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Abstract

Changes in climate and water demand in densely populated regions increasingly affect hydrological systems, and, in turn, impact socioeconomic conditions. In this case study, we identify how the hydrogeological frameworks of two water resource management units, Tietê-Jacaré (TJ) and Piracicaba-Capivari-Jundiaí (PCJ) in Sao Paulo state (Brazil), control the baseflow processes and resilience in the face of streamflow fluctuations in response to anthropogenic activities and climate variation. The results reveal between 40% and 75% contributions of baseflow to total streamflow in basins overlying crystalline and sedimentary aquifers. The basins in PCJ which mostly overly crystalline aquifers, have shorter water residence times and greater dependence on surface water. Therefore, streamflow in the PCJ basins is vulnerable during the drought period and the management model affected the water resilience of the basins (transfer of water to Cantareira System). The TJ basins have greater streamflow contributions from aquifer discharge linked to the presence of important sedimentary aquifers, which improves resilience under changing rainfall patterns, these basins present a more stable situation of resilience. Ultimately, the two management units require different planning strategies with adaptive and dynamic actions to mitigate the social, economic, and environmental effects caused by the variability and reduction of water sources.

Keywords: Surface water, groundwater, resilience, baseflow, hydrograph separation

Key points

1. Assessment of the role hydrogeological framework in the baseflow and its impact on basin water security.
2. Water management challenges faced to intense anthropological actions and changes in rainfall behavior, case of tropical basins in metropolitan regions.

Introduction

Water management depends directly on the correct assessment of data that adequately describe natural and anthropogenic factors that alter the local hydrological cycle (Alley, 2016; Ross 2018). This is a priority activity for densely populated regions that are vulnerable to the effects of climate change. Increased understanding of hydrological processes will allow better management for water availability during water stress (Ali et al., 2019; Wang et al., 2016).

Understanding surface water and groundwater interactions is fundamental for assessing the ability of the hydrological cycle to maintain a stable water supply (water resilience) and planning actions aimed at meeting social demands, without harming the ecological functions of the basins (Falkenmark et al., 2019; Hashimoto et al., 1982; Lott & Stewart, 2016).

The baseflow represents an important hydrological process in watersheds, is a component of the underground system of the hydrological cycle, as it reflects the connection between precipitation, groundwater, and river streamflow (Hall, 1968; Li et al., 2014; Lott & Stewart, 2016; Tallaksen, 1995; Zhang et al., 2017). Due to the ability of aquifers to store the water reserves, the baseflow discharge into the streamflow throughout the annual cycle is responsible to maintain most of part of streamflow in many watersheds in the world (Biswal & Kumar, 2014; Jasechko, 2019).

Baseflow assessment (quantification and origin) in periods of streamflow recession contributes to the understanding of intrinsic hydraulic properties of the subsurface (Stewart, 2015; Owolabi et al., 2020) and the storage capacity of the river basin (Biswal & Kumar, 2014; Biswal & Marani, 2014). For this purpose, recession analysis and (Brutsaert & Nieber, 1977) hydrograph separation are important tools for water management (Chapman & Maxwell, 1996; Eckhardt, 2005).

The quantification of baseflow allows the identification of the proportion of the streamflow derived from groundwater and water discharged from the saturated zone directly to the river (Li et al., 2014; Lott & Stewart, 2016; Scanlon et al., 2002) performed by graph separation, recession analysis, conceptual models and; recursive digital filter (Lott & Stewart, 2016; Partington et al., 2012). Recession analysis aims to quantify the reduction of streamflow in a period without precipitation and to extract descriptive parameters of water storage in the basin (Brutsaert & Nieber, 1977; Sánchez-Murillo et al., 2015; Stewart, 2015).

The southeastern region of Brazil has experienced a challenging situation that has highlighted problems with hydrological resilience in large metropolitan regions. Consecutive drought events between 2011 and 2019 (Cunha et al., 2019) have caused great losses in water reserves designated for supply, intensifying the water crisis in the state of São Paulo (Coutinho et al., 2015; Guzmám et al., 2017; Marengo et al., 2015; Nobre et al., 2016).

