Consistency of Long-Term Trends and Closure of the Surface Water Balance in the Amazon River Basin

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Abstract

We study the consistency of long-term trends in the surface water balance of 63 sub-catchments of the Amazon River basin. Monthly time series of precipitation, evaporation, runoff and soil water storage are obtained from remote sensors and flow stations (CHIRPS, ETR-Amazon, ANA-Brazil and JPL-GLDAS). Missing data during the period 1995-2015 are reconstructed applying an adaptation of the methodology proposed by Kondrashov & Ghil (2006). Empirical mode decomposition (Huang et al., 1998) is applied to filter out different modes of natural variability, with the aim to isolate the long-term trend of time series. The Mann-Kendall and Sen tests are applied to the residue and the sign and magnitude of the trends was obtained. No generalized unidirectional trends were found for the Amazon basin for any of the variables studied (Table 1), although some unidirectional trends were found in groups of sub-catchments that belong to the same stream. The consistency of the general water balance equation [dS/dt=P(t)-E(t)-R(t)], and its long-term approximation [\overline{R} = \overline{P} - \overline{E}] were evaluated. The general water balance does not close for 37 sub-catchments, while in the long-term the error in the balance tends asymptotically to a constant value, different from zero, which indicates that in the period of 20 years studied the long-term condition is fulfilled, but there is no closure for the long-term water balance either. The consistency of the surface water balance equation was also studied regarding the signs of the trends, finding that in 32 (51%) of sub-catchments studied the trend signs are not consistent with the water balance equation. Finally, for the remaining 31 sub-catchments (with trends consistent in signs), the consistency of the water balance equation was evaluated regarding the magnitude of trends, finding closure errors on water balance of trends up to 281% of the average of the magnitudes. We discuss several reasons for the lack of closure of the water balance, including the very existence of trends that violate the stationary hypothesis underlying the long-term approximation of the surface water balance. The used data and some of the results are available on the supplemental files. The Raw Data CSV file contains the spatial average timeseries at the basin that drain to the flow stations for the water balance equation variables. The Filled Data CSV file contains those timeseries after appliying the reconstruction. MKtrends and SenTrendMagnitude CSV files contains the results of the appliying the Mann-Kendall and Sen trend tests to the filled data.

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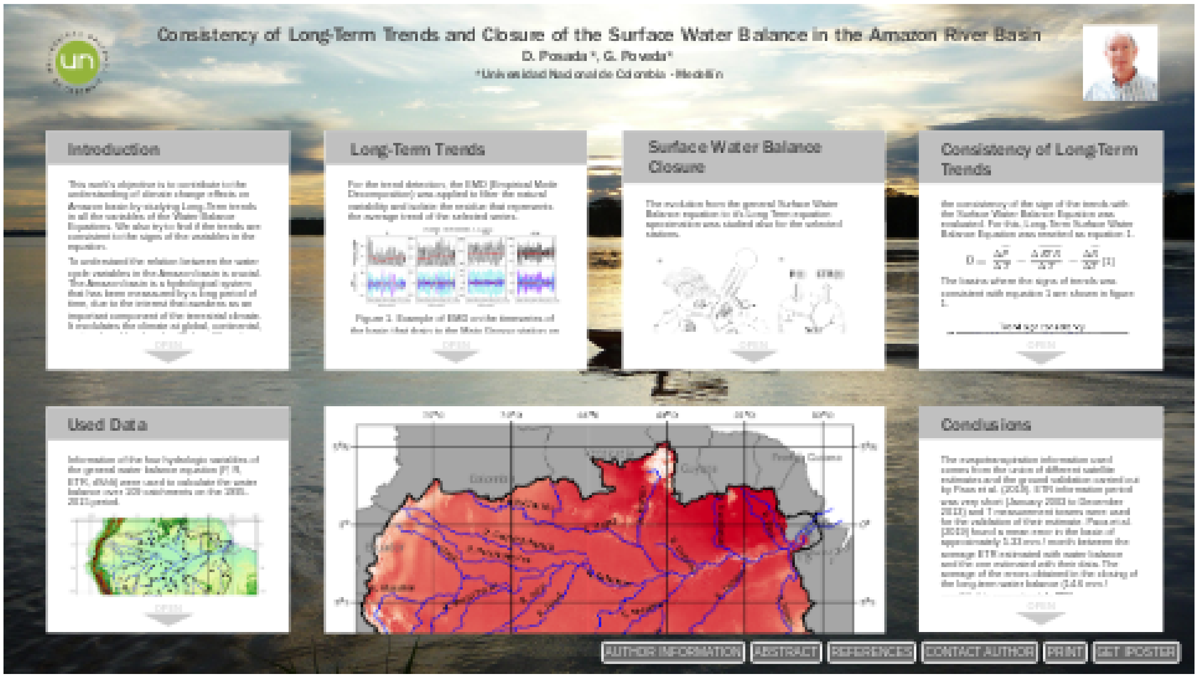

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INTRODUCTION

This work's objective is to contribute to the understanding of climate change effects on Amazon basin by studying Long-Term trends in all the variables of the Water Balance Equations. We also try to find if the trends are consistent to the signs of the variables in the equation.

To understand the relation between the water cycle variables in the Amazon basin is crucial. The Amazon basin is a hydrological system that has been meassured by a long period of time, due to the interest that awakens as an important component of the terrestrial climate. It modulates the climate at global, continental, regional, and local scales (Nobre, Obregón, Marengo, Fu & Poveda, 2009). It is one of the quasi-permanent intense convection centers within the equatorial zone (Lenton et al. , 2007). Amazon forests intense evapotranspiration pumps latent heat into the atmosphere, cooling the low atmosphere. During the summer of the southern hemisphere the intense convection transports pumped latent heat to the high troposphere (Nobre, Marengo & Artaxo, 2009), regulating the strong radiation of the surface. The amazon forest is one of the critical points of the planet (Lenton et al., 2008), and its intervention has significant effects on terrestrial climate. eg at the local scale the massive transformation of the Amazon forest into cropland can trigger an irreversible transformation of the entire forest into a semi-arid savannah. At a global scale different effects are possible depending on the geographical location, eg Amazon deforestation reduces the availability of water resources in Asia due to teleconnections (Rockström et al., 2009).

Data used to obtain the reconstructed series of the water cycle variables in 109 basins are presented on the Used Data box of this Poster. Those variables are Runof, Precipitation, Evapotranspiration, and Soil water storage changes.

On the Long-Term Trends box the Trend detection used techniques are presented, with the obtained results for all the water balance variables.

The evolution from the general Surface Water Balance equation to it's Long Term equation aproximation was studied also for the selected stations with the results presented in the Surface Water Balance Closure box.

Finally, the Consistency of Long-Term Trends box explains the strategy used to evaluate the consistency of the trends with the Surface Water Balance Equation.

LONG-TERM TRENDS

For the trend detection, the EMD (Empirical Mode Decomposition) was applied to filter the natural variability and isolate the residue that represents the average trend of the selected series.

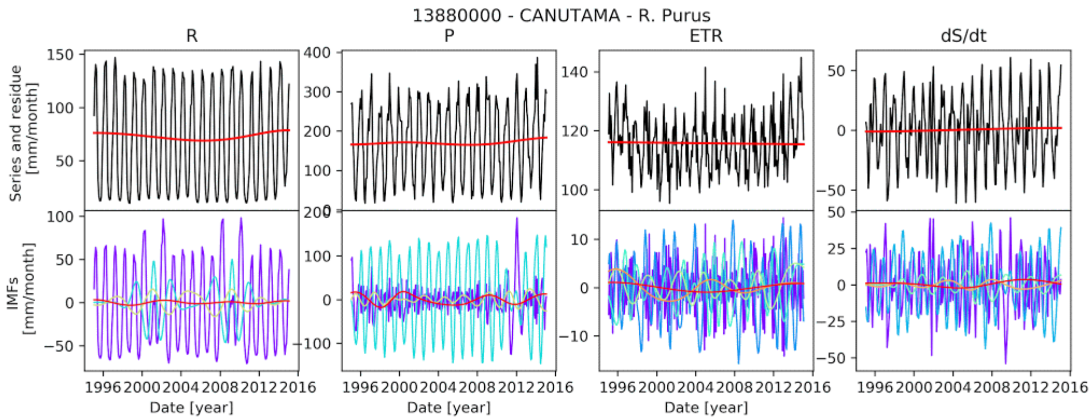


Figure 1. Example of EMD on the timeseries of the basin that drain to the Mato Grosso station on the Guapore river

Then the Mann - Kendall (Hamed y Rao, 1998) and Sen tests (Sen, 1968) were applied to the residue and the sign and magnitude of the trends was obtained.

