São Paulo drought: trends in streamflow and their relationship to climate and human-induced change in Cantareira watershed, Southeast Brazil

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ABSTRACT

The 2013–2015 drought in the Metropolitan Region of São Paulo exposed the lack of resilience of the regional water supply system, highly dependent on the Cantareira reservoirs. In this paper, inflows to each of the four main Cantareira reservoirs are tested for systematic change. Persistent trends in streamflow, rainfall, temperature and evapotranspiration are first evaluated. Streamflow was also tested for step change. Double-mass curves were employed to assess modification in the precipitation–runoff relationship. Subsequently, we used the climate elasticity method and the ABCD model to quantify the relative contribution of climate and human activities into the detected trends. Only Cachoeira and Atibainha sub-basins showed a significant downward trend in streamflow. The results for step change were also significant, and the year of occurrence coincided with breakpoints in precipitation–runoff relationship. For both Cachoeira and Atibainha, human activities had a more significant impact on streamflow reduction than climate variability. Land use and cover maps suggest that the reduction of pasture/abandoned land parallel to an increase in reforestation/silviculture is behind streamflow reduction. The results highlight the importance of coordinating land-use patterns and water management, as an important contributor beyond any considerations of a changing climate. Implications for better managing regional water resources are discussed.

Key words | climate change, climate elasticity, hydrological model, LUCC, streamflow, temporal trends

HIGHLIGHTS

- Decadal downward trend in streamflow found for two of the four Cantareira sub-basins;
- Regional afforestation led to a significant streamflow reduction;
- Land use, climate and water management jointly responsible for drought impact;
- Land occupation needs to be revisited through a formal hydro-economic analysis to reconcile with water management goals in Cantareira;
- Study findings reinforce the urgency to reduce the MRSP water supply system on Cantareira and address and integrated water management plan.

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INTRODUCTION

Ensuring the reliability of water supply services in the Metropolitan Region of São Paulo (MRSP) is increasingly a challenge due to social, climate and environmental dynamics. In 2016, the MRSP population was estimated to be 20.6 million (SEADE Foundation 2016), representing about 10.3% of Brazil’s total population, while covering less than 1% of Brazil’s land area (IBGE 2016). Although Brazil accounts for nearly 20% of the world’s water reserves (Ceratti 2016), most of them (74%) are in the Amazon, rather distant from the main consumption centers. Annual water availability in the Alto Tietê River Basin, where the MRSP is located and which supplies water for part of its population, is merely 201 m$^3$ per capita (World Bank 2012). Consequently, the MRSP becomes highly dependent on water diversion from nearby river basins. The main source is the Cantareira system, a network of reservoirs which transfers water from the Piracicaba River Basin, being responsible for serving nearly half of the MRSP population.

The Metropolitan Region of Campinas (MRC), located downstream of the Cantareira reservoir system, also depends on the Piracicaba River Basin to meet its own needs. The MRC is a highly industrialized and urbanized area, with high population and economic growth rates. These circumstances lead to conflicts in water demand, especially with an expected growth in demand for both the MRC and the MSRP (ANA & DAEE 2016).

The fragility of MRSP water supply has been exposed by recent extreme climate events. During the 2013–2015 drought in Southeastern Brazil, the anomalously low inflows to the Cantareira system caused reservoir storage to be reduced beyond minimum operational level (Sabesp 2015). Emergency structural and non-structural measures were undertaken to prevent the water supply system from collapsing (Braga & Kelman 2016). The restrictions imposed on the water supply were accompanied by an increase in water tariffs, prompting social protests and riots in different parts of the MRSP. The impact of the drought on crops caused food prices to rise. More than 60,000 industries in the state of São Paulo, which represented 60% of the industrial GDP, were affected by the water crisis, as well as commercial establishments, hospitals and schools (Marengo et al. 2015). The years between 1999 and 2004 had already been particularly dry, causing the storage levels of Jaguari-Jacareí, the largest reservoir from Cantareira system, to go to −7% (below minimum operational level) in 2004 (Whately & Cunha 2011).

The Cantareira supply system consists of a series of interconnected reservoirs, namely Jaguari-Jacareí, Cachoeira, Atibainha and Paiva Castro (Figure 1). Inflows to the first three reservoirs, which account for 99.2% of operational storage capacity, have dropped in recent years. The aggregate mean inflow for the Cantareira system in the 2004–2015 period represented only 81.1% of the observed aggregate mean inflow for the 1930–2015 period (ANA & DAEE 2016).