São Paulo state is divided into 22 water resources management units. This study focuses on the Tietê-Jacaré (TJ) and Piracicaba-Capivari-Jundiai (PCJ) units. The combined land surface area is 27,000 km^2, with 107 municipalities and about seven million inhabitants. The area presents environmental diversity and water demands that are representative of other regional or national water resources management units in the state of Sao Paulo and parts of the Paraná river basin.

This study aimed to evaluate the control of hydrogeological frameworks in the baseflow processes and to compare this information to the effects of fluctuations in streamflow, additionally evaluating the impact of anthropogenic actions and changes in climate patterns. This is an unprecedented regional approach and complementary to previous studies in these basins in order to improve our understanding of the hydrological dynamics of baseflow recession and describe water resilience in the region. This study aims to answer the following questions: (1) What is the behavior of the baseflow under different hydrogeological conditions and its role in water resilience? (2) What are the effects of anthropogenic activities or variations in rainfall patterns on streamflow? Some trend can be identified?

Study area

The study area includes two water resource management areas in the State of São Paulo consisting of the large hydrographic regions Tietê-Jacaré (TJ) and the Piracicaba-Capivari- Jundiaí (PCJ, **Figure 1**(a)).

According to Köppen's classification (Peel et al., 2007), the climate in the PCJ and TJ regions can be classified as Subtropical climate with dry winter and hot summer (Cwa) and Tropical climate with dry winter

