to evaporation to the atmosphere. Already Eltahir and Bras (1994) andCosta and Foley (1999) reanalysis of the data using European Center for Medium-Range Weather Forecasts (ECMWF) showed slightly higher values around 65%, but within the margin of error which is 10 to 25%, as according to Rocha (2004) lie further difficulties close the water balance in the Amazon, with errors in that order.

Separately analyzing the percentage of evaporation in each sub-basin, in Figure 03, it can be seen that in the basin Solimoens evaporation exceeds precipitation about 60%, less than all the other sub-basins. The highest values were found in the trumpets and Jari sub-basins 72 and 73%, respectively. However does with concordance with several previous studies, as mentioned. The bowl and Solimoens Tapajós sub-basins, and Black Xingú presented above the average of the remaining 58% and below, showing that there is a balance between them, as mentioned by$\left({}^{E}/_{P}\right)$Callède et al. (2002) and Satyamurty et al. (2013), who claim that the Amazon has great regularity in the annual hydrological regime, where the sub-basins of the drought are compensated by the other sub-basins that are in season full.

Evaporation is less than the flow and precipitation with 950 mm. In the area of precipitation occurring, there is greater cloudiness and therefore less direct radiation required for evaporation. However, most of the rainfall in the Amazon river basin are originated by large-scale weather systems, and therefore, the moisture needed for cloud formation in these weather systems is mainly due to converge oceanic moisture (Figure 04).

Although there are differences between the curves precipitation, flow and evaporation of Figure 03, an analysis was made to identify the relationship between these variables. However, Figure 04 demonstrates the accuracy of the precipitation data, flow and evaporation and also the relationship between them, as through the determination of the relations between the three data sets, the results show correlation coefficients (R2) high: (a) between precipitation and R2 was 0.8722 and (b) between the flow rate and evaporation of R2 was 0.7178, and (c) from precipitation and evaporation R 2, was on the order of 0.9642, indicating, as expected that these variables are very well adjusted to each other, which provesthe linear dependence between them and the consistency of the water balance equation for this scientific discussion.

