Method for the analysis of the relationship between forest cover and streamflow in watersheds

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The relationship between forest cover and streamflow of watersheds is complex and still controversial in the scientific literature. To investigate such relationship we propose an alternative method which requires the following information for each watershed: percentage of forest cover, annual rainfall, average specific streamflow (qₚₑᵣₑ), and minimum mean specific streamflow in seven consecutive days (qₛ). As a case study, we analyzed a dataset composed by 25 watersheds located in the Espírito Santo State (ESS), Brazil. We conducted simple and multiple linear regression analyses as well as partial correlation analysis between the above parameters. To reduce the effect of heterogeneity of environmental factors, watersheds with similar characteristics in term of rainfall, drainage area, and both rainfall and drainage area were grouped by cluster analysis, and the above regression and correlation analysis was repeated on each group. Our results using the whole dataset showed that forest cover has a negative relationship with watershed streamflow. The analysis of homogeneous groups of watersheds showed that the average minimum streamflow during seven days (qₛ) was more sensitive to the presence of forest cover, showing a negative relationship, especially in watersheds with low annual rainfall, while in areas with high precipitation, the annual rainfall showed a strong influence on the hydrological responses of watersheds, masking the effect of forest cover. The proposed method may be easily extended to other areas, and allows the inclusion of other relevant environmental variables according to specific cases.

Keywords: Forests, Cluster Analysis, Water Regime, Land Use, Watershed Management

Introduction
Land-use intensity is a relevant factor of land cover change, which is leading many developing countries to experience the depletion of natural resources (Awotwi et al. 2019). The ecological and economic utilization of water resources has become one of the most challenging topics for the society (Cheng et al. 2019). The increasing water scarcity around the world led to improve the strategies aimed to its mitigation (Wang et al. 2019), though ensuring water security is still a major global challenge. Water scarcity is prevalent in many regions of the world and it is expected to increase in the upcoming years due to population growth, climate change, and land cover changes (Giri et al. 2018).

The ecological and hydrological imbalances caused by land-use changes in watersheds are widely recognized in the scientific community (Giri et al. 2018, Chaves et al. 2019, Nikolic et al. 2019, Sadeghi et al. 2019). However, the influence of forest cover on streamflow at watershed scale is still controversial, as the former has been reported to affect the latter both positively and negatively, depending on the study (Hornbeck et al. 1993, Andréassian 2004, Zhang et al. 2017, Guzha et al. 2018, Mendes et al. 2018, Schenk et al. 2020). This is due to the complexity of their relationship, which involve many environmental variables, so that each watershed can show unique hydrological characteristics, according to local environmental conditions (Andréassian 2004).

Considering the above-mentioned uncertainties, studies that investigate the effects of forests on hydrological streamflows are necessary. So far, these studies have been generally carried out using paired experimental watersheds or long-term time-trends. Paired studies focus on two watersheds that are close and similar in terms of environmental, physical, and climatic aspects. Most of the experiments (e.g., the implementation of forest management practices) are implemented in one of the watersheds, while the other is kept as control (Brown et al. 2005). This approach is generally adopted in watersheds smaller than 100 km² (Zhang et al. 2017). Conversely, time-trend studies are usually based on historical series data and include theories of evapotranspiration and energy balance, hydrologic modeling, or a combination of hydrographs and statistical analysis. These strategies are well-accepted for large watersheds, especially when environmental and hydrologic data are limited (Hewlett et al. 1969, Zhang et al. 2017). A significant portion of the current knowledge on the hydrological response of
streamflows to forest management comes from studies relying on the above consoli-
dated methods, which have been con-
ducted worldwide (Hombeck et al. 1993, 
Zhang et al. 2001, Andréassian 2004, Brown 
et al. 2005, Neary 2016, Zhang et al. 2017, 
Awotwi et al. 2019). On the other hand, 
several criticisms regarding the use of 
these methods have been claimed in the 
literature. The experimental watersheds 
are criticized mainly for their high cost, lack 
of representativeness, and difficulty to 
transfer the results to different areas. 
Time-trend studies are also challenged be-
cause of the lack of a calibration period 
and a climate control in order to disentan-
gle the effects of vegetation on the water 
balance from the effects of climate (Hew-
let et al. 1969, Neary 2016).

Studies that correlate forest cover with 
streamflow have been conducted in moni-
tored watersheds for several years, where 
hydrological data are obtained before and 
after the forest management (Brown et al. 
2005), or through analysis of historical data 
sets. The main disadvantage of this ap-
proach is related to the need of monitoring 
forest cover, rainfall, and streamflow over 
several years, and to the damages caused 
by forest suppression. Therefore, new ap-
proaches are needed to investigate such 
relationships in order to provide a deeper 
knowledge in watershed science and sup-
port environmental stewardship.