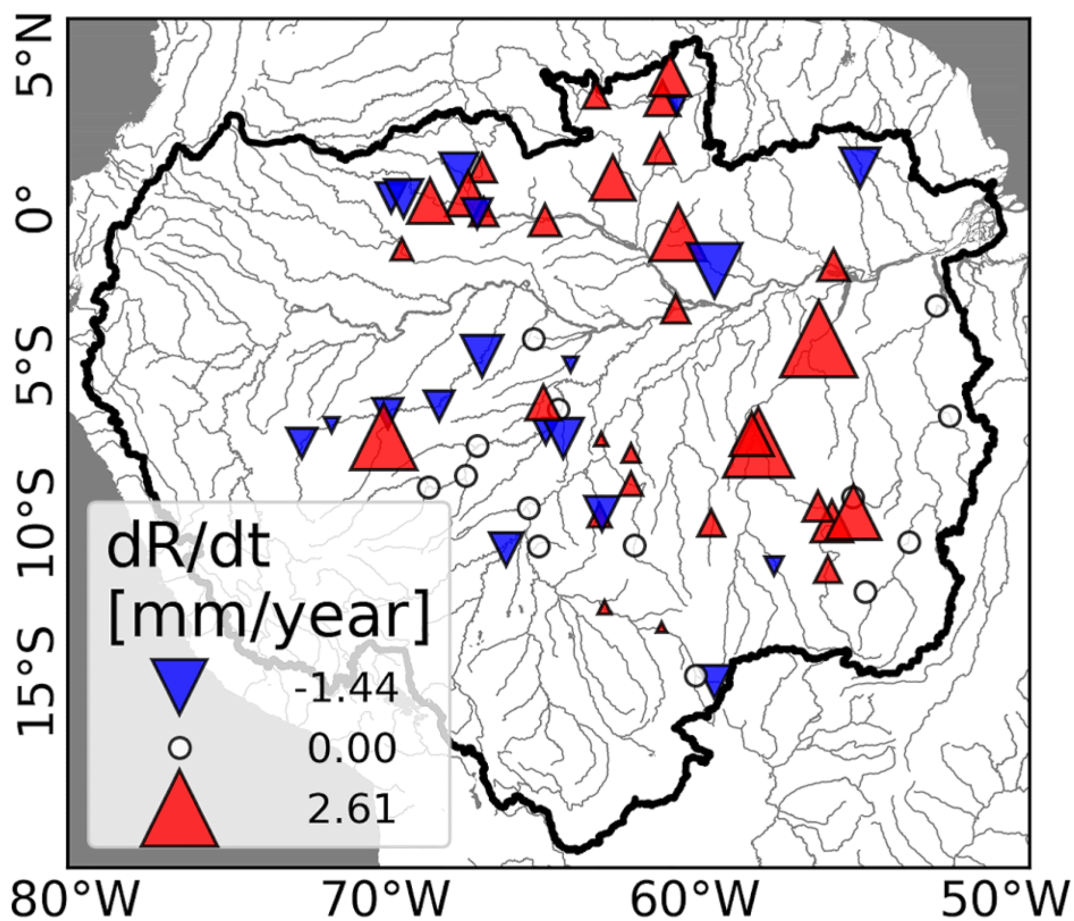


Figure 2. Map of Long-Term Trends found at the surface water balance variables of the Amazon basin

As it is shown in Figure 3, the conclusions of the previous authors on the lack of homogeneity of the trends found in the hydrological variables were confirmed. There is no unidirectionality in the trends found in any of the variables in the Amazon basin (Costa & Foley, 1999; Debortoli et al., 2017; Marengo, 2009; Oliveira et al., 2014).

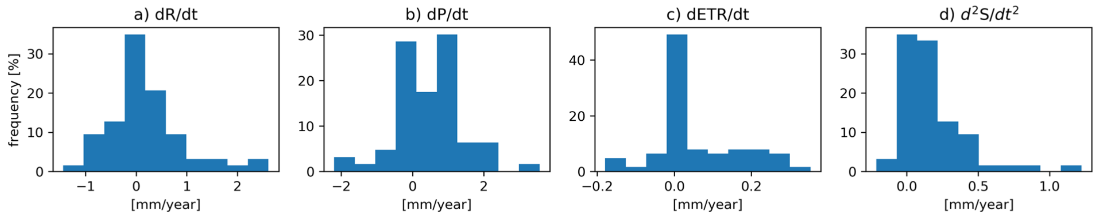


Figure 3. Histogram of the Long-Term Trends

SURFACE WATER BALANCE CLOSURE

The evolution from the general Surface Water Balance equation to it's Long Term equation aproximation was studied also for the selected stations.

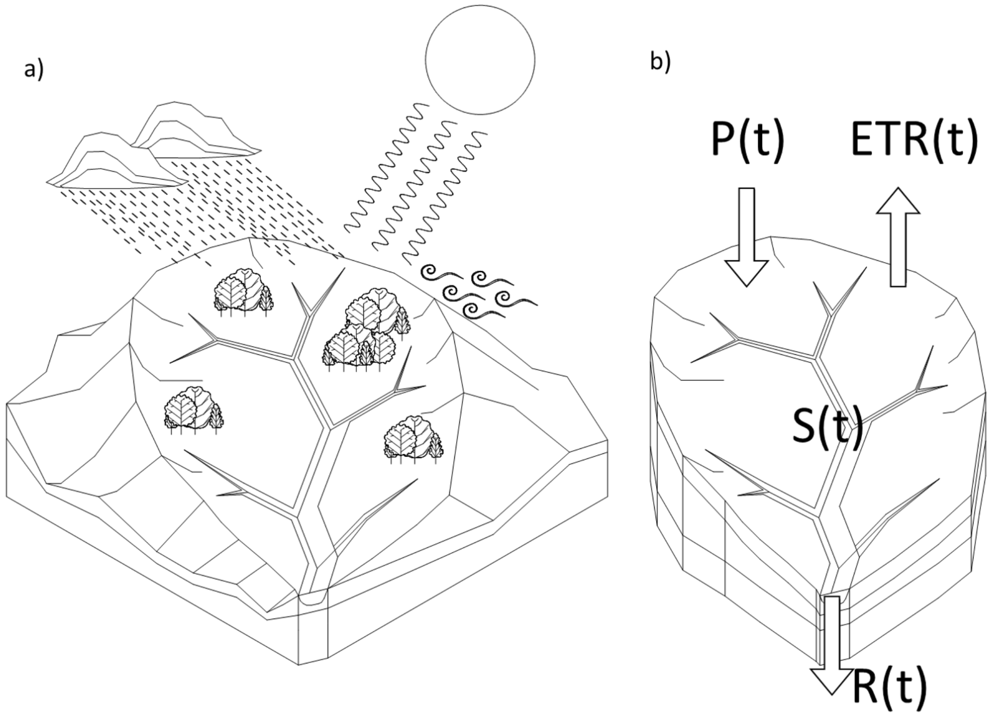


Figure 1. Control volume for the surface water balance equation

As it is shown in figure 1, S (t) is the volume of water stored in the control volume per unit area. S (t) includes both the water stored in the soil, and the water found on the surface in a certain time interval, and the water exchanges described above are represented by the arrows, which indicate the entry of water into the control volume by account of precipitation P (t), and the output by account of evapotranspiration ETR (t) and runoff at the outlet of the basin R (t). Equation 1 shows the mathematical expression that relates all the variables.

$$dS(t)/dt = P(t) - ETR(t) - R(t) \ [1]$$

If the integral of the equation is calculated in a time interval equal to T and multiplied on both sides by 1 / T, equation 2 is obtained.

$$\frac{\lceil S(T)-S(0) \rceil}{T} = \frac{1}{T}\int_0^T P(t)dt - \frac{1}{T}\int_0^T ETR(t)dt - \frac{1}{T}\int_0^T R(t)dt \ [2]$$

One can calculate the right side of equation and the left side appart to find out how big must be T to reach the Long Term condition of the Surface Water Balance (see equation 3).

$$0 = \overline{P} - \overline{ETR} - \overline{R} \ [3]$$

The results of the left side and the right side of the equation 2 for different T are shown in Figure 2. We found that even thought both sides trends asymptotically to a constant value in less than 20 years, this value isn't zero for the right side of the equation. That means that in most of the basins the long term condition is fullfilled but there is a closure error in the balance of the variables.

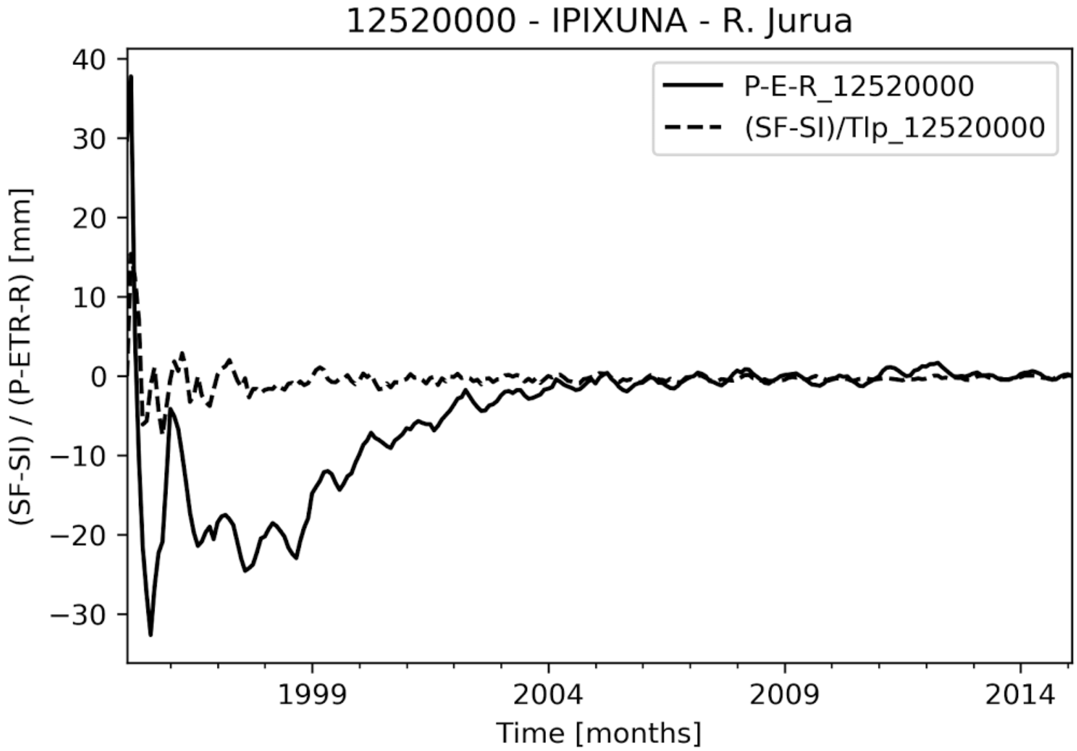


Figure 2. Left side and right side of equation 2 for different values of T

CONSISTENCY OF LONG-TERM TRENDS

the consistency of the sign of the trends with the Surface Water Balance Equation was evaluated. For this, Long-Term Surface Water Balance Equation was rewrited as equation 1.