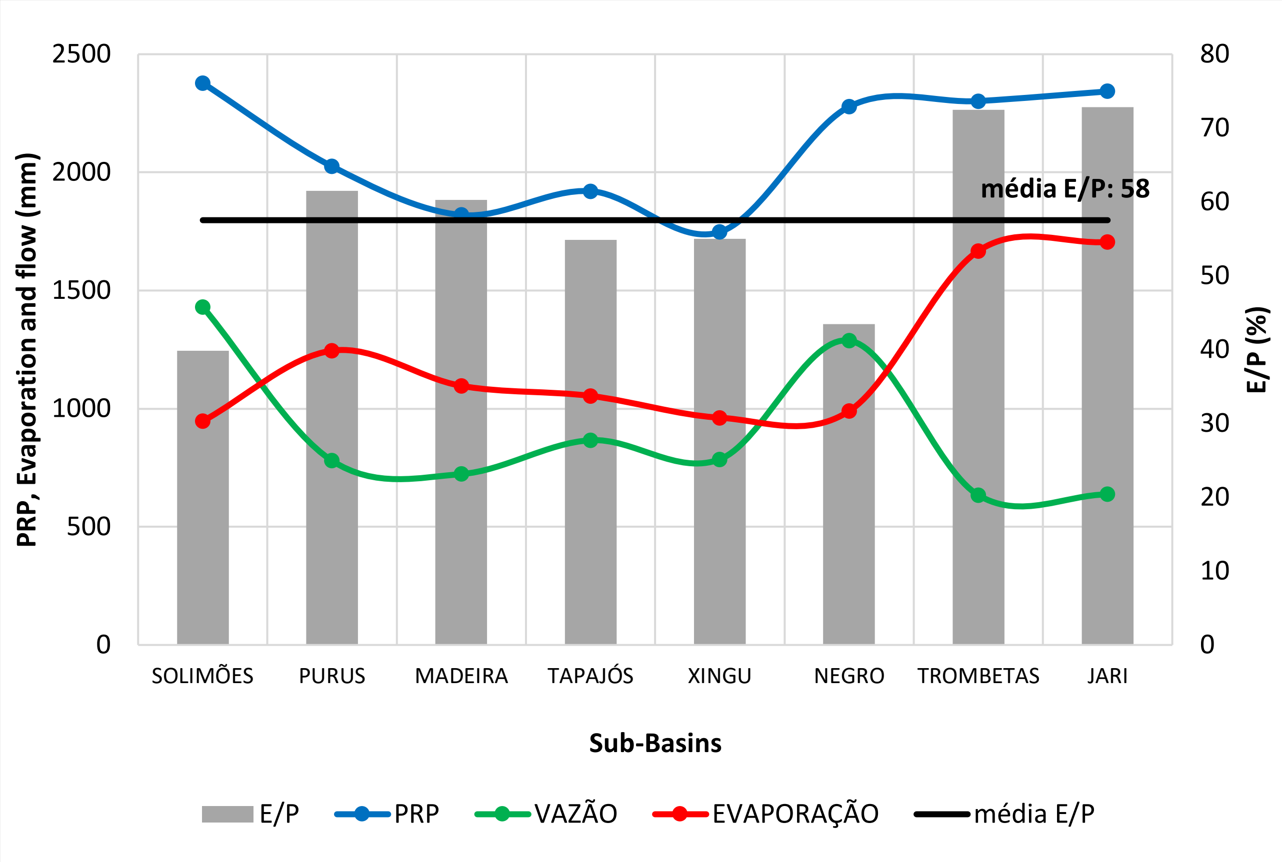

Figure 03: Water Balance in the Amazon Basin sub-basin.

Table 03: Water Balance in the Amazon River Basin.

SUB-BASINS	PRECIPITATION (mm)	REFERENCE FLOW (mm)	EVAPORATION (mm)	E/P (%)
Solimões	2377,64	1430,60	947,04	40
Purus	2025,24	779,76	1245,48	61
Madeira	1819,70	723,21	1096,49	60
Tapajós	1920,47	866,42	1054,04	55
Xingu	1747,71	785,87	961,84	55
Negro	2277,80	1288,03	989,77	43
Trombetas	2301,73	633,96	1667,77	72
Jari	2342,62	637,25	1705,37	73
Average of the Amazon Basin	2101,61	893,14	1208,48	58

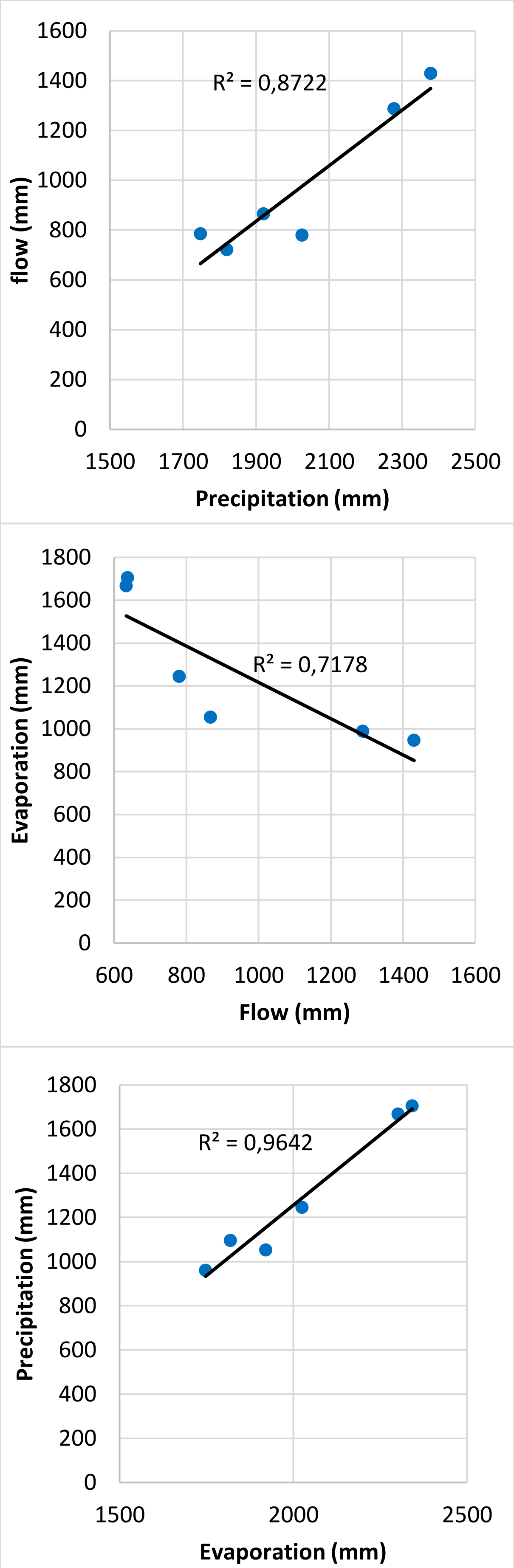

Figure 04: Correlation Polynomial in the Amazon Basin, from: (a) flow and precipitation; (B) Flow Evaporation and (c) Precipitation and Evaporation