In this study, we propose an alternative 
methodology based on simple statistics 
where neither forest suppression nor the 
manipulation of large volumes of historical 
data is required. Both rainfall and water-
shed size are included as influencing fac-
tors in the hydrological response. Several 
watersheds are used to improve regional 
representativeness and allow the simulta-
neous analysis of large areas in different re-

gions. The low cost and easy applicability of 
this method can mainly benefit regions 
with a lack of resources to implement 
paired watershed experiments. Addition-
ally, this approach is also beneficial to re-

regions where the development of long-term 
continuous monitoring of hydrological and 
forestry variables is challenging.

To test the proposed methodology, we 
conducted our study in Southeastern Brazil, 
which is historically affected by strong regional differences in the volume of 
available water and has experienced 
worrying drought periods and water 
scarcity in recent years (Ferreira et al. 
2018). According to the National Water 
Agency of Brazil (ANA 2017), the drought 
affected 48 million people in Brazil from 
2013 to 2016. In 2014, the Southeastern re-

gion, which is the most populated in the 
country, faced the highest drought of the 
21st century, causing a water supply crisis. 
On the other hand, in 2018 the drought 
was less intense, causing an increment in 
the water reservoirs. However, the total 
rainfall after that year remained lower than 
expected (Cunha et al. 2019).

The unprecedented drought in Brazil may 
be a direct consequence of inflow deple-
tion from the Amazon watershed, which 
normally brings rainfall to Midwest and 
Southeastern Brazil (Lawrence & Vandecar 
2015, Awan et al. 2016). Despite this, 
Brazil has the largest amount of fresh wa-
ter on the planet (Shiklomanov 1993). 
These facts bring up discussions about the 
management of water resources and the 
need of a deeper knowledge on the influ-
ence of environmental variables on fresh 
water supply.

In this study, we focused on the relation-
ship between streamflow and forest cover 
using environmental and empirical hydro-
logical data from governmental agencies. 
The main goal was to test a new method to 
efficiently determine the correlation be-
tween forest cover and streamflow in wa-
tersheds and its application to other re-

gions. We finally propose the adopted 
methodology as a viable alternative to long 
years of watershed monitoring data or sup-
pression management.

Material and methods

Rationale

We used data recorded from several wa-
tersheds in one typical hydrological year. 
The short period of analysis is compen-
sated by studying several watersheds at 
the same time under different environmen-
tal and land use conditions, which allows a 
better regional representation. The dataset 
included the following types of informa-
tion: the percentage of forest cover, an-
ual rainfall, average specific streamflow, 
and minimum average specific streamflow 
in seven consecutive days. Simple and mul-
tiple regression analysis as well as partial 
correlation were applied to disentangle the 
effect of forest cover and rainfall on water-
shed streamflow. To reduce the effect of 
heterogeneity of environmental factors, 
watersheds with similar characteristics in 
term of rainfall, drainage area, and both 
rainfall and drainage area were grouped by 
cluster analysis, and the above regression 
analysis was repeated on each group. A 
flowchart summarizing the proposed 
methodology is reported in Fig. 1.

Data sources

We selected 25 watersheds located in the 
Espírito Santo State (ESS), Southeastern 
Brazil (Tab. 1). According to the Köppen clime 
classification, the study area presents 
the following four major climates: Am, Aw, 
Cwa, and Cwb (Alvares et al. 2013). The 
vegetation type in the area is part of the 
tropical Atlantic Rainforest.

We focused on records from the stream-
flow and rainfall data platforms of the ESS, 
which were collected in the hydrological 
year 2007/2008 (beginning in October 2007 
and ending in September 2008). This 
dataset was chosen since it was the most 
recent and complete survey of land use of 
the ESS (see below) and provides informa-
tion from previous and subsequent years. 
The average annual rainfall for the selected 
period (1074 mm) was within the normal

![Fig. 1 - Flowchart of the proposed method. Firstly, regression and partial correlation analysis were applied on the whole data set of 25 watersheds. Cluster analysis was then performed to identify groups of watersheds with similar environmental characteristics. Finally, regression and correlation analyses were repeated separately for each group of watersheds.](image-url)
long-term range for ESS (186 \pm 210 \text{ mm year}^{-1}) indicates that the selected year is representative of local historical conditions. Additionally, we compared the geographical distribution and patterns of rainfall for the period 2007/2008 with the historical records to confirm its hydrological representativeness (Fig. 2).

We delimited the watersheds by referring to the upstream drainage area of each streamflow station using a Hydrologically-Consistent Digital Elevation Model (HCDEM). The HCDEM was created from the Digital Elevation Model (DEM) of SRTM (Space Shuttle Radar Topographic Mission), which was obtained from the United States Geological Survey (USGS - https://earthexplorer.usgs.gov/) with a 30-meter resolution. Firstly, we created a mosaic of images and filled DEM sinks. To improve terrain representation, specifically regarding hydrological consistency, we reconditioned the DEM and created the HCDEM using the AGREE algorithm (Hellweger 1997), available in the Arc Hydro Tools package of the software ArcGIS® ver. 10.3.1 (ESRI, Redwoods, CA, USA).