According to Tomer & Schilling (2009), there are several factors influencing the watershed hydrology, namely, vegetation type, soil properties, geology, terrain, climate, land-use practices, besides spatial patterns of interactions.
among them. The effect of climate variability on streamflow is mostly given by the variability of precipitation and potential evapotranspiration (Scanlon et al. 2007; Ward et al. 2009; Chang et al. 2010; Chien et al. 2013). Land use and cover change (LUCC), reservoir operation and direct water extraction from surface and groundwater and its effects express human-induced change (Chang et al. 2016).

Marengo et al. (2015) noted the decrease in annual precipitation over Cantareira region since 1990. Salviano et al. (2016) used the database from the University of East Anglia Climatic Research Unit to investigate trends in different climate variables in Brazil from 1961 to 2011. In the Cantareira region, mean temperature showed an increasing trend for all months between 1961 and 2011, with potential evapotranspiration growing proportionally, whereas no significant trends were found for precipitation.

Other studies report modifications in land use and land cover (LULC) in the region. Caram (2010) performed an analysis for the Piracicaba River Basin and, in the area corresponding to Jaguari-Jacareí, Cachoeira and Atibainha catchments, the land area occupied by pasture decreased between 1978 and 2003, while urban areas and reforestation/silviculture expanded. After performing land-use classification based on Landsat images for the years 1986 and 2005, Pereira & Teixeira Filho (2009) concluded that the native forest and pasture areas are being replaced by silviculture upstream Atibainha and Cachoeira reservoirs.

Several studies have been carried out to quantify the relative importance of climate variability and human-induced change in runoff. Two different approaches have been widely used for that purpose: process-based and statistical methods. In the first approach, physically based hydrological models are calibrated for the period preceding the detected changes in streamflow. To separate the impacts of climate variability and human interference, streamflow is then simulated using meteorological data for the subsequent period, but with fixed model parameters, which embed original LULC conditions (Xu et al. 2014). Among the statistical methods, climate elasticity is a commonly used measure. It estimates the proportional response of streamflow to changes in precipitation and potential evapotranspiration (Chang et al. 2016). Often both approaches are compared. Examples are found in Chang et al. (2016), Liu et al. (2015), Negash (2014) and Zhan et al. (2014).

There is a perception that climatic changes may be primarily responsible for the recent water supply crisis, and hence, identifying and attributing the source of streamflow reduction is important (Otto et al. 2016). Given this context, the aims of this study are (1) to investigate whether a systematic change in streamflow is occurring in Cantareira watershed; and, in the affirmative case, (2) to characterize the nature of the changes in reservoir inflows, using climate elasticity and the ABCD hydrological model to separate the relative influence of climate variability and human interference.

**STUDY AREA AND DATA**

The Cantareira watershed (46°43′–45°51′ W, 23°26′–22°36′ S) has a total drainage area of approximately 2,280 km² (Whately & Cunha 2007) and can be subdivided into four sub-basins, corresponding to the catchment area for each of its four main reservoirs: Jaguari-Jacareí, Cachoeira, Atibainha and Paiva Castro. The first three belong to the Piracicaba River Basin, whereas the Paiva Castro sub-basin is part of Alto Tietê River Basin (Figure 2).

The Cantareira watershed comprises, fully or partially, twelve different municipalities, four of which belong to the state of Minas Gerais, and the other eight, to the state of São Paulo. The altitude ranges from around 1,800 m in the northeastern part of the watershed to approximately 700 m near the MRSP. For most of the Cantareira watershed, the climate is characterized by mild dry winters and hot wet summers (Cwa in Köppen’s classification system); downstream, it is characterized by the absence of a dry season and hot summers (Cfa); whereas the tepid summers typify the climate in the lower part of the basin (Cfb) (PCJ Basin Agency 2011). The rainy season runs from October to April, with most precipitation falling between December and February (PCJ Basin Agency 2011). The temperature ranges, approximately, between 14 and 26 °C throughout the year. Annual precipitation varies between 1,200 mm and 2,000 mm, the more rainfall occurring in the higher altitudes (INMET 2009).

Mean monthly inflow data for each of the four reservoirs were provided by Basic Sanitation Company of the State of São Paulo – SABESP, and the details on the calculation of the series of naturalized flows are found in ANA & DAEE (2016). Raw monthly precipitation data were gathered from
different gauges across the Cantareira watershed, from the Waters and Electric Energy Department of the State of São Paulo – DAEE, Water Management Institute of Minas Gerais – IGAM-MG, Brazil National Water Agency – ANA and from SABESP. Rainfall data were not always consistent, and the spatial–temporal coverage also limited. The years with observed rainfall data did not overlap fully for all the gauges in the region. Consequently, we restricted the time window of our analysis between 1976 and 2009 (34 years), which was found to be the longest period with at least two or three functioning stations for each sub-basin. The final selection of rainfall stations used in this study is listed in Table 1 and indicated in Figure 3.