$$0 = \frac{\Delta\overline{P}}{\Delta T} - \frac{\Delta\overline{ETR}}{\Delta T} - \frac{\Delta\overline{R}}{\Delta T} \text{ [1]}$$

The basins where the signs of trends was consistent with equation 1 are shown in figure 1.

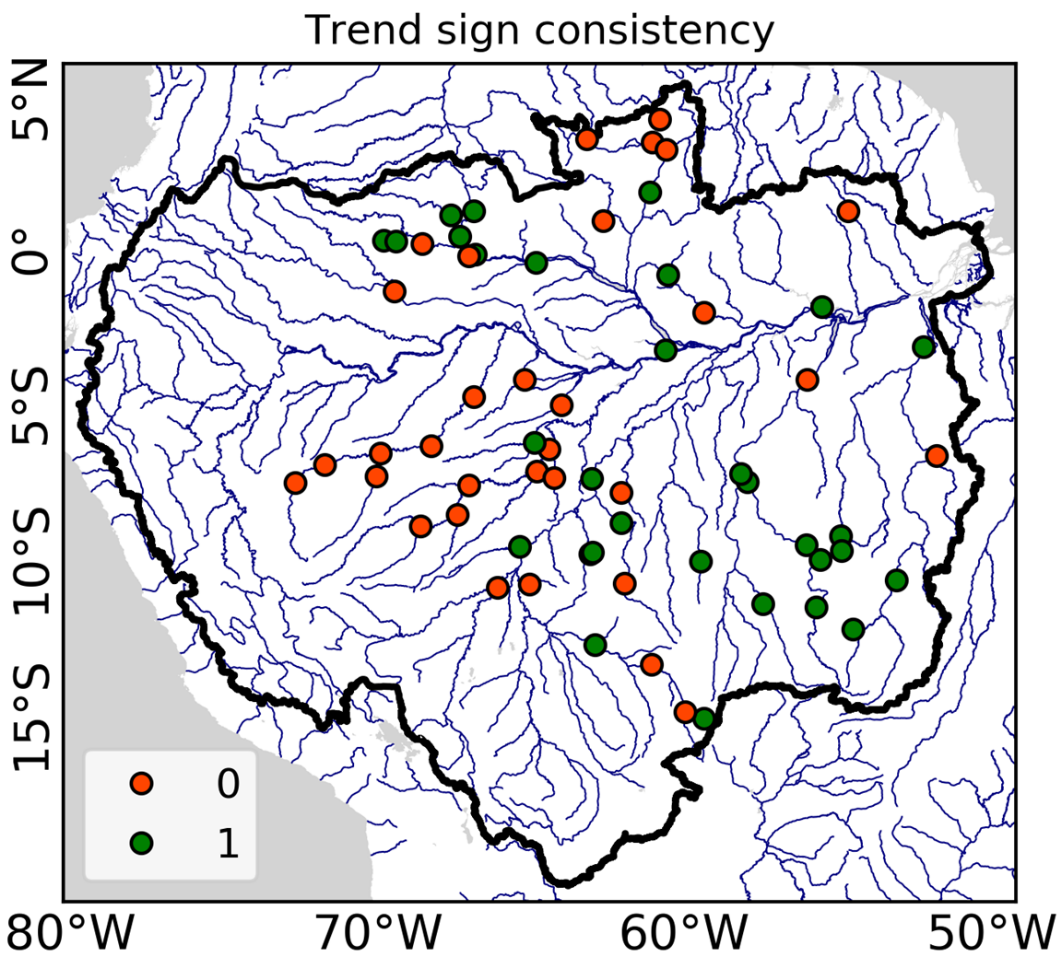


Figure 1. Stations where trends showed sign consintency (green)

USED DATA

Information of the four hydrologic variables of the general water balance equation (P, R, ETR, dS/dt) were used to calculate the water balance over 109 catchments on the 1995-2015 period.

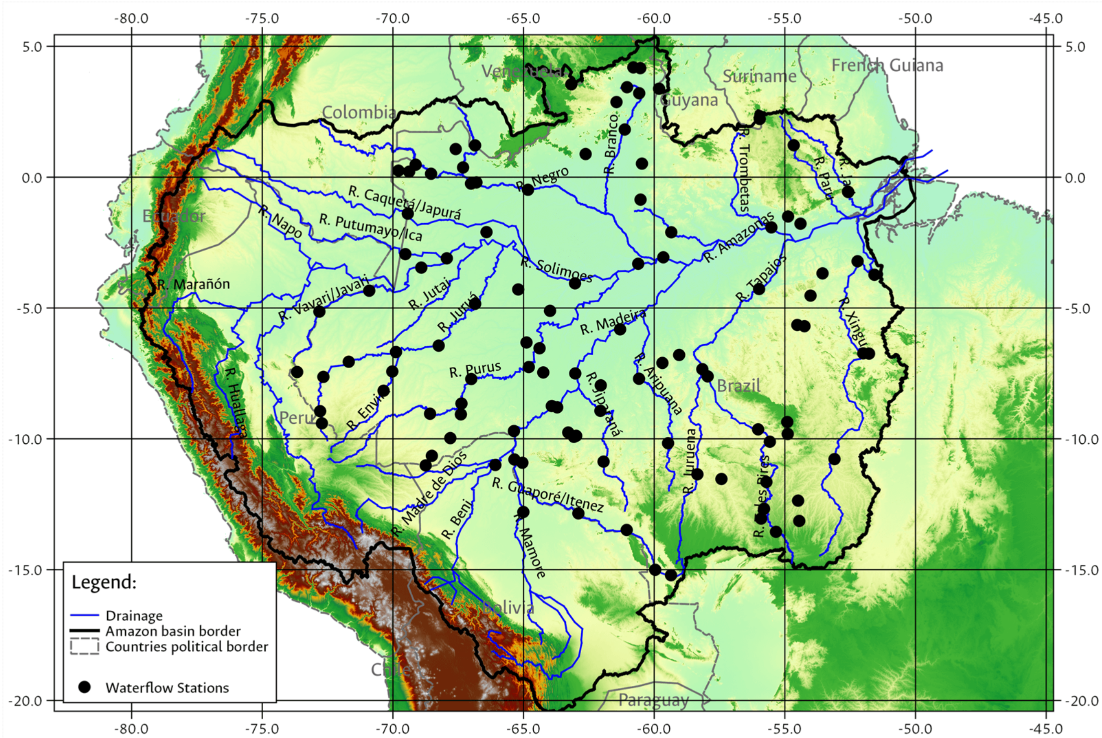


figure 1. Waterflow stations that mark the outlet of the studied basins

The studied basins are those who drain on the waterflow stations shown in figure 1. The waterflow data were provided by the Brazil's National Water Agency (ANA), and were used to estimate monthly runoff (R) timeseries.

Precipitation data were obtained from Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) (Funk et al. 2014).