The watershed delimitation was obtained by successive applications of the following tools of the HCDEM in the Hydrology toolbox in ArcMap®: fill, flow direction, flow accumulation, stream definition, snap pour point, and watershed. We used the river station locations at the mouths of the main rivers as references for allocating the pour points in the snap pour point tool. Finally, the automatic delimitation of the watersheds under study was performed using the watershed tool.

**Water streamflow**

The streamflow data for the hydrological relationship between forest cover and streamflow

**Tab. 1** - Data from the watersheds under study in Espírito Santo State, Brazil. (q_{ave}): average specific annual streamflow (L s\(^{-1}\) km\(^2\)); (q_{min}): minimum specific streamflow with seven days duration (L s\(^{-1}\) km\(^2\)).

| ID  | Watershed name                  | Area (km\(^2\)) | Streamflow \((\text{m}^3\text{s}^{-1})\) | \(q_{ave}\) | \(q_{min}\) | Rainfall (mm) | Forest cover (%) |
|-----|---------------------------------|-----------------|----------------------------------------|------------|------------|--------------|-----------------|
| 1   | Pedro Canário                   | 1665.9          | 3.1                                     | 0.3        | 690.8      | 4.7          | 15.7            |
| 2   | São Jorge da Barra Seca         | 451.7           | 4.6                                     | 1.0        | 820.3      | 15.7         | 23.4            |
| 3   | Laranja da Terra                | 1331.7          | 10.1                                    | 4.1        | 1023.2     | 23.4         | 25.8            |
| 4   | Baixo Guandu                    | 2143.2          | 4.7                                     | 1.1        | 908.0      | 25.8         | 28.5            |
| 5   | Córrego da Paba                 | 879.4           | 3.7                                     | 0.2        | 818.8      | 28.5         | 21.7            |
| 6   | Ponte do Pancas                 | 919.3           | 3.6                                     | 0.2        | 814.3      | 21.7         | 15.7            |
| 7   | São Gabriel da Palha            | 1029.4          | 8.2                                     | 1.2        | 848.8      | 15.7         | 58.0            |
| 8   | Valsugana Velha - Montante      | 90.3            | 13.8                                    | 0.5        | 1010.1     | 58.0         | 48.5            |
| 9   | Santa Leopoldina                | 1011.6          | 7.2                                     | 3.0        | 1042.2     | 48.5         | 10.0            |
| 10  | Córrego do Galo                  | 979.0           | 10.9                                    | 5.0        | 1218.8     | 40.2         | 45.7            |
| 11  | Fazenda Jucuruaba               | 1688.6          | 11.5                                    | 5.3        | 1241.8     | 45.7         | 58.2            |
| 12  | Matilde                         | 207.3           | 23.1                                    | 9.4        | 1480.9     | 58.2         | 24.0            |
| 13  | Usina Fortaleza                 | 223.0           | 12.1                                    | 3.1        | 1282.6     | 24.0         | 11.0            |
| 14  | Ínus                            | 433.5           | 14.4                                    | 5.8        | 1257.8     | 11.0         | 12.0            |
| 15  | Terra Corrida - Montante        | 594.0           | 13.4                                    | 5.3        | 1281.2     | 12.0         | 17.1            |
| 16  | Itaici                          | 1047.4          | 13.1                                    | 4.1        | 1303.4     | 17.1         | 30.1            |
| 17  | Ibitirama                       | 341.6           | 28.1                                    | 5.2        | 1354.2     | 30.1         | 18.5            |
| 18  | Rive                            | 2221.0          | 14.7                                    | 4.9        | 1355.0     | 18.5         | 30.3            |
| 19  | Pacotuba                        | 2759.6          | 13.6                                    | 3.7        | 1358.5     | 18.2         | 33.9            |
| 20  | Fazenda Lajinha                 | 436.2           | 12.4                                    | 2.6        | 1305.7     | 33.9         | 30.3            |
| 21  | Castelo                         | 976.1           | 14.0                                    | 2.3        | 1364.7     | 30.3         | 31.9            |
| 22  | Usina São Miguel                | 1457.5          | 15.1                                    | 3.3        | 1403.1     | 31.9         | 23.1            |
| 23  | Coutinho                        | 4604.4          | 14.9                                    | 3.7        | 1377.8     | 23.1         | 22.6            |
| 24  | Usina Paineiras                 | 5169.3          | 14.2                                    | 3.9        | 1377.8     | 22.6         | 22.1            |
| 25  | Guacuí                          | 411.9           | 25.0                                    | 8.2        | 1452.5     | 22.1         | 27.2            |
|     | **Mean**                        |                 | **1322.9**                               | **3.6**    | **1175.7** | **27.2**     |                 |
|     | **Standard deviation**          |                 | **1272.6**                               | **2.3**    | **241.2**  | **13.9**     |                 |