Daily temperature data were retrieved from the Brazilian National Institute of Meteorology – INMET. Only two stations, sufficiently close to the Cantareira watershed and with altitudes compatible with its elevation range, were chosen, since most of the surrounding stations have missing data between 1976 and 2009. The meteorological stations are also referenced in Table 1 and marked in Figure 3.

Missing values in monthly precipitation data were filled using the Normal Ratio Method (Chow et al. 1988). The missing precipitation value $P_x$ is calculated as:

$$ P_x = \frac{1}{n} \sum_{i=1}^{n} N_x N_i P_i $$

where $P_i$ denotes the recorded precipitation for the $i$th neighboring station, $N_x$ is the normal precipitation for the station ‘x’ with the missing value, $N_i$ is the normal precipitation for the $i$th neighboring station and $n$ is the total number of neighboring stations being considered, $n \geq 3$. The distance from station ‘x’ to each of the neighboring stations should be preferably less than 100 km. Prior to filling missing values, the correlation between station ‘x’ and each of the neighboring stations was tested.

The consistency of precipitation records was checked by plotting the double-mass curve of cumulative monthly precipitation of a target station against the cumulative monthly precipitation in the region. Inconsistent precipitation records
### Table 1 | Rainfall gauges and meteorological stations

#### Rainfall gauges

| Name                          | Operator | Longitude          | Latitude          | Altitude [m] | Annual mean [mm] |
|-------------------------------|----------|--------------------|-------------------|--------------|------------------|
| Joanópolis                    | DAEE-SP  | 46° 16' 00" W     | 22° 55' 59" S    | 920          | 1,579            |
| Usina Flores                  | DAEE-SP  | 46° 25' 01" W     | 22° 54' 01" S    | 940          | 1,596            |
| Camanducaia                   | IGAM-MG  | 46° 08' 49" W     | 22° 45' 36" S    | 1,040        | 1,523            |
| Faz. Retiro                   | SABESP   | 46° 06' 60" W     | 22° 55' 59" S    | 1,180        | 2,063            |
| Barragem Cachoeira            | SABESP   | 46° 19' 09" W     | 23° 02' 28" S    | 828          | 1,606            |
| Crioulos                      | DAEE-SP  | 46° 18' 01" W     | 23° 04' 01" S    | 900          | 1,566            |
| Barragem Atibainha            | SABESP   | 46° 23' 33" W     | 23° 09' 53" S    | 791          | 1,521            |
| Nazaré Paulista               | DAEE-SP  | 46° 24' 01" W     | 23° 11' 00" S    | 790          | 1,507            |
| Taperá Grande                 | SABESP   | 46° 27' 00" W     | 23° 19' 12" S    | 760          | 1,571            |
| Barragem Paiva Castro         | SABESP   | 46° 40' 45" W     | 23° 19' 48" S    | 750          | 1,541            |

#### Meteorological stations

| Name                          | Operator | Longitude          | Latitude          | Altitude [m] |
|-------------------------------|----------|--------------------|-------------------|--------------|
| São Paulo (Mir. de Santana)   | INMET    | 46° 37' 12" W     | 23° 28' 48" S    | 792          |
| Itapira                       | INMET    | 46° 48' 19" W     | 22° 24' 54" S    | 633          |

![Figure 3](http://iwaponline.com/hr/article-pdf/51/4/750/730713/nh0510750.pdf)  
*Figure 3* | Localization of meteorological stations and rainfall gauges used in this study.
were adjusted following the recommendations in Allen et al. (1998).

The areal precipitation for each of the four sub-basins was calculated as the simple arithmetic mean of monthly precipitation values for gauges within a specific catchment.

Potential evapotranspiration (ETo) is used as an input for both the climate elasticity method and the ABCD model. For Cantareira, the available ETo measurements did neither cover the 1976–2009 time window nor any sufficiently long period of time for the purposes of this study. Consequently, ETo across Cantareira needed to be estimated empirically. The Hargreaves–Samani (Hargreaves & Samani 1985; McMahon et al. 2013) equation is deemed to be one of the simplest – it only requires daily measurements of temperature – and most reliable empirical equations for ETo estimation (Jensen et al. 1990, 1997; Hargreaves & Allen 2003; Shahidian et al. 2012). Thus, ETo across Cantareira was estimated with the R package ‘Evapotranspiration’ (Guo et al. 2019), utilizing the Hargreaves–Samani formulation, with temperature data from meteorological stations indicated in Table 1.