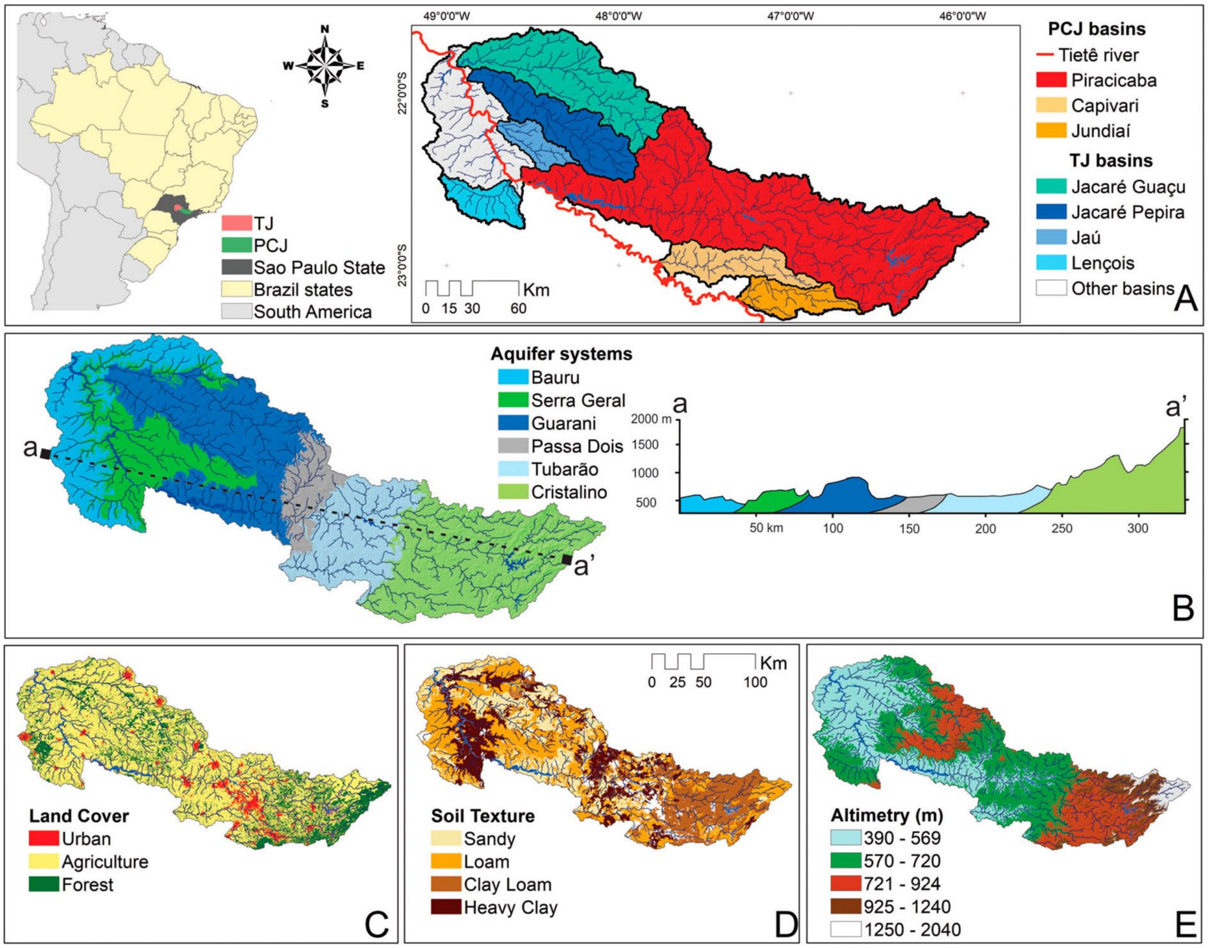

Figure 1. Main basins in the TJ (Tietê-Jacaré unit) and PCJ (Piracicaba-Capivari-Jundiaí unit) and location (a), aquifer systems and profile (b), land cover (c), soil texture (d) and elevation (e) maps. Altimetry, Rivers and Basins SRTM 30 m (Shuttle Radar Topography Mission) of NASA (National Aeronautics and Space Administration); Land Use from Secretariat for the Environment of the State of São Paulo (1: 100,000) elaborated satellite imagery Landsat-5 (Land Remote Sensing Satellite) 2010 (São Paulo, 2010); Geology map (1:500,000) from CPRM, 2006 and; Soil texture map (scale from 1:100,000 to 1:500,000) from Rossi (2017).

(Aw) types, respectively, both climate types are characteristically present a temperature average around 22°C. The average rainfall ranges from 1300 to 1500 mm/year in the study area (**Table 1**).

The basins within PCJ are partially inserted in the relief form of the Atlantic Plateau and the Depression Peripheral. The basins within TJ are located in the Western Plateau. The elevation ranges from 400 to 2000

Table 1. Climatic and morphological characteristics of the main basins.

Unit	*Basins*	*Rainfall (mm/year)*	*Area (km^2)*	*Elevation max. (m asl)*	*Elevation min. (m asl)*	*Surface slope mean (%)*	*River length (km)*
PCJ	Piracicaba	1508	12865	2039	427	14	2845
	Capivari	1326	1587	970	462	9	336
	Jundiaí	1376	1142	1314	492	14	255
TJ	Jacaré-Guaçu	1403	4055	1030	395	7	830
	Jacaré-Pepira	1408	2577	1045	390	8	530
	Lençóis	1371	959	842	423	8	209
	Jaú	1411	752	842	424	7	165

PCJ: Piracicaba-Capivari-Jundiaí; TJ: Tietê-Jacaré.

m asl, with soft undulating relief (Figure 1(e) and Table 1). The basins in PCJ region present a mean surface slope from 9% to 14% and the basins in TJ region have a mean slope of about 8% (Table 1).

Two major hydrogeological domains are present in the study area: (I) crystalline, represented by crystalline aquifer systems; and (II) sedimentary, represented by aquifers of the Paraná sedimentary basin.

From east to west (Figure 1(b)), the hydrogeological framework of the study area is composed of the crystalline aquifer system, formed by a complex of igneous and metamorphic rocks of the Precambrian, superimposed by aquifer units associated with the sediments and basalts of the Paraná sedimentary basin. At the base of the sequence is the Tubarão Aquifer System associated with glacio-marine sediments (diamictites, rhythms, siltstones, claystones, shales) of Permo-Carboniferous age. The Passa Dois Aquiclude represents the impermeable base for the sandy reservoirs of continental origin of the Guarani Aquifer System, which is covered by the basalts associated with the Serra Geral Aquifer System. The sequence ends with the Cretaceous continental sandstones that make up the Bauru Aquifer System (CPRM, 2006; DAEE et al., 2005; Milani, 2004).

In terms of land cover, agricultural land use dominates both regions (Figure 1(c)). The PCJ basins also include large urban and forested areas (São Paulo, 2010). Soil texture according to the pedological map (Rossi, 2017) (Figure 1(d)) in the PCJ region is loam to clay loam and in the TJ region sandy and loam are predominant, with a heavy clay soil in the same area of Serra Geral Aquifer System outcrop.