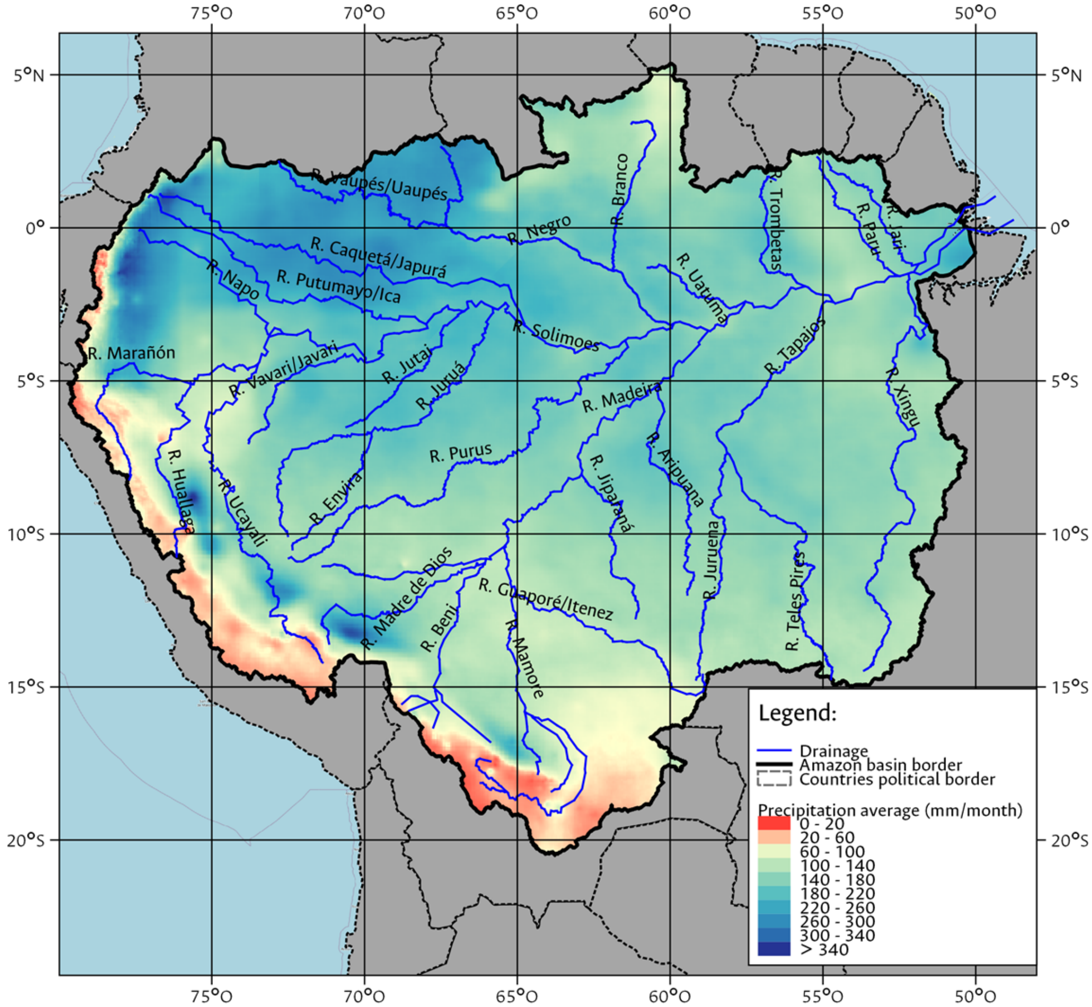


figure 2. Precipitation average over the Amazon basin

The used Evapotranspiration data corresponds to the dataset calculated for Paca et al. (2019) using different sources of satellite data and ground validation with atmospheric towers.

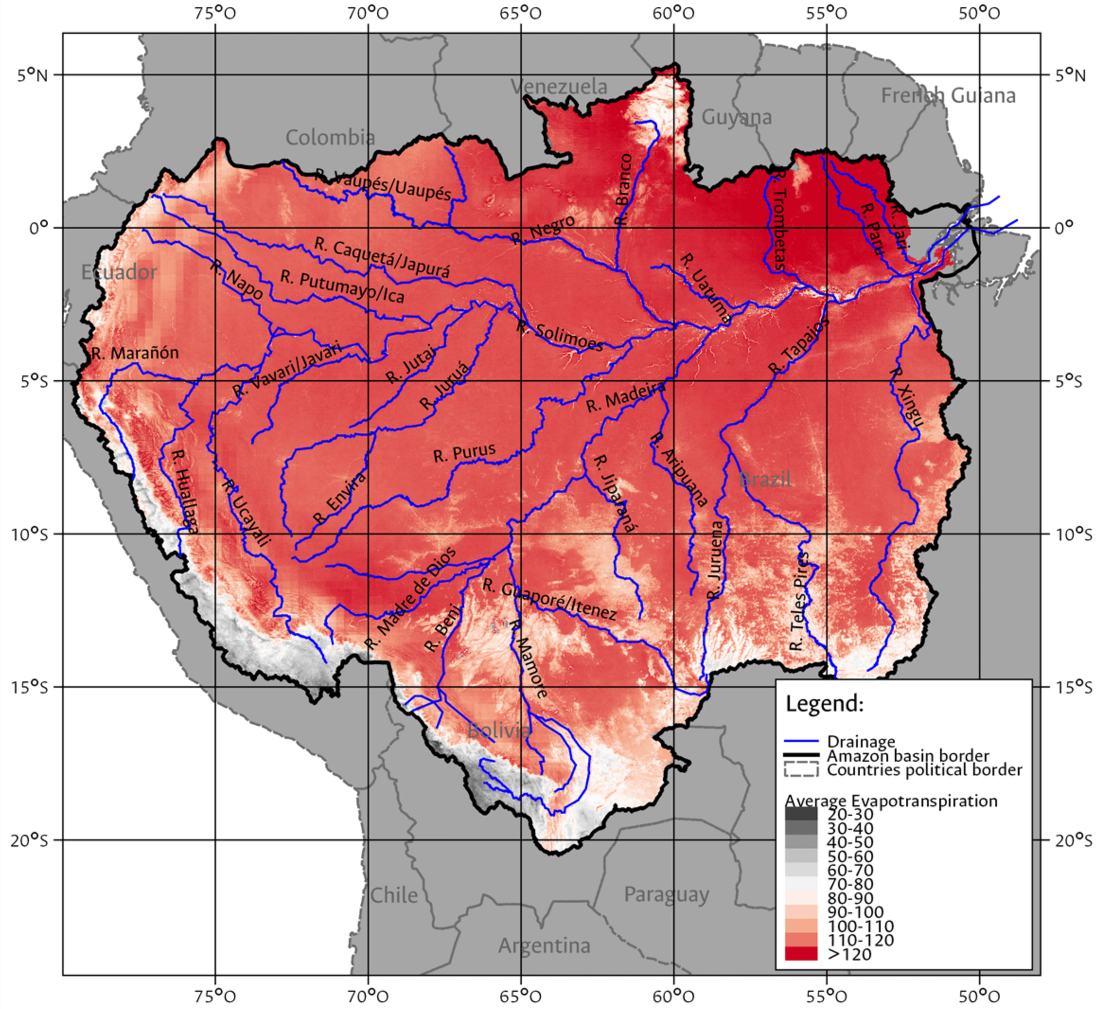


figure 3. Average Evapotranspiration

Finally the used Soil Water Storage data is the JPL Tellus Level-3 (Jet Propulsion Laboratory) that was made by merging data from the NOAH model and from GLDAS (Global Data Assimilation System).

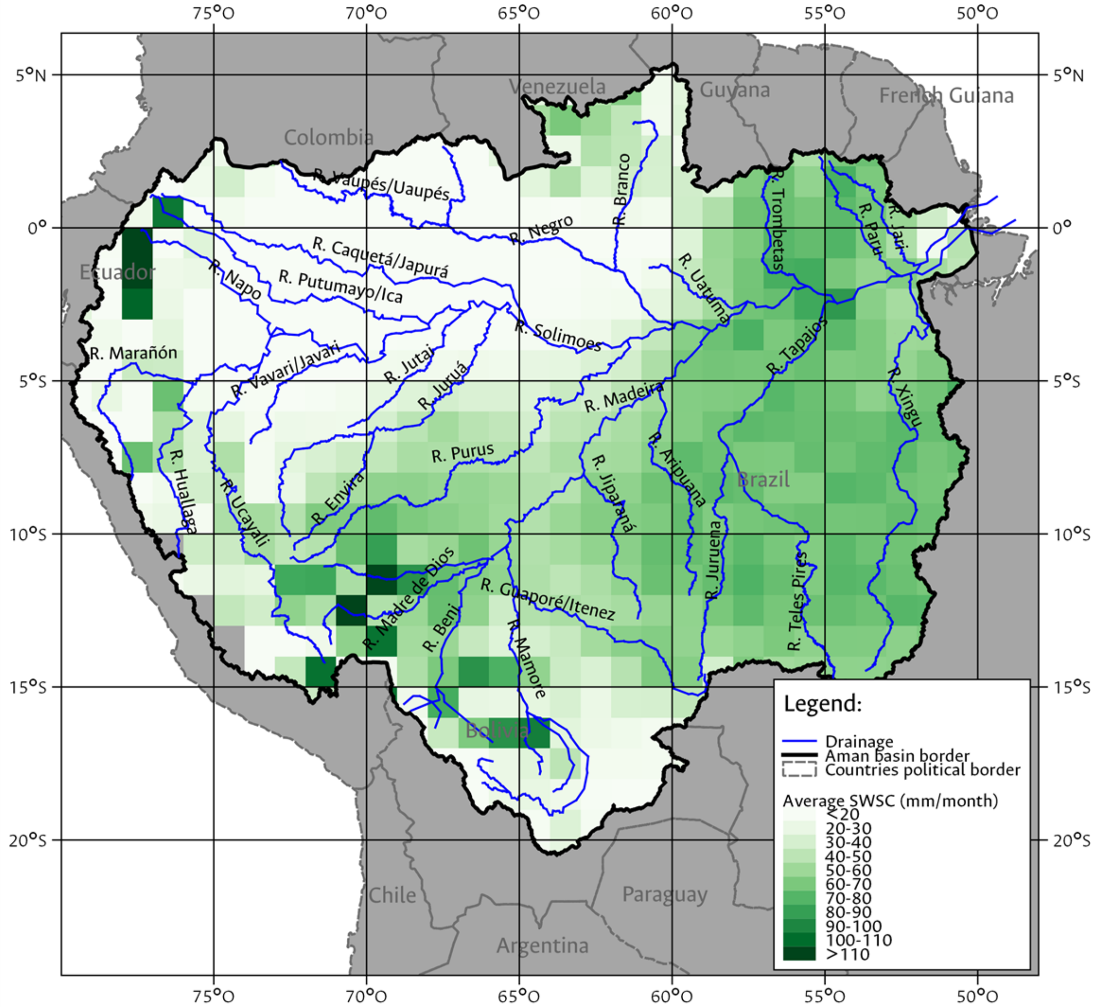
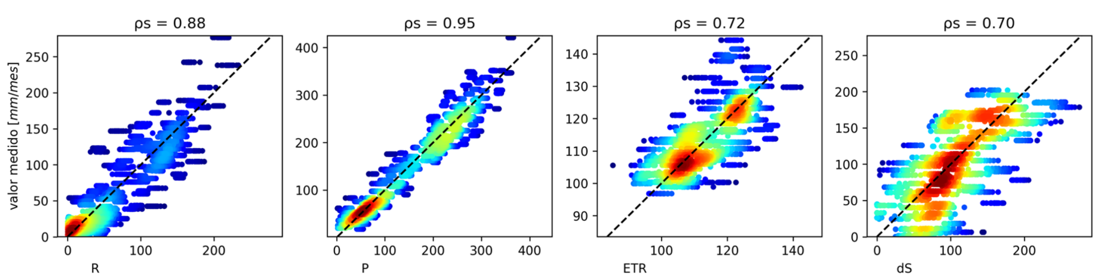