Data on water grants within the Cantareira watershed were retrieved from ANA (ANA 2016) (Figure 4). LULC maps for Cantareira watershed for the years of 1989, 1999 and 2003 were provided by the ‘SocioAmbiental’ Institute – ISA, while the 2010 map was provided by the ‘Terceira Via’ NGO (Figures 5 and 6).
METHODS

Trends and breakpoint analysis

Hydro-meteorological time series – Annual Streamflow (AS), Annual Precipitation (AP), mean annual temperature (MAT) and potential evapotranspiration (ETo) – were checked for the presence of temporal trends, utilizing the Mann–Kendall test (Mann 1945; Kendall 1975), the Spearman’s Rho test (Spearman 1904; Glasser & Winter 1961), and linear regression. The Hurst exponent (Hurst 1951; Weron 2002) was estimated for each AS series to further support the detection of long-range dependence.

In order to detect possible breakpoints in hydro-meteorological time series, the Cumulative Deviations test (Buishand 1982), the Worsley Likelihood Ratio test (Worsley 1979) and Pettit test (Pettitt 1979) were applied.

The double-mass curve of cumulative measured runoff against cumulative computed runoff was used to validate the occurrence of trends and breakpoints in streamflow data. A linear regression of observed streamflow onto effective precipitation – which takes into account the effect of the previous year's precipitation on current year runoff – was performed, and model parameters are used to calculate the ‘computed streamflow’. Cumulative computed streamflow was plotted against cumulative measured streamflow. Breaks of the slope are a sign of modification in precipitation–runoff relation. Further details are found in Searcy & Hardison (1960).

Estimation of climate variability and human-induced changes impact on streamflow

Following the identification of breakpoints in AS and changes in precipitation–runoff relationship, the AS time series was divided into two different periods. The period before the breakpoint was named the ‘reference period’ and the period after the breakpoint, the ‘disturbed period’. The impacts of climate variability and human-induced change were supposed negligible for the reference period. Here, we assume that the difference ΔQ between average AS in the

Figure 5 | LULC maps of Cantareira watershed for the years 1989, 1999, 2003 and 2010 (‘Socioambiental’ Institute and ‘Terceira Via’ NGO).
reference period and disturbed period can be expressed as:

$$\Delta Q = \Delta Q_C + \Delta Q_H$$

(2)

where $\Delta Q_C$ refers to variation in streamflow due to climate variability and $\Delta Q_H$ to the variation due to human-induced changes. The partitioning was estimated through the climate elasticity method and hydrological modeling using the ABCD model.

**Climate elasticity method**

Schaaake (1990) pioneered the concept of climate elasticity of streamflow. It denotes the proportional response of runoff to changes in a climatic factor $X$ (potential evapotranspiration or precipitation, in this case). It is expressed as:

$$\varepsilon_X = \frac{\partial Q}{\partial X/X}$$

(3)

The Budyko hypothesis (Budyko 1948) assumes water balance is governed by the amount of available energy, or the atmospheric demand (represented by potential evapotranspiration $-\text{ETo}$), and water availability (represented by precipitation $-P$). From the Budyko hypothesis and the long-term water balance equation ($Q = P - E$), it derives that the ratio of annual evapotranspiration to precipitation ($E/P$) is a function of $\varphi = \text{ETo}/P$, dubbed the aridity index, and that precipitation ($\varepsilon_P$) and potential evapotranspiration ($\varepsilon_{\text{ETo}}$) elasticity of streamflow can be assessed through (4) (Arora 2002):

$$\varepsilon_P = 1 + \frac{\varphi F'(\varphi)}{1 - F(\varphi)}, \quad \varepsilon_P + \varepsilon_{\text{ETo}} = 1$$

(4)

There are different expressions available in the literature for the estimation of $F(\varphi)$. They are summarized in Table 2 (Zhan et al. 2014).

The impact of climate variability on streamflow variation is then calculated as:

$$\Delta Q_C = [\varepsilon_P (\Delta P/P) + \varepsilon_{\text{ETo}} (\Delta \text{ETo}/\text{ETo})]Q$$

(5)
was constrained to be within the range $(0.5$ < $H < 1.0)$. A perceptible break in slope is observed for Cachoeira and Atibainha basins, and the year of the break agrees with the results of step change tests (1989 and 1998, respectively).
Figure 7 | Annual precipitation (AP) and annual streamflow (AS) for: Jaguari-Jacareí (a); Cachoeira (b); Atibainha (c); Paiva Castro (d) catchments; mean annual temperature (MAT) (e) and potential evapotranspiration (ETo) (f) for Cantareira watershed.