Anthropogenic activities

The river basins within PCJ have one of the highest urban development in São Paulo State, leading to greater water demand for the urban and industrial sectors. The economic activities of the basins represent 17% of the GDP (Gross Domestic Product) of the São Paulo State (PCJ, 2018a, 2018b). Challenges to water resilience in these basins include reduction in available surface water quality, scarcity of underground water resources and demands from the metropolitan region of Campinas and São Paulo (São Paulo, 2017).

The TJ basins have important agro-industrial activity in the sugar and alcohol sector and have greater water resilience due to the availability of groundwater sources, although there are some evidence of water stress (São Paulo, 2017; TJ, 2019).

The PCJ unit has a complex adaptation to supply the regional demand: (I) transfer the water to the Cantareira System (formed by a set of reservoirs, tunnels and channels that connect the Piracicaba river basin with the headwaters of the Tietê river basin), whose main purpose is to store water for the public supply of the São Paulo Metropolitan Region (SPMR) and municipalities in the PCJ basin, approximately 15 million inhabitants; (II) maintains an exchange system between the Atibaia, Jundiaí and Capivari rivers to meet the demands of the Campinas Metropolitan Region (CMR) and; (III) has water sources compromised by pollution, high demand and low productivity of the aquifers in the region (CETESB, 2018; São Paulo, 2017).

The water budget of the PCJ unit shows these interferences, the Capivari river presents greater releases than its natural availability, and the Jaguari, Atibaia, and Jundiaí rivers have pumping above the natural availability. The Corumbataí and Camanducaia (for more information of this subbasin see Figures 2 & 3) rivers basins have less anthropogenic interference (pumping or releases) in the streamflow (**Figure 2**; PCJ, 2018a, 2018b).

The water transferred to the Cantareira system is transported from the Jacareí and Jaguari dams built in 1981 in the Jaguari river basin (22 $m^3 s^{-1}$) and the Atibainha and Cachoeira dams built in 1975 in the Atibaia basin (9 $m^3 s^{-1}$) and supply from the RMC (PCJ, 2018b).

A study performed with a dataset of gauging station from 1930 to 2012 identified the existence of the streamflow reduction in the basins