**Fig. 2** - Geographical pattern of the rainfall in the Espirito Santo State (ESS). (Left panel): rainfall distribution in the hydrological year 2007/2008; (right panel): historical mean rainfall distribution.
The average annual streamflow rate (Qave) was calculated for each watershed. The minimum specific streamflow with seven days duration (q7) was automatically calculated for each watershed. The isohyetal analysis was performed using together all the 25 watersheds, grouping the watersheds by similarity. The relationships of the percentage of forest cover and the rainfall with the average specific annual streamflow (Qave) and the minimum specific streamflow with seven days duration (q7) were estimated using simple and multiple linear regression. The results obtained from the data of all 25 watersheds are presented in Table 2 and Tab. 3. As expected, we found a significant relationship between rainfall and streamflow. According to the partial correlation coefficients, higher streamflow rates are associated with higher rainfall rates in the watersheds. This is in agreement with previous studies (Tu et al. 2004, Mendes et al. 2018, Zabaleta et al. 2018), and confirms that rainfall acts as the main input component of water in the hydrological cycle, boosting the other stages of the cycle and the flows of water bodies.

To establish any relationship between forest cover and streamflow, the previously delimited watersheds were used as a mask and forest cover was calculated for each watershed. The classes of silvicultural crops composed of exotic species, such as eucalypts, rubber, and pine trees, were excluded from the analysis as their ecological systems differ substantially from native forests. However, according to the orthophotomosaic, the silvicultural crop areas were negligible during 2007 and 2008, and no streamflow stations were present in most of these sites, making it impossible to establish any relationship between forest cover and streamflow.

Statistical analyses
The relationships of the percentage of forest cover and the rainfall with the average specific annual streamflow (Qave) and the minimum specific streamflow with seven days duration (q7) were estimated using simple and multiple linear regression. Also, a partial correlation between forest cover and streamflow was applied using the rainfall as a fixed effect. The analyses were performed using together all the 25 watersheds, and the significance of the results was assessed by the F-test with a = 0.10.

As watersheds naturally presented different sizes, the contrasting rainfall regimes may influence their hydrological behavior. Thus, the linear regression and the partial correlation were applied separately after grouping the watersheds by similarity. Three different approaches of watershed grouping were adopted according to: (a) homogeneous regions of rainfall; (b) drainage area; and (c) both rainfall and drainage area. We used the hierarchical cluster analysis along with Ward’s method (Ward 1963) based on the average Euclidean distance as a measure of similarity between watersheds.

Results and discussion
Joint analysis of the watersheds
The results obtained from the data of all 25 watersheds are presented in Tab. 2 and Tab. 3. As expected, we found a significant relationship between rainfall and streamflow. According to the partial correlation coefficients, higher streamflow rates are associated with higher rainfall rates in the watersheds. This is in agreement with previous studies (Tu et al. 2004, Mendes et al. 2018, Zabaleta et al. 2018), and confirms that rainfall acts as the main input component of water in the hydrological cycle, boosting the other stages of the cycle and the flows of water bodies.

Watershed grouping
Cluster analysis based on rainfall similarity allowed to detect four groups of watersheds, considering the assumed cut point (Fig. 3). The group composed of Santa Leopoldina, Laranja da Terra, and Valsugana Velha watersheds was discarded, as it was formed by only three members and thus was deemed insufficient to perform the statistical analyses. The remaining three watershed groups (P1, P2, and P3) were organized following a decreasing order of average rainfall (Fig. 3a). Group P1 included watersheds with the highest average rainfall (1391.6 ± 45.8 mm), group P2 had an intermediate average rainfall (1270.2 ± 32.2 mm), and group P3 had the lowest average rainfall (816.9 ± 71.0 mm). Cluster analysis of watersheds based on their drainage area resulted in four groups (Fig. 3b). The group formed by the Coutinho and Usina Paineiras watersheds (the largest of the data set) was discarded due to the insufficient number of water-sheds. The remaining three groups (A1, A2, and A3) were organized according to their mean area (Fig. 3b): group A1 (average size of 1895.4 ± 503.2 km²); group A2 (average size of 977.5 ± 60.2 km²); and group A3 (average size of 354.4 ± 154.9 km²).

Finally, the cluster analysis carried out according to both drainage areas and rainfall year 2007/2008 was obtained from streamflow stations of the ESS, which are freely available at the National Information System on Water Resources (Sistema Nacional de Informações Sobre Recursos Hídricos, SNIRH – http://www.snrh.gov.br/hidroweb). For some of the stations pre-processed data were not available, and raw data was considered. In the pre-processing step, we filled the gaps using simple linear regression between streamflows and the station elevations. The stations with a gap rate above 3% were disregarded since they presented atypical values according to the tendency of the hydrographs. After pre-processing, 25 streamflow stations were selected for further analyses.