figure 4. Average Soil Water Storage Variation

The time series of the 4 variables were reconstructed to homogenize the recording period from 1995 to 2015 and apply the long-term trend detection methodology. For this an adaptation of the reconstruction method presented by Kondrashov & Ghil (2006) was used and then validated.



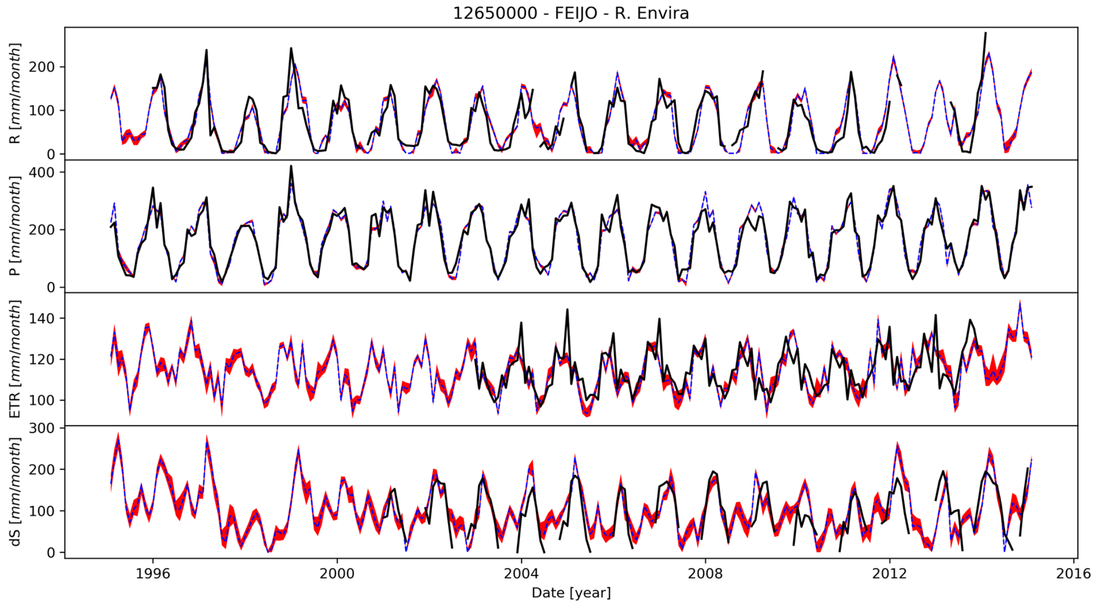


Figure 5. Example of the reconstruction results of the basin that closes at the *Feijo* station on the *Envira* River

The validation results were used to select the timeseries with the best reconstruction performance and use those for the other analyses. The 64 statons shown in Figure 6 were selected for this study, in which it was shown that the probability that the reconstruction will obtain series with favorable results for three error indicators is greater than 70 %.