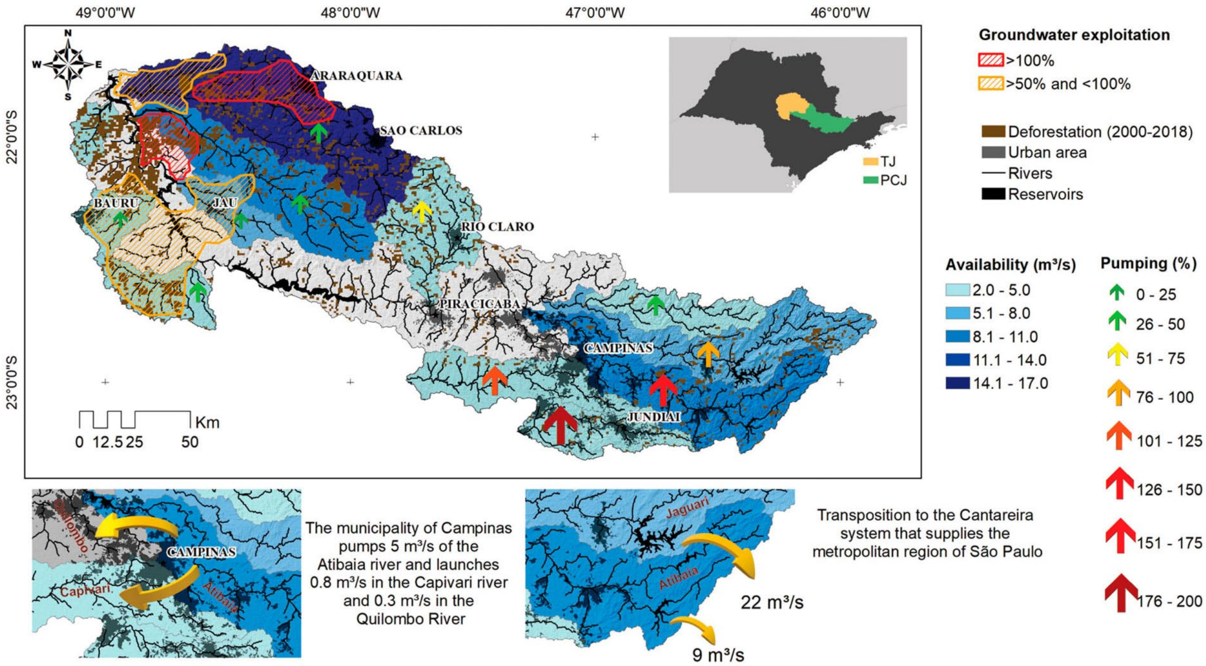

Figure 2. Availability of surface water resources in the PCJ and TJ basins and actions that influence the hydrological regime (transpositions, pumping stations, deforestation, urbanization, reservoirs and groundwater exploitation) from status reports for the years 2018 and 2019 (PCJ, 2018a; TJ, 2019). Pumping (%) is the proportion of water extracted in relation to the ecological streamflow of the basins and Groundwater Exploitation (%) is the percentage extracted of the groundwater recharge (renewable/exploitable reserves).

of the Atibaia and Jaguari rivers due to the transfer of water to the Cantareira system started in 1980 (Frederice & Brandão, 2016).

A concerning situation front to a future reduction in mean precipitation based on simulations and increasing of water demand scenarios, with important impacts on hydrological patterns and the supply system (Gesualdo et al., 2019; Sánchez-Román et al., 2009).

The Capivari river is affected by the municipality of Campinas, which pumps water from the Atibaia river (5 $m^3\ s^{-1}$) and discharges part of its effluent in the Capivari river (0.8 $m^3\ s^{-1;}$ SANASA, 2015) increasing its streamflow.

In the TJ unit, the exploitation of groundwater is concerning. Some municipalities are requiring attention and others have exceeded the recommended limit (exceeds the groundwater recharge), like in the region of the city of Araraquara (Figure 2; São Paulo, 2017; TJ, 2019). Another important issue in the TJ unit is the recent conversion of more than 1740 km^2 of native vegetation for agricultural use in the period from 2000 to 2018 (approximately 15% of the total area, Figure 2; IBGE, 2020; TJ, 2019).

Materials and methods

Data sources

Fifteen representative river gauging stations were selected, nine distributed in five basins in the PCJ and six stations in six basins in the TJ. The instrumentation is part of the hydrological monitoring network of the National Water Agency (ANA) and the Department of Water and Electricity (DAEE, 2020, **Figure 3**, **Table 2**).

Stream gauging stations with monitoring periods greater than 10 years (prior to 2017) were selected. The starting year of data collection for the selected gauges ranges from 1931 to 1976 (Supplementary Table 1).

Rain gauge stations were selected by Thiessen polygon delineation and based on monitoring periods equivalent to the river gauging stations. Thirteen rain stations were used for recession analysis (Supplementary Table 1). For the other analyses, 18 stations were used (Figure 3).

Remote sensing data were obtained from the Giovanni Portal v4.33 by NASA (National Aeronautics and Space Administration). Data included the monthly precipitation of GPM IMERG v6 (Global Precipitation Measurement) with spatial resolution of 0.1° (Huffman et al., 2019).

Hydrograph separation and recession analysis

We applied hydrograph separation following Eckhardt (2005) which uses two parameters, the maximum baseflow index (BFI_{max}) and the recession constant (c). The BFI_{max} was calculated from the ratio of flow duration curves (Q_{90} and Q_{50}), as proposed by Collischonn and Fan (2013) for streamflow stations located in the central and south regions of Brazil (Equation (1)).