Figure 05 shows the balance annual water in the right side of the sub-basins, precipitation and flow curves-behaved in the same way as in the months of greater precipitation, was also the month of higher throughput and reduced evaporation, because when occur precipitation $\left({}^{E}/_{P}\right)$ peaks content is lower, as in 1983, 1987, 1998 were El Nino years. In all the years of El Niño rain levels were below average, where rainfall is inhibited by warming of Pacific waters, as during La Niña events in the years 2010 to 2012 showed no rainfall above average, as happened in other events. It was also found that the linear trend increased slightly, that is, the percentage of evaporation that occurs from the precipitation increased slightly over the 31 year.

Still looking at Figure 05 in all with a strong El Nino years (strong Nina La) evaporation from the precipitation was increased (decreased) especially in the final phase of these events. However, during other ENs event 2006-2007 evaporation decreases, and in the 2005-2006 and 2007-2008 LNs, evaporation increased, this can be explained by the emergence of different events in the same year, interfering with total annual precipitation and therefore the water balance. The average reached $\left({}^{E}/_{P}\right)$ 58%, an amount equal to the total of the basin, in agreement with other studies, such as Rebougas and Braga (2002) and Marengo, et al. (2001), Rocha (2004), Molion (1975), Marques (1978), and Ferreira (1987), Nizhizawa and Loike (1992) and Ethair (1994).

Figure 06 shows the average water balance in the left margin for the entire study period and found that the linear trend had a small decrease, unlike what occurred on the right bank.

The flow curves of precipitation and behaved in the same manner as the rainfall is higher month was also higher flow rate, as does the right bank, described above. Evaporation is also related to precipitation, or upon the occurrence of precipitation smaller indices E / P was larger, as evidenced in 1983, 1992, 1997 and 2012, which were El Nino years.

In all the years in which there were strong El Niño (La Niña) rain levels were below (above) average. However in other periods of El Nino, such as 2004-2005, 2006-2007, 1986 and 1994, rain levels were above average, due to anomalies that Pacific TSM by changing the total annual, in the same way It occurred at the right margin. However in the La Niña events every rainfall were above average.

The ratio E/P on the left bank, as shown in Figure 06, was 62%, 04% above the index on the right bank, and when applied to the extreme precipitation events it was found that in all the years with strong El Niño (strong Nina La) precipitation was transformed into evaporation is increased (decreased) to the atmosphere.

In Figure 06 the curves of precipitation and behaved in the same way as the right edge, as the rainfall is higher month was also higher throughput. Evaporation is also related to precipitation, or upon the occurrence of a minor precipitation $\left({}^{E}/_{P}\right)$ rates were higher, as evidenced in 1983, 1992, 1997 and 2012, which were El Nino years. In all the years in which there were strong El Niño (La Niña) rain levels were below (above) average. However, in ENs at a lower intensity, such as the years of 1986, 1994, 2004-2005 and 2006-2007 rain levels were above average, due to anomalies that Pacific TSM by changing the total annual likewise that occurred in the right margin. However, in the La Niña events every rainfall were above average.

The index $\left({}^{E}/_{P}\right)$ on the left bank, as shown in Figure 06, was 62%, 04% above the index $\left({}^{E}/_{P}\right)$ on the right bank, and when applied to the extreme precipitation events it was found that in all the years with strong El Niño (strong La Nina) evaporation from the precipitation increased (decreased) to the atmosphere.