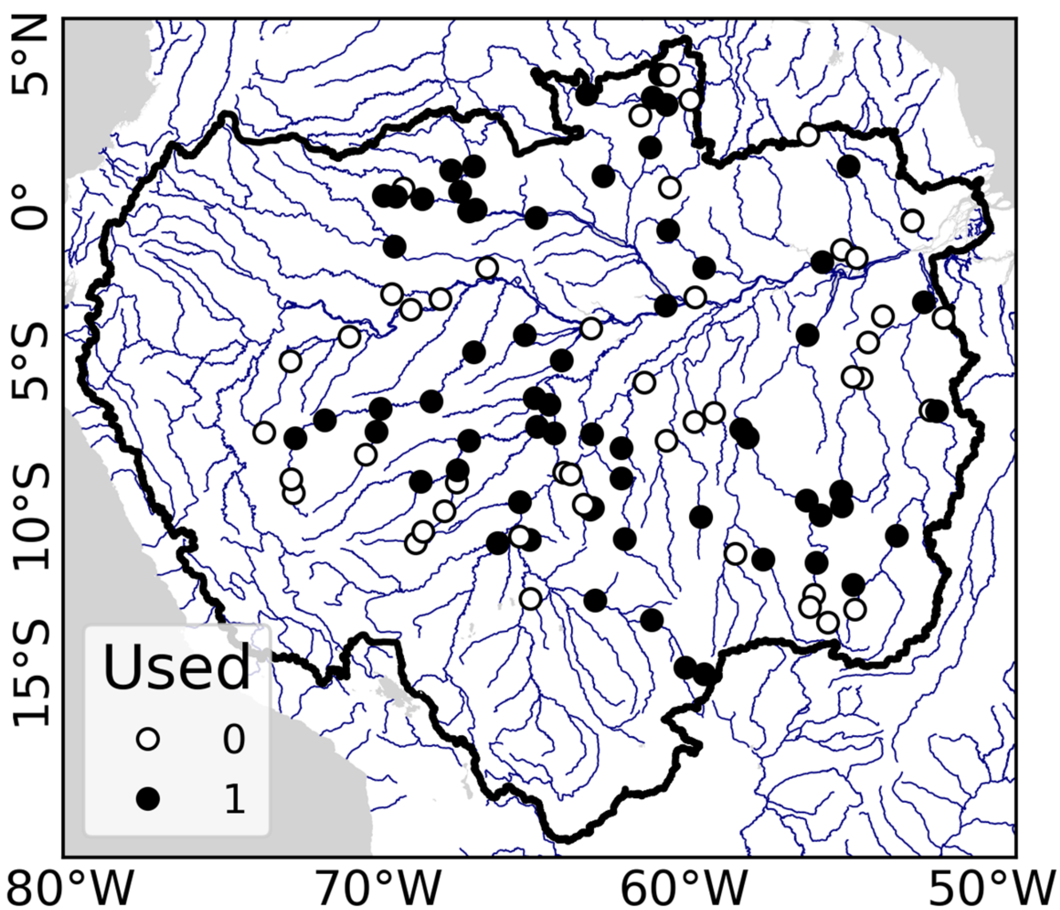
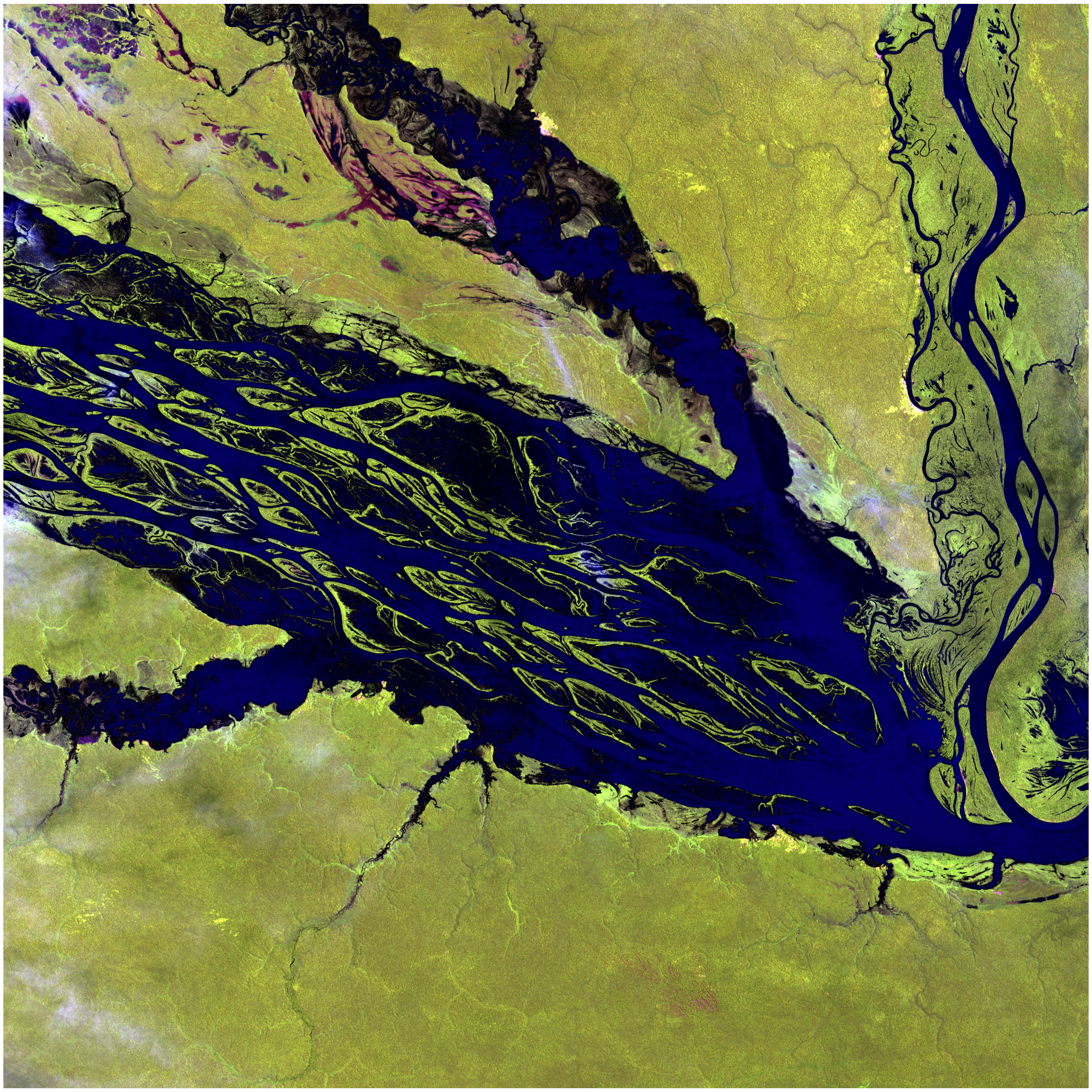
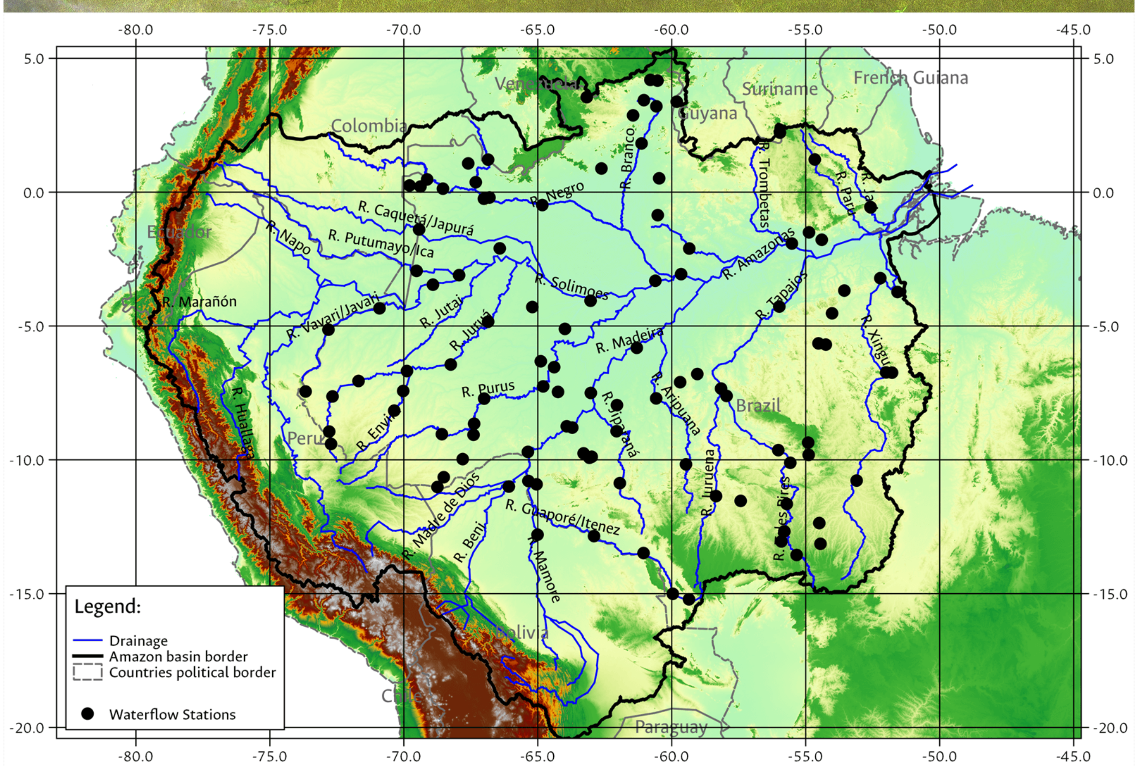
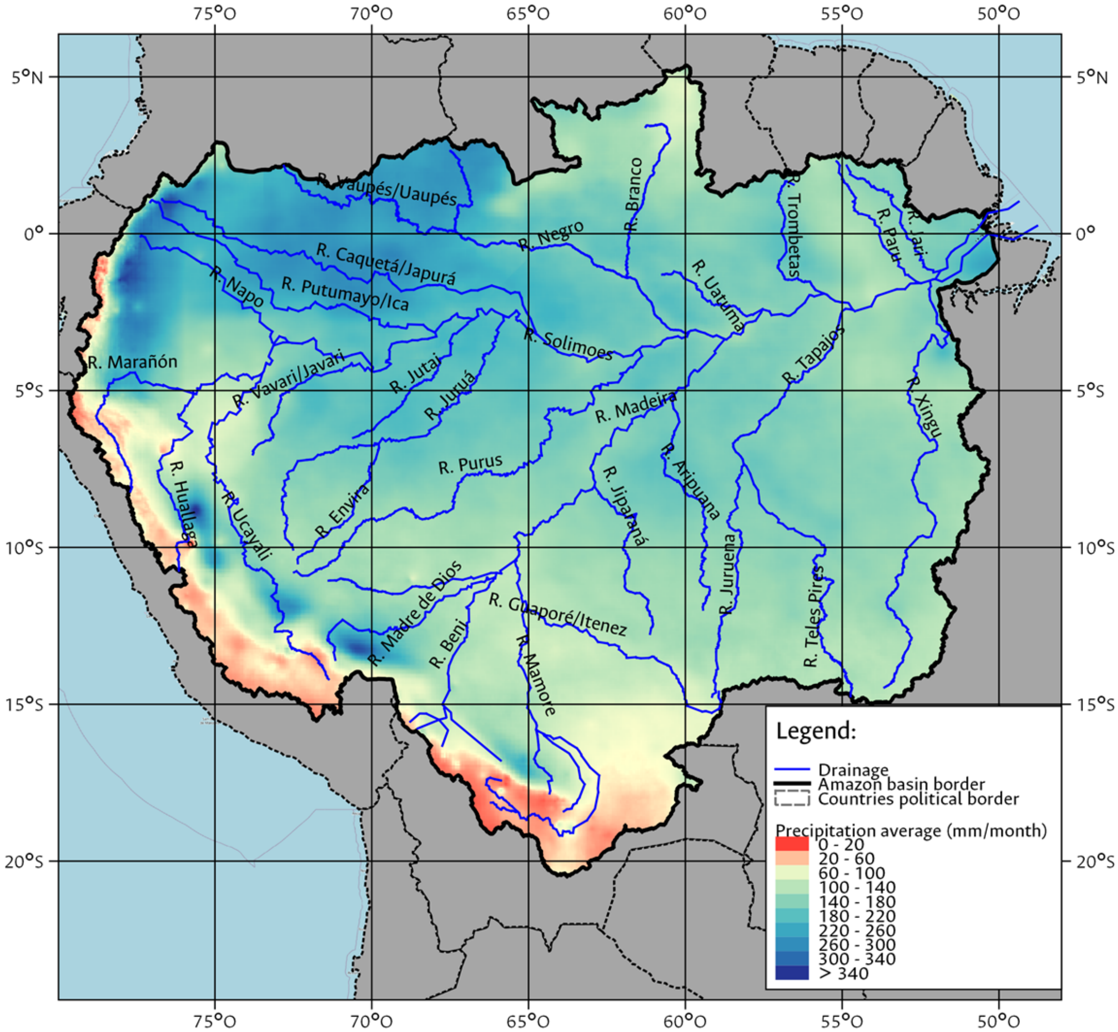
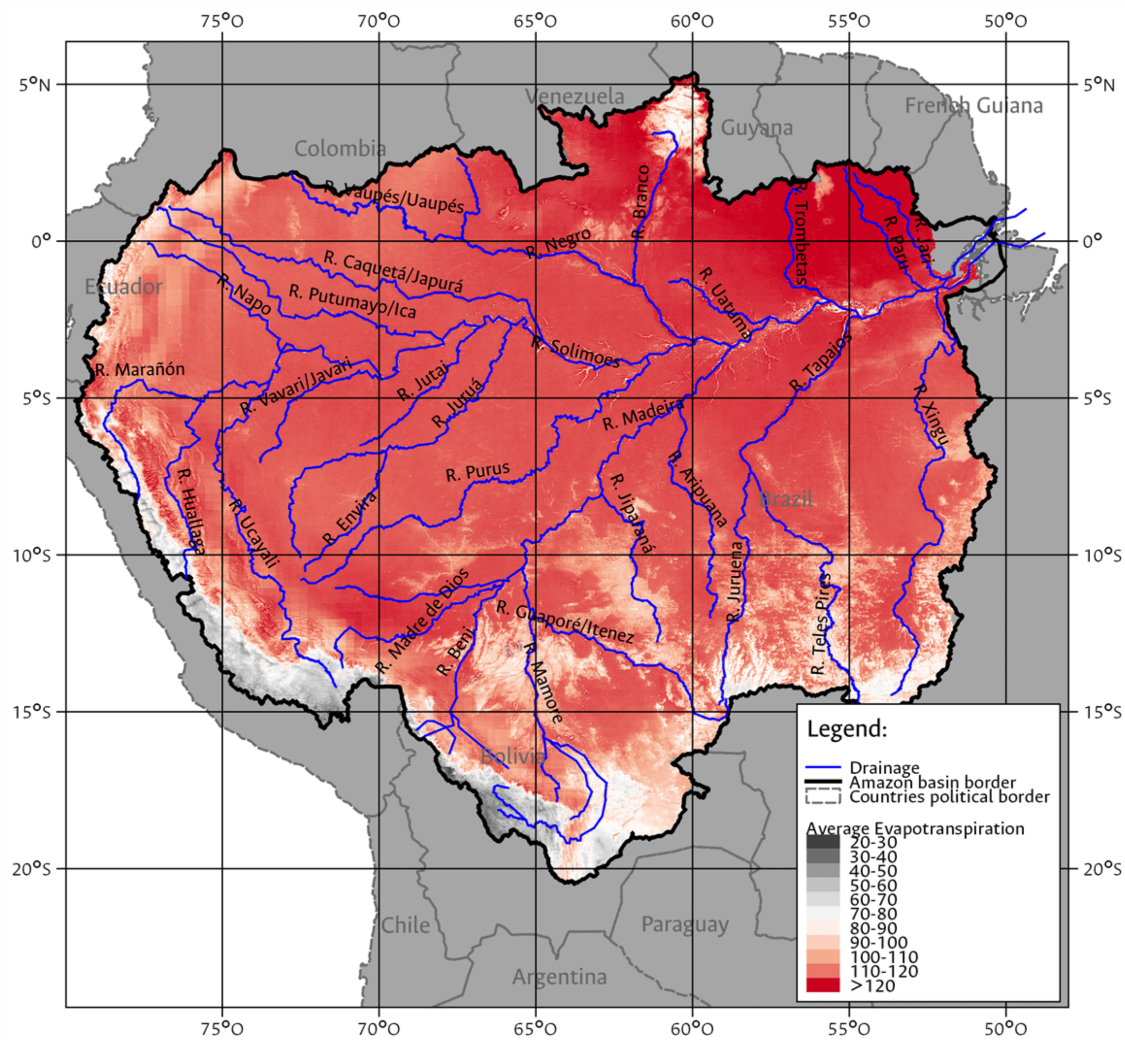