Figure 8 | Double-mass curves of cumulative computed inflows versus cumulative measured inflows.
Impact of climate variability and human-induced change on streamflow

Following the results of step change tests and double-mass curves, we divided the Cachoeira and Atibainha AS time series in two different periods (reference and disturbed): 1976–1989 and 1990–2009 for Cachoeira and 1976–1998 and 1999–2009 for Atibainha, respectively. Table 6 contains the average AS, AP and ETo for each sub-basin for the reference and disturbed periods, as defined above.

Climate elasticity

The relative contribution of climate variability to the reduction of streamflow is first assessed through the climate elasticity method. Table 7 shows the values for \( \varepsilon_P \) and \( \varepsilon_{ETo} \).
for each of the different expressions of $F(\phi)$ for Cachoeira and Atibainha basins, and the associated contribution of climate variability ($\Delta Q_c$) and human-induced change ($\Delta Q_h$).

For the Cachoeira basin, the elasticity coefficient of AS to AP ranges between 1.85 and 2.30. This means a decrease of 10% in precipitation provokes a reduction in streamflow between 18.5 and 23.0%. In the case of Atibainha basin, a decrease of 10% in precipitation causes streamflow to decline between 19.8 and 24.2%. The coincidence of results was expected since Cachoeira and Atibainha share very similar characteristics.

Concerning the relative contribution of climate and human-induced changes in decreasing streamflow, for the Cachoeira basin, the contribution of climate ranged between 28.8 and 36.7%, while the contribution of human-induced changes ranged between 63.3 and 71.2%. For Atibainha basin, the contribution of climate oscillated between 39.5 and 48.5%, and contribution of human-induced changes, between 51.5 and 60.5%.

**ABCD model**

The ABCD model was calibrated and validated for Cachoeira and Atibainha basins. For Cachoeira, monthly precipitation, potential evapotranspiration and streamflow between 1976 and 1984 were used for model calibration. Monthly series from 1985 to 1989 were used for model validation. The NSE values were 0.83 and 0.65 for calibration and validation periods, and WBE values were $-0.16$ and 5.62%, respectively. As for Atibainha, monthly precipitation, potential evapotranspiration and streamflow between 1976 and 1990 were used for model calibration, and monthly series from 1991 to 1998 were used for model validation. The NSE values were 0.71 and 0.64 for calibration and validation periods, and WBE values were 0.93 and $-3.85\%$, respectively. NSE values were greater than 0.60 for model calibration and validation with Cachoeira and Atibainha data, indicating satisfactory model performance (see Appendix A – Supplementary information).

Table 8 shows the average simulated and observed AS for reference and disturbed periods. According to this approach, for Cachoeira basin, the relative contribution of climate variability in streamflow reduction is 30.9%, and the relative contribution of human-induced changes, 69.1%. As for Atibainha basin, the relative contribution of climate variability is 47.3%, and the relative contribution of human-induced changes is 52.7%.

The relative contribution of climate variability and human-induced change to streamflow reduction given by the ABCD model lies within the range determined by the climate elasticity method for both Cachoeira and Atibainha basins, indicating that the results from the two different approaches are in agreement.

| $F(\phi)$ | $\epsilon_p$ | $\epsilon_{\Delta H}$ | $\Delta Q_c$ [mm] | $\Delta Q_h$ [mm] | $\Delta Q_c$ [%] | $\Delta Q_h$ [%] |
|-----------|--------------|-----------------|--------------------|-----------------|----------------|----------------|
| Cachoeira  | Schreiber    | 1.85            | -0.85              | -99.0           | -244.6         | 28.8           | 71.2           |
|           | Ol’dekop     | 2.30            | -1.30              | -126.2          | -217.4         | 36.7           | 63.3           |
|           | Budyko       | 2.03            | -1.03              | -109.7          | -233.9         | 31.9           | 68.1           |
|           | Turc-Pike    | 2.07            | -1.07              | -112.3          | -231.3         | 32.7           | 67.3           |
|           | Fu           | 1.96            | -0.96              | -105.4          | -238.2         | 30.7           | 69.3           |
|           | Zhang et al. | 1.90            | -0.90              | -101.5          | -242.1         | 29.5           | 70.5           |
| Atibainha  | Schreiber    | 1.98            | -0.98              | -75.2           | -115.3         | 39.5           | 60.5           |
|           | Ol’dekop     | 2.42            | -1.42              | -92.3           | -98.2          | 48.5           | 51.5           |
|           | Budyko       | 2.15            | -1.15              | -81.8           | -108.6         | 43.0           | 57.0           |
|           | Turc-Pike    | 2.19            | -1.19              | -83.4           | -107.1         | 43.8           | 56.2           |
|           | Fu           | 2.05            | -1.05              | -78.0           | -112.5         | 40.9           | 59.1           |
|           | Zhang et al. | 1.99            | -0.99              | -75.4           | -115.1         | 39.6           | 60.4           |