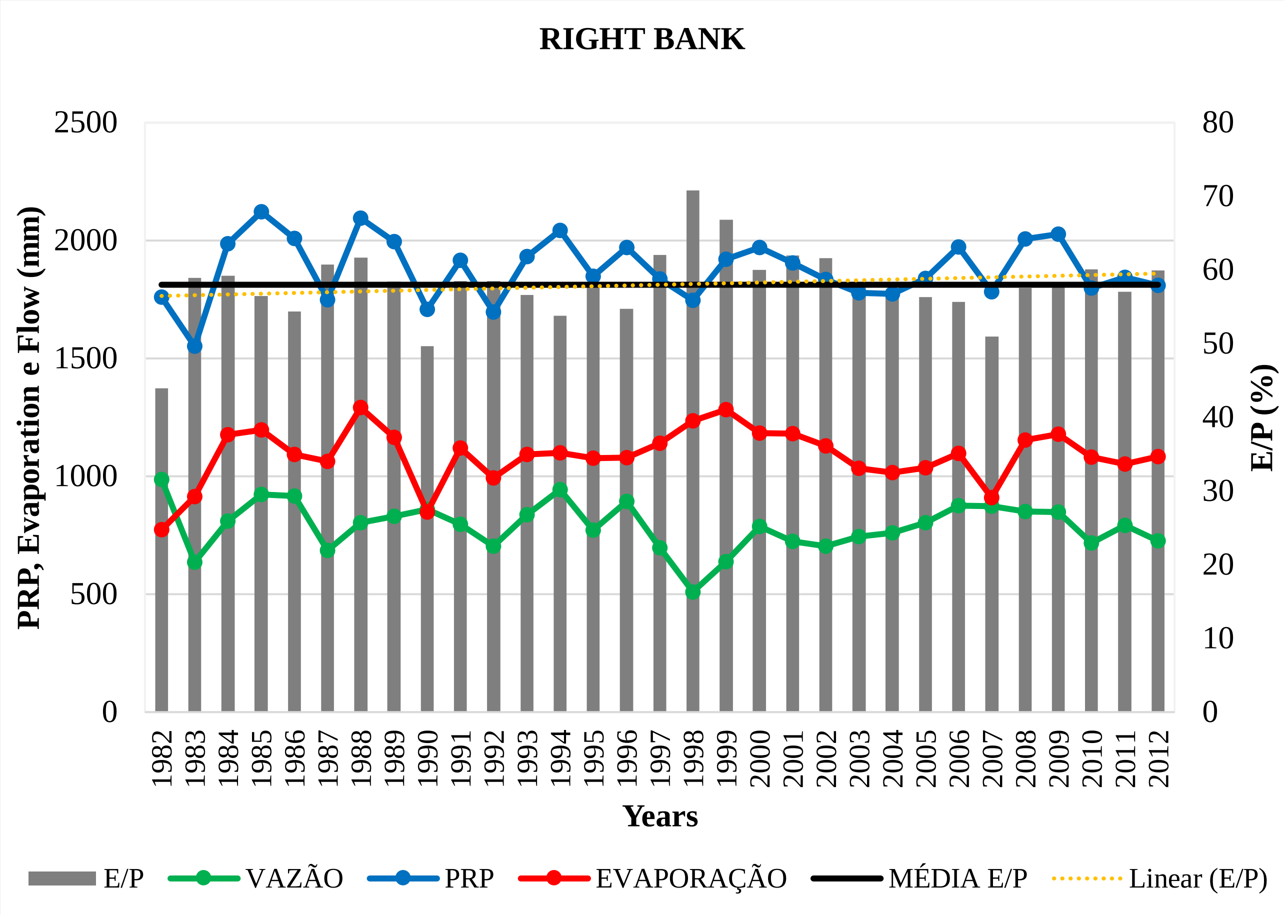

Figure 05: annual water balance in the right margin of the Amazon basin.