figure 6. Selected basin stations

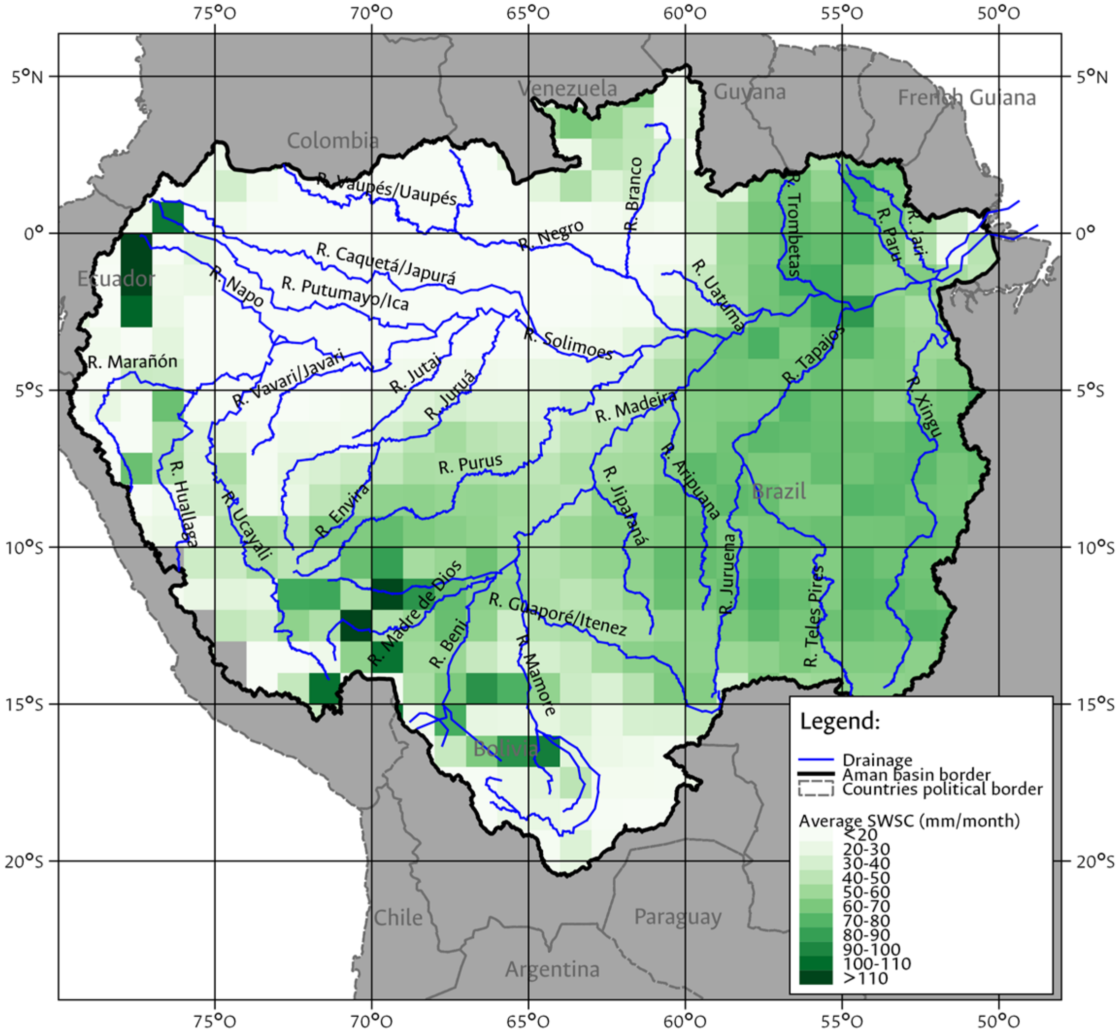



-80.0
-75.0
-70.0
-65.0
-60.0
-55.0
-50.0
-45.0
5.0
0.0
-5.0
-10.0
-15.0
-20.0
Colombia
Ecuador
Peru
Brazil
Guyana
Suriname
French Guiana
Paraguay
R. Negro
R. Branco
R. Trombetas
R. Amazonas
R. Tapajós
R. Xingu
R. Caquetá/Japurá
R. Putumayo/Iça
R. Napo
R. Marañón
R. Vavari/Javari
R. Jutaí
R. Juruá
R. Solimões
R. Madeira
R. Purus
R. Envira
R. Huallaga
R. Aripuanã
R. Juruena
R. Madre de Dios
R. Beni
R. Guaporé/Itenez
Mamore
Legend:
Drainage
Amazon basin border
Countries political border
Waterflow Stations


75°O
70°O
65°O
60°O
55°O
50°O
5°N
0°
5°S
10°S
15°S
20°S
R. Vaupés/Uaupés
R. Negro
R. Branco
R. Trombetas
R. Paru
R. Jari
R. Caquetá/Japurá
R. Putumayo/Ica
R. Napo
R. Marañón
R. Solimoes
R. Uatumã
R. Tapajós
R. Xingu
R. Vavari/Javari
R. Jutai
R. Juruá
R. Madeira
R. Purus
R. Envira
R. Huallaga
R. Ucayali
R. Jiparaná
R. Aripuanã
R. Juruena
R. Teles Pires
R. Madre de Dios
R. Beni
R. Guaporé/Itenez
R. Mamore
Legend:
Drainage
Amazon basin border
Countries political border
Precipitation average (mm/month)
0 - 20
20 - 60
60 - 100
100 - 140
140 - 180
180 - 220
220 - 260
260 - 300
300 - 340
> 340



75°O
70°O
65°O
60°O
55°O
50°O
5°N
0°
5°S
10°S
15°S
20°S
Venezuela
Colombia
Guyana
French Guiana
Ecuador
Brazil
Bolivia
Chile
Paraguay
Argentina
R. Vaupés/Uaupés
R. Negro
R. Branco
R. Trombetas
R. Paru
R. Jari
R. Caquetá/Japurá
R. Putumayo/Ica
R. Napo
R. Uatumã
R. Solimoes
R. Marañón
R. Vavari/Javari
R. Jutaí
R. Juruá
R. Tapajós
R. Xingu
R. Madeira
R. Purus
R. Envira
R. Huallaga
R. Ucayali
R. Jiparaná
R. Aripuanã
R. Juruena
R. Teles Pires
R. Madre de Dios
R. Guaporé/Itenez
R. Beni
R. Mamore
Legend:
Drainage
Amazon basin border
Countries political border
Average Evapotranspiration
20-30
30-40
40-50
50-60
60-70
70-80
80-90
90-100
100-110
110-120
>120