| | Cachoeira Observed | Atibainha Observed | Cachoeira | Atibainha |
|---|-------------------|-------------------|-----------|-----------|
| Reference [mm] | 834.4 | 820.1 | 651.8 | 656.6 |
| Disturbed [mm] | 728.0 | 476.2 | 561.8 | 466.2 |
| $\Delta Q_c$ | $-106.3$ | $-237.7$ | $-90.0$ | $-100.4$ |
| $\Delta Q_h$ | 30.9 | 69.1 | 47.3 | 52.7 |
DISCUSSION

Changes in streamflow

It is observed that, since 1998, the interannual variation for both AP and AS in all Cantareira sub-basins was reduced. This coincides with the onset of a shorter negative phase of Pacific Decadal Oscillation (PDO), which lasted for about 4 years (1999–2002) (Peterson et al. 2006). PDO is considered to influence the flow regime of Eastern Paraná Basin, where Cantareira watershed is located: lower (higher) river flows are observed during PDO negative (positive) phase (Capozzoli et al. 2017; Silva & Silva 2017). Along with that, 1998–1999 and 2000–2001 were La Niña years, which caused the effects of PDO cold phase to be magnified (Wang et al. 2014).

Nevertheless, only Cachoeira and Atibainha AS series showed significant results in trend and breakpoint analysis for all tests performed. Meanwhile, AP series did not exhibit any significant trend for any of the four sub-basins, and MAT/ETo test results were not unanimous as to characterize a definite upward trend. Even though the combination of AP and MAT/ETo patterns in the Cantareira watershed might suggest a tendency for reduced streamflow, the magnitude of detected streamflow reduction in Cachoeira and Atibainha invalidate the hypothesis that the observed phenomenon is mostly due to climatic variations. Besides, all sub-basins are reduced in area and adjacent, which means the detected differences between Cachoeira and Atibainha and the other sub-basins must be a result of particular circumstances not directly related to climate. As for Jaguari-Jacareí and Paiva Castro, it is reasonable to affirm that the evolution of streamflow is largely explained by climatic variation.

The estimates obtained for Hurst exponents are in accordance with the conclusions of Vogel et al. (1998) on the $H$ values for streamflow series. Considering the results of previous tests, which detected the presence of trends for Cachoeira and Atibainha, $H$ values for these two basins were expected to be close to 1.0. Paiva Castro streamflow series, however, did not display any significant trend according to the preceding analysis and yet $H = 0.80$. In this regard, it is worth noticing that the underlying factors behind the so-called Hurst effect remain a subject of considerable debate, possibly resulting from a variety of processes and their specific interactions (Maftei et al. 2016).

Contribution of climate variability and human-induced change to streamflow reduction

The results yielded by both the climate elasticity analysis and the ABCD modeling support the above-mentioned conclusions. For both Cachoeira and Atibainha, human-induced change has been identified as the major driver of streamflow reduction. This is coherent with the fact that the Jaguari-Jacareí and Paiva Castro sub-basins do not present any significant downward trend in streamflow, despite being subject to very similar climatic dynamics.

According to ANA & DAEE (2016), surface water withdrawals upstream of the Cantareira reservoirs are insignificant considering the precision of operational flow data. In addition, the region has a crystalline basis and aquifers are classified as ‘fissures’, characterized by low productivity (Vieira & Vieira 2016). Indeed, the active water grants within the Cantareira watershed totaled approximately 0.88 m$^3$/s in July 2016, the largest withdrawals happening in Camanducaia (0.275 m$^3$/s) and Mairiporã (0.178 m$^3$/s) (Figure 4). Under the supposition that water withdrawals were lower or at most equal in the past, it is safe to consider that neither surface nor groundwater extraction play a significant role in explaining the decreasing AS in Cachoeira and Atibainha basins from 1976 to 2009.