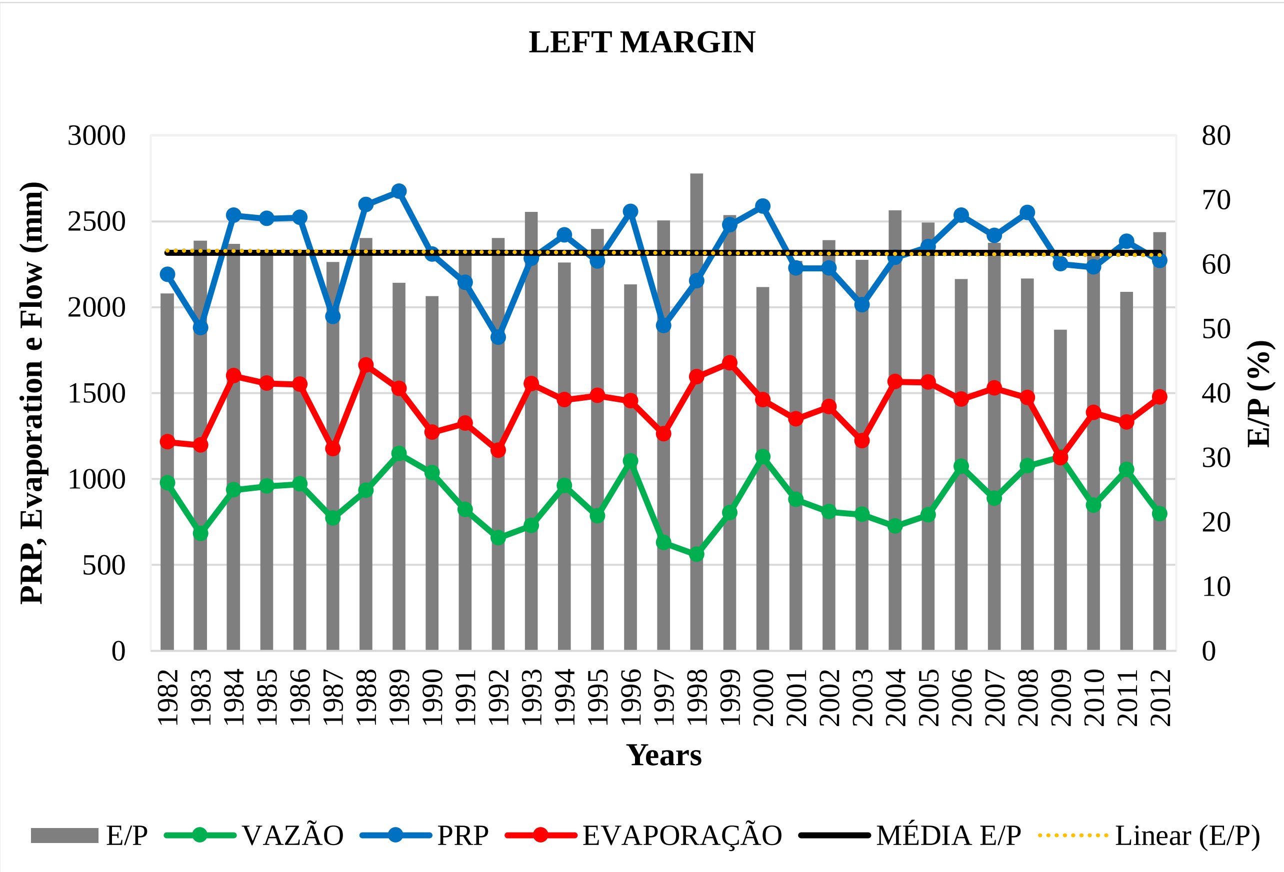

Figure 06: Annual Balance Hydride on the left bank of the Amazon basin.

Figure 07 shows $\left({}^{E}/_{P}\right)$ the average between events El Nino and La Nina the left margin and right margin, and found that the evaporation rate behavior from the precipitable water has a small difference during events, for the right $\left({}^{E}/_{P}\right)$ bank the this difference is only 1%, it is higher during La Niña event, with 58%, and lower during the El Niño event, with 57%. When evaluating the left margin is noticed that $\left({}^{E}/_{P}\right)$ acts in reverse, that is, in the event El Nino, It is greater than 65 % and less during the event La Nina, 62%, also generating a small difference of only 3%, in agreement with studies Callède et al. (2002) who claim that the Amazon has great regularity in the annual hydrological regime, that is the sub-basins lying in the dry regime are offset by sub-basins lying in the flood season. In addition, El Niño and La Niña affect unlike Amazon, as stated by Zeng (2008), Yoon and Zeng (2010), Marengo et al. (2012), Aragon et al. (2007).

When analyzing the Amazon basin, seen in Figure 07, the $\left({}^{E}/_{P}\right)$ it is higher during El Niño events, with a rate of around 58%, but with little difference in relation to the events La Niña, which is 57%. This higher rate during El Niño events, causes moisture to the region is inhibited due to the warming of the Pacific waters, which is in line with expectations that during El Niño years.