The average annual streamflow rate (Qave) and the average minimum streamflow rate for seven days (Q7) for the hydrological year 2007/2008 were obtained for each station. We also estimated the respective specific streamflows (Qave and q7), which are calculated as the ratio between the streamflow (Q) and the drainage area (km²) of each watershed.

Rainfall
Daily rainfall data was obtained from the daily gridded meteorological variables in Brazil (https://utexas.app.box.com/v/Xavier-et-al-JOC-DATA – Xavier et al. 2016), which consists of a grid dataset (0.25° x 0.25°) spatially interpolated from station rainfall data. Total annual rainfall for the hydrological year 2007/2008 was obtained for each grid point covering the ESS. To obtain the annual rainfall for each watershed with a spatial resolution of 30 m, we interpolated this variable over the entire state using the ordinary kriging (linear model) in ArcGIS ver. 10.3.1 (Silva et al. 2011).

### Tab. 2 - Simple linear regression between streamflow, forest cover, and rainfall for all 25 watersheds; (Qave): average specific annual streamflow (L s⁻¹ km⁻²); (q7): minimum specific streamflow with seven days duration (L s⁻¹ km⁻²); (R²): coefficient of determination.

| Variable | Stats | Rainfall | Forest cover |
|----------|-------|----------|--------------|
| Qave     | R²    | 0.68     | 0.06         |
| p-value  | <0.001| 0.228    |              |
| q7       | R²    | 0.61     | 0.04         |
| p-value  | <0.001| 0.346    |              |

### Tab. 3 - Multiple linear regression and partial correlation between streamflow, forest cover, and rainfall for all 25 watersheds; (Qave): average specific annual streamflow (L s⁻¹ km⁻²); (q7): minimum specific streamflow with seven days duration (L s⁻¹ km⁻²); (R²): coefficient of determination.

| Variable | Stats | Rainfall | Forest cover |
|----------|-------|----------|--------------|
| Qave     | R²    | 0.69     |              |
| p-value  | <0.001|          |              |
| r_p      | R²    | 0.61     |              |
| p-value  | <0.001| 0.06     |              |
| q7       | R²    | 0.77     |              |
| p-value  | <0.001| 0.8      |              |
Relationship between forest cover and streamflow

allowed to detect four groups of watersheds. The group formed by the Coutinho and Usina Paineiras watersheds was discarded due to the insufficient number of watersheds. The remaining three groups (AP1, AP2, and AP3) were as follows (Fig. 3c): the group AP1 included the watersheds with the largest areas (1589.9 ± 687.8 km²) and medium/high rainfall rates (1320.8 ± 68.6 mm); the group AP2 included the medium-sized watersheds (1058.0 ± 610.3 km²) and lower rainfall rates (886.3 ± 118.6 mm); and the group AP3 included the smallest watersheds (378.2 ± 134.6 km²) with the highest average rainfall (1345.0 ± 88.7 mm).

Analysis by groups of homogeneous watersheds

Tab. 4 and Tab. 5 show the simple linear regression analysis, the multiple linear regression analysis, and the partial correlation between streamflow, forest cover, and rainfall for each cluster of watersheds formed as a function of rainfall, drainage area, and Drainage area and rainfall simultaneously. As already observed for the joint analysis (see above), the annual rainfall predominantly affects the watershed streamflow (Tab. 4, Tab. 5). In general, there were no significant effects of rainfall for the cluster of watersheds according to similar rainfall rates (P1, P2, and P3 groups), due to the reduction of the data variance within the groups which lowered the statistical power of the applied test. A significant association between minimum streamflow and rainfall (p-value = 0.036) was found for group P3, which included the watersheds with intermediate precipitation, with a negative tendency (r = -0.84). This means that an increase in rainfall implies a reduction in the streamflow, thus contrasting the physical processes of inflow and outflow of water in the watershed. However, the environmental heterogeneity of the region, which is composed of coastal to mountainous areas, may have a great influence on local evapotranspiration, infiltration, and water storage rates due to the presence of other environmental factors not analyzed in this work, such as geological or pedological aspects. Moreover, in some cases, environmental factors may not directly explain changes in the streamflow regime but may be an effect of anthropogenic influences (Santos et al. 2010). Therefore, the region that comprises the watersheds Côrrego do Galo, Fazenda Jucuruaba, Iúna, Fortaleza, Terra Corrida, Itaici, and Fazenda Lajinha requires further research regarding, e.g., soil hydraulic properties to better understand the factors influencing water availability in those waterscours.