LUC analysis

Previous studies analyzed the relationship between afforestation and deforestation processes and alterations in the watershed hydrological cycle. Bosch & Hewlett (1982) reviewed 94 experimental catchment studies to determine the effect of vegetation change on water yield. The study concluded that, generally, afforestation leads to decreased water yield and deforestation leads to increased water yield. A number of other studies assessed the effects of alterations in vegetation in water yield, arriving at similar conclusions (Hornbeck et al. 1993; Sahin & Hall 1996; Stednick 1996; Vertessy 1999). These effects are known to be influenced by plantation species, original vegetation type,
plantation age, mean annual precipitation, topography, catchment size and proportion of changes in cover (Farley et al. 2005; Liu et al. 2016; Filoso et al. 2017).

In agreement with previous results, little oscillation is observed in LULC in Jaguari-Jacareí throughout the years in terms of proportional area. From 1989 to 2010, most pasture/abandoned land/exposed soil conversion to other LULC types was due to reforestation/silviculture and secondary forest cover in medium or initial stage of regeneration (5.33% of Jaguari-Jacareí basin area). On the other hand, pasture/abandoned land/exposed soil advanced primarily over areas of primary/secondary forest cover in the advanced stage of regeneration and reforestation/silviculture (2.99%). Overall, no substantial transition is noticed (see Appendix B – Supplementary information).

Diversely, the area occupied by pasture/abandoned land/exposed soil has been gradually decreasing in Cachoeira basin since 1989, parallel to a steady increase in reforestation/silviculture. It can be inferred that reforestation/silviculture, primarily, and secondary forest cover in medium or initial stage of regeneration is replacing pasture/abandoned land/exposed soil. This is confirmed by LULC transition rates: between 1989 and 2010, the conversion of pasture/abandoned land/exposed soil to reforestation/silviculture and secondary forest cover in medium or initial stage of regeneration sums up to 14.41% of Cachoeira basin area, while the opposite pattern only accounts for 1.84%. Considering the impact of LUCC to be accumulative, the previous analysis offers a plausible explanation for the observed decreasing trend in Cachoeira reservoir inflows since 1989.

In Atibainha basin, a relatively significant increase in pasture/abandoned land/exposed soil area is observed between 1989 and 1999, whereas little change happens in reforestation/silviculture and native forest cover areas. This modification in pasture/abandoned land/exposed soil area must be regarded with caution, since in 1989, around 25 km² of land (7.8% of Atibainha basin area) could not be properly categorized due to the presence of clouds and shadow, a situation that was not repeated for the subsequent years. This fact may translate into the overestimation of the increase in pasture/abandoned land/exposed soil between 1989 and 1999. This supposition is supported by the fact that no clear response of streamflow to a presumable deforestation process is observed for the 1989–1999 interval. From 1999 to 2003, analogously to Cachoeira, pasture/abandoned land/exposed soil area is gradually shrinking, while a slow expansion in reforestation/silviculture is perceived, and native forest cover oscillates little. A more expressive alteration is observed between 2003 and 2010, also suggesting the replacement of pasture/abandoned land/exposed soil for reforestation/silviculture, mostly, and secondary forest cover in the medium or initial stage of regeneration. Indeed, the conversion of pasture/abandoned land/exposed soil to reforestation/silviculture and secondary forest cover in the medium or initial stage of regeneration corresponds to 13.54% of Atibainha basin area, whereas the reverse process was 3.36%.

Thus, for both Cachoeira and Atibainha basins, LUCC offers a plausible explanation for the observed decreasing trend in AS.

After surveying landowners in Cantareira watershed, Pereira & Teixeira Filho (2009) found that the substitution of pasture by silviculture is being driven by the lower prices of milk. Moreover, the Brazilian government has been responsible for stimulating forestry production by means of exclusive lines of credit and subsidies in recent decades (Brazilian Silviculture Society 2006).

In the case of Paiva Castro, an increase in streamflow would be expected as a result of deforestation and urbanization (Lull & Sopper 1969; Bosch & Hewlett 1982; Sahin & Hall 1996). However, the series of AS exhibited no detectable trend/shift in such direction; precipitation and streamflow relationship remained presumably the same. There are several arguments to address this apparent conflict: (i) former analysis indicates that reductions in forest cover of less than 20%, which is the case for Paiva Castro, cannot be detected through streamflow data (Bosch & Hewlett 1982; Stednick 1996); (ii) unlike the other Cantareira sub-basins, forest cover and reforestation/silviculture remained as the predominant LULC (≥50% of Paiva Castro basin area) for all years analyzed; the pasture/abandoned land/exposed soil areas originated between 1989 and 2003 were interspersed with fragments of forest cover (Figure 5), probably functioning as obstacles to water flow (Zhou et al. 2015) and offsetting the expected outcome of deforestation; (iii) it has been observed that the magnitude of yield changes due to deforestation are positively
correlated with the amount of rainfall (Bosch & Hewlett 1982; Vertessy 1999; Brown et al. 2003); because the 1989–2003 interval was below average in terms of precipitation, it may also have masked potential streamflow increase; (iv) urban development is mostly concentrated near the reservoir inlet; this and the fact that the basin is only partially urbanized may cause any urban effects to be countered by discharge from non-urban areas (Lull & Sopper 1969).