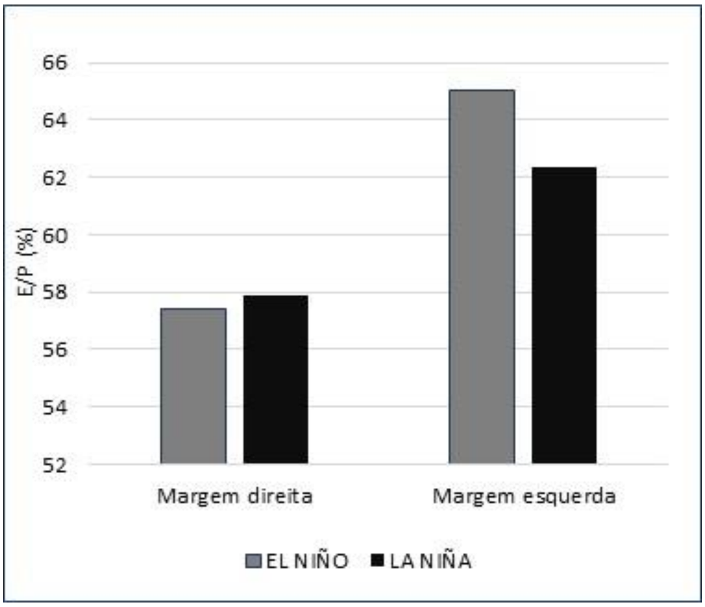

Figure 07: Evaporation Rate in years of El Niño and La Niña in the northern and southern troughs in the Amazon Basin.

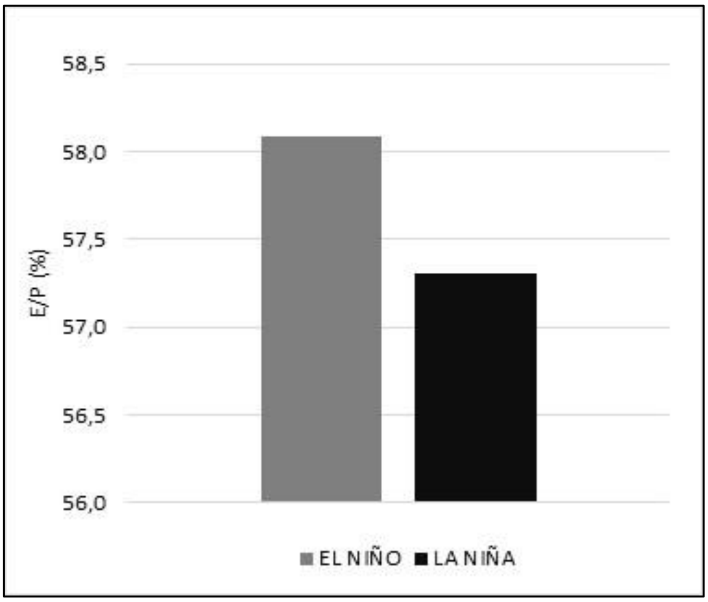

Figure 08: Evaporation Rate in years of El Niño and La Niña in the Amazon Basin.

Conclusions

The Amazon basin has a great diversity in the water balance, both in time and in space, as in each sub-basin, which flows into the main river, and in each period precipitation, flow and evaporation behave differently. In all the sub-basin when precipitation increases and evaporation decreases the flow rate increases, however, this ratio is variable between the right margin and the left margin.

In the left margin, the Black sub-basins, trumpets, and Jari showed the highest rainfall and lower flow compared with the right edge of the sub-basin.

When it comes to the average rate of I / P bowl throughout the period studied, it was shown that more than half of the precipitation, that is, 58% is transformed into steam, returning to the atmosphere, according to several authors. However on the left bank the rate is higher than the right bank with a 04% rate of increase, it proves that the tributaries and sub-basins in different locations have balanced water balance for the Amazon Basin.

Beyond space, time also interferes with the water balance, for the average of the entire basin climatological the rate of E/P is greater during the events El Nino, because during their occurrence the evaporation is greater. However separating the data on each bank, the variability of E/P is different during the El Niño and La Niña, as the left bank E/P is larger and on the right bank the highest E/P occurs during La Niña, but with lower values, as mentioned above.

It was concluded that the water balance is different in the various regions of the Brazilian Amazon basin, and there is a positive trend to evaporation, so it was proven by deforestation in the region, furthermore, it was shown that the simplified equation Water Balance it is well suited to an annual analysis of the water balance in the sub-basins of the Amazon.

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