Regarding the influence of forest cover in the first group by rainfall (P1, P2, and P3), we found a significant relationship with average and minimum streamflows (Tab. 4, Tab. 5). In both cases, the relationship showed a negative tendency (r = -0.52), which means that lower streamflows occurred in watersheds with a higher forest cover and vice-versa. Furthermore, we observed that the minimum streamflows (q1)

| Cluster Analysis | Watershed groups | Variables | Streamflow qmin | Streamflow qmax |
|------------------|------------------|-----------|-----------------|-----------------|
|                   |                  |           | R²   | p-value | R²   | p-value |
| By rainfall       | P1               | Rainfall  | 0.21 | 0.218 | 0.68 | 0.006 |
|                   |                 | Forest    | 0.16 | 0.285 | 0.30 | 0.126 |
|                   | P2               | Rainfall  | 0.22 | 0.285 | 0.41 | 0.120 |
|                   |                 | Forest    | 0.82 | 0.005 | 0.03 | 0.710 |
|                   | P3               | Rainfall  | 0.23 | 0.333 | 0.37 | 0.202 |
|                   |                 | Forest    | 0.00 | 0.981 | 0.00 | 0.971 |
| By drainage area  | A1               | Rainfall  | 0.95 | <0.001 | 0.62 | 0.037 |
|                   |                 | Forest    | 0.17 | 0.365 | 0.36 | 0.155 |
|                   | A2               | Rainfall  | 0.88 | 0.002 | 0.64 | 0.032 |
|                   |                 | Forest    | 0.00 | 0.986 | 0.15 | 0.390 |
|                   | A3               | Rainfall  | 0.60 | 0.014 | 0.71 | 0.004 |
|                   |                 | Forest    | 0.09 | 0.437 | 0.00 | 0.962 |
| By rainfall and drainage area | AP1           | Rainfall  | 0.94 | <0.001 | 0.52 | 0.069 |
|                   |                 | Forest    | 0.39 | 0.136 | 0.09 | 0.525 |
|                   | AP2             | Rainfall  | 0.57 | 0.018 | 0.50 | 0.033 |
|                   |                 | Forest    | 0.45 | 0.049 | 0.03 | 0.637 |
|                   | AP3              | Rainfall  | 0.57 | 0.048 | 0.65 | 0.028 |
|                   |                 | Forest    | 0.16 | 0.376 | 0.14 | 0.400 |

Tab. 4 - Simple linear regression between streamflow, forest cover, and rainfall for the watershed groups obtained by cluster analysis. (qmin): average specific annual streamflow (L s⁻¹ km⁻²); (qmax): minimum specific streamflow with seven days duration (L s⁻¹ km⁻²); (R²): coefficient of determination.
were strongly influenced by rainfall and forest cover (Tab. 5). This allows to hypothe-
size that during the drought periods, mini-
imum streamflows in this region (Pedro Canário, Baixo Guandú, Barra de São Gabriel, Ponte do Pancas, São Jorge, and Córrego da Piaba watersheds) are more sensitive to low rainfall due to the pres-
ence of forests.

According to Tucci & Clarke (1997), the amount of water that reaches the ground, the undrained part tends to infiltrate. Un-
der these conditions, infiltration into forest soils is usually high, producing lower sur-
face runoff. Besides, the increase in foliage surface area is closely related to the in-
crease in rainfall interception and evapo-
transpiration rate. As a result, evapotran-
spiration is responsible for returning large volumes of water to the atmosphere, de-
pending on the type of forest cover, stage, or density, and influencing the loss of soil moisture by the withdrawal of water from the plant roots.

A widely discussed hypothesis in the sci-

ten community about the relationship be-

tween forests and streamflows is the “infiltration-evapotranspiration trade-off,” postulated by Bruijnzeel (1989a, 2004) and supported by other studies (Roa-García et al. 2015, Krishnaswamy et al. 2013, Ghimire et al. 2014). This hypothesis suggests that, as the forest cover is reduced, the water lost as streamflow due to reduced infiltra-
tion may outweigh the gains in the base-
flow as evapotranspiration is reduced, which results in a decrease of watershed flows. On the other hand, since the infiltra-
tion capacity is conserved, the gains from reduced evapotranspiration may be higher, resulting in increased flows with reduced forest cover (Bruijnzeel 1989a, 2004). In this study, we observed higher streamflows in less forested areas and vice-versa. According to the land use survey that we used, approximately 49% of the Espírito Santo State land is composed of pastures, rocky outcrops, exposed soil, mining areas, and built-up areas. These land uses can re-

duce the infiltration capacity of soils com-
pared to forest soils (Bruijnzeel 1989a, 2004, Roa-García et al. 2011, Zabaleta et al. 2018, Peña-Arancibia et al. 2019). In addition, we found that about 20% of the state territory is occupied by crops and forest crops, both of which use machinery in the production cycle and can cause soil compaction. Fi-

nally, according to State Civil Defense (Gov-

erno do Estado do Espírito Santo 2020), the occurrence of hydrological disasters is usually common in the study area when the rainfall saturates the drainage capacity of soils and urban systems. This event oc-

curs mainly because of the disordered ur-

ban occupation on slopes and river banks (Governo do Estado do Espírito Santo 2020), which should be ideally covered by vegetation.