Between 2003 and 2010, the LUCC trend from former years in Paiva Castro was ‘reversed’. Contradicting the empirical evidence, AS series did not accuse any significant decrease associated with afforestation, differently from Cachoeira and Atibainha basins. A number of hypothesis can be drawn to explain this supposed contradiction: (i) unlike Cachoeira and Atibainha basins, afforestation in Paiva Castro basin was probably more influenced by the context of the Conservation Units within the watershed rather than driven by silviculture expansion (Ehlers 2007; São Paulo 1998, 1985); in this regard, a number of studies have stated that, by prioritizing fast-growing species and short rotations, Eucalyptus plantations are associated with a more intensive use of water (Bosch & Hewlett 1982; Farley et al. 2005; Aranda et al. 2012); (ii) afforestation in Paiva Castro most probably did not happen abruptly between 2003 and 2010, and, besides, its impact on streamflow is known to be gradual (Farley et al. 2005); (iii) taking also into account the fact 2009 was an exceptionally wet year, it is plausible to argue that the available time window is not sufficiently long to allow a proper appreciation of the events discussed.

**SUMMARY AND CONCLUSIONS**

In this study, we analyzed AS in each of the sub-basins of Cantareira watershed, namely Jaguari-Jacareí, Cachoeira, Atibainha and Paiva Castro, to identify trends and the timing of structural changes in streamflow and their relationship with climate variability and LUCC.

Only Cachoeira and Atibainha basins showed a significant decreasing trend in AS ($p < 0.05$) in the period between 1976 to 2009, whereas AP time series did not follow the same pattern in these two sub-basins, nor did ET0. Meanwhile, MAT showed a significant increasing trend ($p < 0.10$) for two of the three tests performed.

Step change detection was performed for AS time series. Neither Jaguari-Jacareí nor Paiva Castro basins showed significant results for step change detection. The years of 1989 and 1998 were identified as breakpoints for Cachoeira and Atibainha basins, respectively. The double-mass curve of cumulative computed streamflow versus cumulative observed streamflow confirmed that the relationship between precipitation and streamflow was altered for Cachoeira and Atibainha basins after the respective breakpoint years, though no modification was noticed for Jaguari-Jacareí or Paiva Castro basins.

The relative impact of climate variability and human-induced change on Cachoeira and Atibainha basins streamflow reduction was assessed through the climate elasticity method and the calibration of the ABCD hydrological model. For Cachoeira basin, the average AS between 1990 and 2009 represented 58.2% of the average AS between 1976 and 1989. The impact of climate variability on streamflow reduction was estimated to be between 28.8 and 36.7%, and the impact of human-induced change, between 63.3 and 71.2%. As for Atibainha basin, the average AS between 1999 and 2009 represented 71.0% of the average AS between 1976 and 1998. The impact of climate variability was estimated to be between 39.5 and 48.5%, and the impact of human-induced change, between 51.5 and 60.5%. The analysis of LUCC in the region revealed that silviculture and native forest cover are gradually substituting abandoned land and pasture areas. Since regional water withdrawals from both surface and groundwater are not significant, we conclude that the parcel of streamflow reduction attributed to human-induced change is chiefly explained by LUCC.

The role of afforestation in determining the water balance of a region has engendered debate over the last few decades, with results indicating increases or decreases in the streamflow. In this setting, the finding that the afforestation activity associated with increasing Eucalyptus plantations over a wide area have led to streamflow reduction is significant. Given that this effect has evolved over a two-decade period of increasing afforestation and is manifest as a change in the rainfall–runoff relationship, this land-use strategy needs to be revisited through a formal hydro-economic analysis to provide better
coordination between LULC patterns and water management in Cantareira. The detected trends regarding climate change, LUCC and demand for water reinforce the urgency to reduce the MRSP water supply system on Cantareira and address and integrated water management plan.

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SUPPLEMENTARY MATERIAL

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