75°O
70°O
65°O
60°O
55°O
50°O
5°N
0°
5°S
10°S
15°S
20°S
Venezuela
Guyana
French Guiana
Colombia
Ecuador
Brazil
Bolivia
Chile
Paraguay
Argentina
R. Vaupés/Uaupés
R. Negro
R. Branco
R. Trombetas
R. Paru
R. Jari
R. Caquetá/Japurá
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R. Putumayo/Ica
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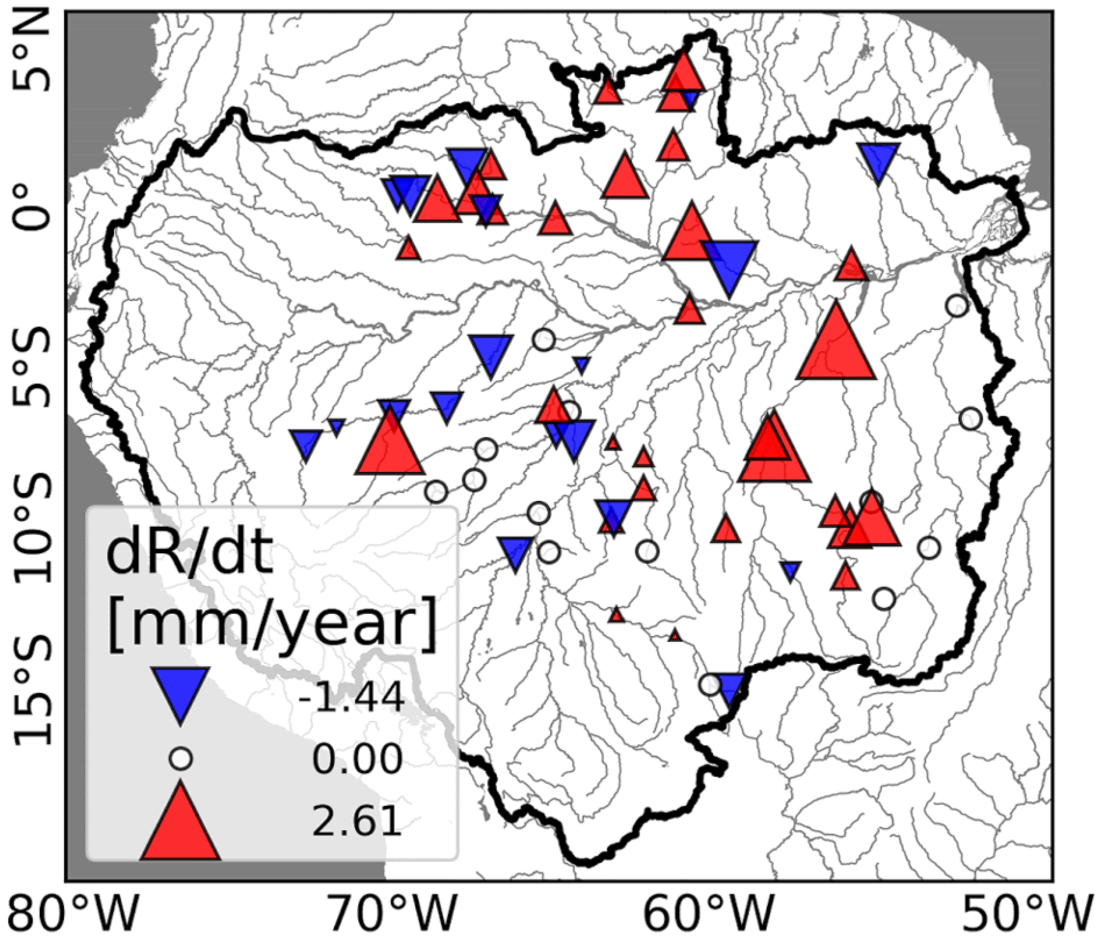
R. Juruena
R. Teles Pires
R. Madre de Dios
R. Guaporé/Itenez
R. Beni
R. Mamore
Legend:
Drainage
Aman basin border
Countries political border
Average SWSC (mm/month)
<20
20-30
30-40
40-50
50-60
60-70
70-80
80-90
90-100
100-110
>110


5°N
0°
5°S
10°S
15°S
80°W
70°W
60°W
50°W
dR/dt
[mm/year]
-1.44
0.00
2.61

CONCLUSIONS

The evapotranspiration information used comes from the union of different satellite estimates and the ground validation carried out by Paca et al. (2019). ETR information period was very short (January 2003 to December 2013) and 7 measurement towers were used for the validation of their estimate. Paca et al. (2019) found a mean error in the basin of approximately 5.33 mm / month between the average ETR estimated with water balance and the one estimated with their data. The average of the errors obtained in the closing of the long-term water balance (14.6 mm / month), it is approximately 30%.

Soil water storage information is also a great source of uncertainty. Data from the JPL Tellus Level-3 laboratory (GLDAS / NOAH) were used as an estimate of the anomalies in soil water storage. This information has a very coarse spatial resolution (pixel of 110km per side approx.) and a very short data period (January 2001 to December 2014) with a large amount of missing information in that period in the Andes mountain range. Missing information was periodical which made the reconstruction difficult since the periodic nature of the missing ones eliminates the oscillatory modes that occur with the same frequency, and it is precisely in the estimation of these modes that the reconstruction is based.

The reconstruction results reflected the limitations of the available information on ETR and dS. For the reconstruction method implemented in this work, it was found for all the watersheds that the flow and precipitation variables have less dispersion and reconstructed values closer to measures.

The application of the decomposition in empirical modes confirmed that the residual is capable of adequately representing the mean trend of the series. It was found that all the variables (P, R, ETR and dS) present non-significant or zero trends with greater frequency. But in the case of significant trends (different from zero), the highest frequencies were presented for positive trends.

The conclusions of the previous authors about the lack of homogeneity of the trends found in the hydrological variables were confirmed. There is no unidirectionality in the trends found in any of the variables in the Amazon basin (Costa & Foley, 1999; Debortoli et al., 2017; Marengo, 2009; Oliveira et al., 2014).

The evolution of the general water balance equation to the long-term condition was studied, finding that the left side of the general balance equation rapidly tends to zero, taking values very close to zero at the end of the proposed interval of 20 years. However, when the right side of the general balance equation was evaluated it was found that the values were very diferent from the right side of the balance equation. In the long term it was found that for almost all basins the expression tends asymptotically to a constant value, but that value was very different from zero in most basins, sometimes reaching 60% of the value of the mean runoff. This allows us to conclude that the long-term condition is fulfilled as there is an asymptotic approximation to a constant value, but the closing of the balance does not occur for most of the study variables.

AUTHOR INFORMATION

ABSTRACT

We study the consistency of long-term trends in the surface water balance of 63 sub-catchments of the Amazon River basin. Monthly time series of precipitation, evaporation, runoff and soil water storage are obtained from remote sensors and flow stations (CHIRPS, ETR-Amazon, ANA-Brazil and JPL-GLDAS). Missing data during the period 1995-2015 are reconstructed applying an adaptation of the methodology proposed by Kondrashov & Ghil (2006). Empirical mode decomposition (Huang et al., 1998) is applied to filter out different modes of natural variability, with the aim to isolate the long-term trend of time series. The Mann-Kendall and Sen tests are applied to the residue and the sign and magnitude of the trends was obtained. No generalized unidirectional trends were found for the Amazon basin for any of the variables studied (Table 1), although some unidirectional trends were found in groups of sub-catchments that belong to the same stream.

The consistency of the general water balance equation [$dS/dt=P(t)-E(t)-R(t)$], and its long-term approximation [*\overline{R} = \overline{P} - \overline{E}*] were evaluated. The general water balance does not close for 37 sub-catchments, while in the long-term the error in the balance tends asymptotically to a constant value, different from zero, which indicates that in the period of 20 years studied the long-term condition is fulfilled, but there is no closure for the long-term water balance either. The consistency of the surface water balance equation was also studied regarding the signs of the trends, finding that in 32 (51%) of sub-catchments studied the trend signs are not consistent with the water balance equation. Finally, for the remaining 31 sub-catchments (with trends consistent in signs), the consistency of the water balance equation was evaluated regarding the magnitude of trends, finding closure errors on water balance of trends up to 281% of the average of the magnitudes. We discuss several reasons for the lack of closure of the water balance, including the very existence of trends that violate the stationary hypothesis underlying the long-term approximation of the surface water balance.

Table 1. Number of monthly series of hydrological variables exhibiting trends.

Variable	Increasing	Decreasing	No Trend
Precipitation	41	7	16
Evaporation	24	8	32
Runoff	31	19	14
dS/dt	47	11	6

(https://agu.confex.com/data/abstract/agu/fm20/0/7/Paper_741070_abstract_707688_0.jpg)

REFERENCES

(Nobre, Obregón, Marengo, Fu & Poveda, 2009)

(Lenton et al. , 2007)

(Nobre, Marengo & Artaxo, 2009)

(Rockström et al., 2009)

(Lenton et al., 2008)

(Hamed y Rao, 1998)

(Sen, 1968)