The reduction in water infiltration into soil restricts the replenishment of ground-

water (Bruijnzeel 2004). The “infiltration-
evapotranspiration trade-off” hypothesis could explain a possible reduction in streamflows on less forested areas, which contrasts with the increases detected in our study. Thus, the negative relationship between forest and streamflow in addition to the stronger association found in drought periods is more related to gains at-

tributed to the reduction in the evapotran-
spiration of the Atlantic Rainforest rather than to the improvement of the soil infiltra-
tion capacity.

Increases in streamflows due to decreas-
ed forest cover can be associated with wa-

ter losses through forest evapotranspira-
tion (Zhang et al. 2001). Annual evapotran-
spiration of areas with rare periods of wa-
ter deficit in tropical forests, specifically in Brazil, can reach 70% of the incident rainfall (Bruijnzeel 1990). The various evapotran-
spiration rates of Brazilian forests (Dias et al. 2015, Bosquilia et al. 2018, Mello et al. 2019) provide material to understand wa-
ter outflows to the atmosphere in water-

sheds with forest cover, as well as their im-

pact on the volume of water that leaves the corresponding watercourses.

The negative association between forest cover and streamflows is likely a conse-
quence of water consumption by vegeta-
tion. This event is significant during drought or low rainfall periods, and affects the wa-

ter availability of watersheds under these circumstances. Regarding the nega-

tive relationship between forest cover and wa-

ter availability, similar results were ob-
tained in other studies under different metho-
dologies and different vegetation types worldwide (Hornbeck et al. 1993, Roa-García et al. 2011, Brown et al. 2013, Mendes et al. 2018).

Regarding the difference between these results and the analysis of the 25 water-

sheds, besides the rainfall rate, we believe that this pattern is an effect of watersheds size, which may influence the hydrological

Tab. 5 - Multiple linear regression and partial correlation between streamflow, forest cover, and rainfall for the watersheds groups obtained by cluster analysis. (q_{ave}): average specific annual streamflow (L s^{-1} km^{-1}); (q_{p}): minimum specific streamflow with seven days duration (L s^{-1} km^{-1}); (R^2): coefficient of determination; (r_p): coefficient of partial correlation.

| Cluster Analysis | Watershed groups | Streamflow q_{ave} | Streamflow q_{p} |
|------------------|------------------|--------------------|------------------|
|                   | Variables        | R² p-value | r_p p-value | R² p-value | r_p p-value |
| By rainfall       |                  |           |       |           |       |
| P₁               | Rainfall         | 0.22 0.469 | 0.27 0.512 | 0.68 0.032 | 0.74 0.036 |
|                  | Forest           | 0.14 0.740 |              | -0.03 0.949 |              |
| P₂               | Rainfall         | 0.82 0.032 | 0.10 0.858 | 0.72 0.107 |              |
|                  | Forest           | -0.88 0.022 |              | -0.72 0.107 |              |
| P₃               | Rainfall         | 0.57 0.284 | 0.75 0.141 | 0.91 0.028 | 0.95 0.012 |
|                  | Forest           | -0.66 0.224 |              | -0.92 0.025 |              |
| By drainage area |                  |           |       |           |       |
| A₁               | Rainfall         | 0.96 0.002 | 0.97 0.001 | 0.68 0.105 | 0.70 0.119 |
|                  | Forest           | -0.36 0.489 |              | -0.87 0.434 |              |
| A₂               | Rainfall         | 0.93 0.006 | 0.96 0.002 | 0.69 0.099 | 0.79 0.060 |
|                  | Forest           | -0.61 0.196 |              | -0.37 0.470 |              |
| A₃               | Rainfall         | 0.64 0.046 | 0.78 0.023 | 0.72 0.023 | 0.85 0.008 |
|                  | Forest           | 0.32 0.435 |              | -0.16 0.712 |              |
| By rainfall and drainage area | | | | | |
response. Afterwards, the effect of the spatial scale on hydrological responses caused by changes in forest cover is still poorly understood and inconclusive. However, it is known that large and small watersheds can present different hydrological responses to the same factor analyzed (Zhang et al. 2017). Thus, the drainage area was tested as a criterion for watershed clustering.

Regression analysis carried out for the groups A, A, and A showed that only rainfall significantly affected the streamflow, while the influence of forest cover did not have a significant influence on streamflow (Tab. 4, Tab. 5). In this case, clustering of watersheds based on drainage area may have aggregated heterogeneous watered in terms of rainfall amount and patterns, which could mask the effect of forest cover. Again, rainfall is a crucial factor for understanding streamflow dynamics. The large size of the watersheds (Tab. 1) can explain the strong influence of rainfall since there is less control of events and actions with higher heterogeneity of environmental factors (Bruijnzeel 1990).

As a result, the watershed size increases, the effects of forest cover change in term of hydrological response is generally less pronounced (Zhang et al. 2017). Our results showed that the percentage of forest cover had a significant influence on streamflow when the watershed groups based on drainage area and rainfall (AP, AP, and AP) are considered. Besides, we found a significant influence of forest cover on the average streamflow (q) for the AP, group (varied sizes and lower rainfall) using a simple linear regression (R² = 0.45, p-value = 0.049 – Tab. 4). In the same group, the influence of forest cover on minimum streamflow (q) was not significant (R² = 0.03, p-value = 0.637), even though R² was significant by partial correlation (r = 0.87, p-value = 0.005) using the rainfall as a fixed effect.

The annual runoff is more sensitive to forest cover at different spatial scales in watersheds with limited rainfall, causing more significant hydrological responses (Zhang et al. 2017). In addition, the annual runoff also has an influence on water losses and affects the annual streamflows. As a result, our study shows that the lower rainfall increased in the group AP, was a driving factor for the occurrence of the significant relationship between minimum streamflows (q) and forest cover. When the annual rainfall is lower, the minimum streamflow during drought periods may be more sensitive to rainfall as well as to the water demand of forests, which is probably higher in warmer and drier periods.

The effect of forests on flow patterns in the dry season is one of the most contradictory aspects in forest hydrology, with conflicting evidence for different combinations of forests, rainfall, and soil conditions. During the drought season, the effect of the balance between infiltration capacity and evapotranspiration becomes even more prominent (Bruijnzeel 1989), which may explain the detection of a significant relationship between forest cover and minimum streamflow (q) in this study.

We observed that all the significant partial correlation coefficients between streamflow and forest cover were negative, which means that smaller streamflows occurred in watersheds with a higher percentage of forest cover and vice-versa. We also observed the same tendency for most non-significant relationships. This is the opposite of the general belief that forests would increase the amount of water available in rivers. However, this is a controversial subject and our results may not be definitive about this topic.

Based on the dynamic of the balance between infiltration and evapotranspiration, we emphasize the importance of prioritizing good soil management practices among the land uses that already exist in watersheds. For example, reforestation of watersheds should be well planned considering the hydrological and soil conditions at each site. Indeed, the replacement of other land uses with forested areas may not always reflect substantial gains in streamflows (Ghimire et al. 2014). In some cases, soil surface conditions and the groundwater storage capacity can have a higher influence on water production during droughting periods than deforestation or reforestation (Peña-Arancibia et al. 2019).

Although forests do not always increase the annual water yield in watersheds, it can affect other important hydrological mechanisms. For example, forest loss can weaken the regulating mechanisms of tropical watersheds, altering river flow regimes and possibly leading to extreme events, such as floods and/or water shortage (Salazar et al. 2018). Also, the quality of water resources and the environment in watersheds is positively affected by forest cover. Considering parameters such as soil structure, runoff control and flow variability over the seasons, sediment production, and water chemical properties (Anderson & Lockaby 2011, Roa-García et al. 2011, Mello et al. 2018), a larger forest cover may ensure a safer and more reliable water supply for local population (Krishnaswamy et al. 2013).

Large-scale deforestation in tropical rainforests can influence the tropospheric moisture flows and atmospheric processes that regulate the transition between dry and rainy seasons. According to observations of reciprocal feedbacks on climate-forest for the Amazon, deforestation can delay the onset of rainfall at regional scale, as discussed by Chambers & Artaxo (2017), Laurence & Williamson (2001), and Wright et al. (2017). Further analysis of the influence of vegetation evapotranspiration on the beginning of the rainy season in the Brazilian Atlantic Rainforest is necessary to generalize this process.

Conclusions

Water security for human society is a real need and a worldwide concern. On the other hand, population growth and the development of productive activities are closely related to land-use changes and the conversion of forest areas.

In this study, we analyzed the relationships between streamflow, rainfall and forest cover over the period 2007/2008 in the Espírito Santo State, southeastern Brazil, by grouping watersheds with similar physical and/or environmental characteristics. This approach can help local managers to better understand how forest management can reduce or increase hydrological availability.

The average minimum streamflow during seven days (q) was more sensitive to the presence of forest cover, showing a negative relationship, especially in watersheds with low annual rainfall. Regarding the areas with high rainfall levels, the annual rainfall showed a strong influence on the hydrological responses of watersheds, regardless of the percentage of forest cover.

The methodology applied in this study is a viable and easy-to-apply alternative to (but not a substitute of) consolidated methods in hydrological science, such as experimental watersheds and long-term time-trends. Our approach can be usefully replicated in other regions, as long as the hydrological variables for the analyzed period fall within their normal historical range, since it does not require the experimental suppression of forest cover and allows the simultaneous study of several watersheds, which can be very useful for water management. Moreover, other environmental variables related to the hydrological dynamics of watersheds may be included in the analysis, aimed to throw light in greater detail on this complex association.

Acknowledgements

We thank the National Council for Scientific and Technological Development (CNPq) for the financial support of this study.

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