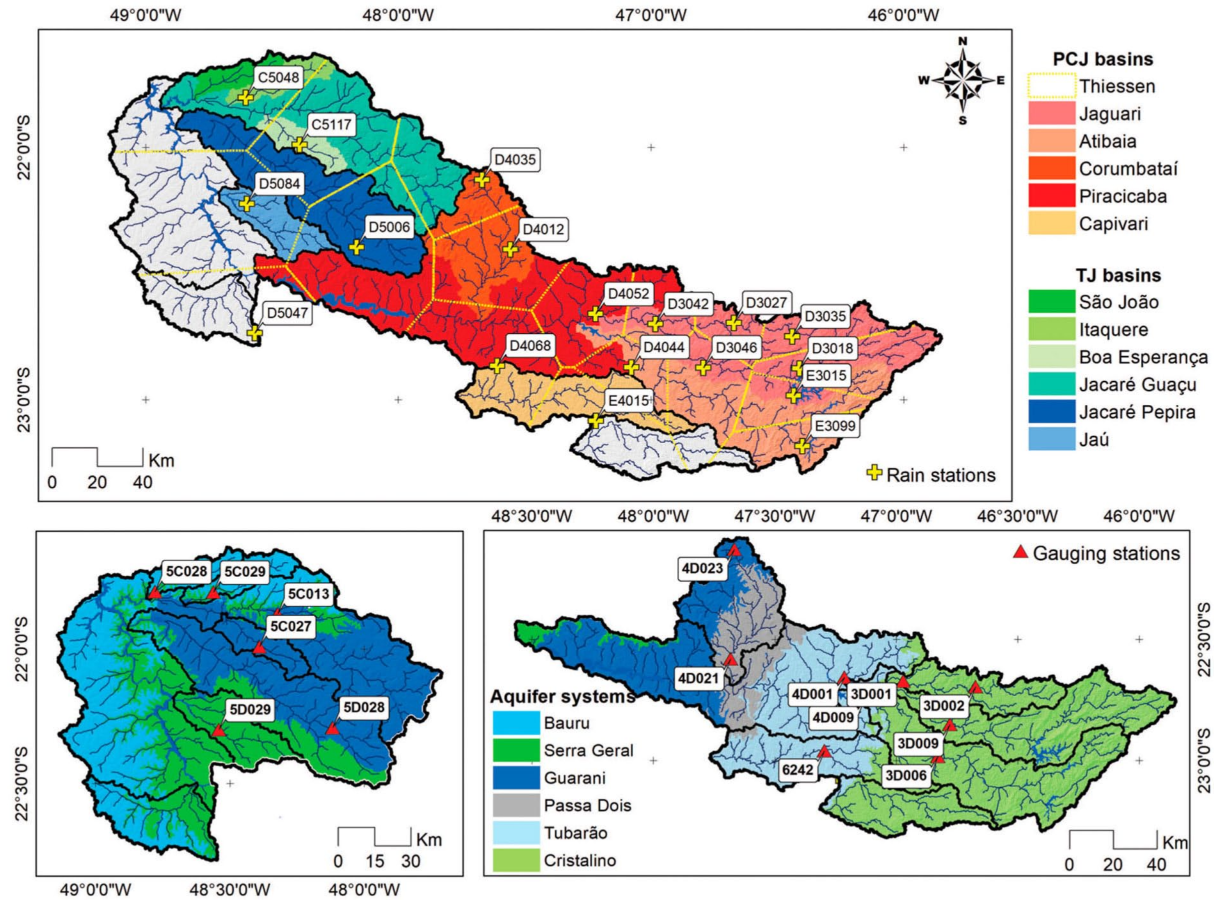

Figure 3. Location of the river and rain gauging stations in the studied basins and presentation of aquifer system distribution in the PCJ and TJ units.

$$BFI_{max} = 0,8344\,\frac{Q_{90}}{Q_{50}} + 0,2146 \qquad (1)$$

The recession constant (c) was calculated based on the duration of the characteristic recession (k) obtained through the recession analysis, according to the methodology proposed by Brutsaert and Nieber (1977, Equation (2)).

$$c = e^{-1/k} \qquad (2)$$

The recession analysis is a parameterization of the relationship between the recharge and discharge of an aquifer (Biswal & Kumar, 2014;

Table 2. Parameters for the hydrograph separation, recession characteristics, minimum storage and average baseflow.

Basins	*Station*	*Area (km^2)*	BFI_{max}	*c*	*k(mean)*	Q_{bf} (Ls^{-1} km^{-2})	*S (mm) until 1980*	*S (mm) after 1980*
Atibaia	3D006	1920	0.62	0.9305	13.8 ± 4.0	12.5 ± 4.6	8.9 ± 2.4	8.0 ± 3.4
	4D009	2738	0.60	0.9387	16.2 ± 3.1	11.1 ± 4.6	6.7 ± 2.7	5.3 ± 2.9
Jaguari	3D009	1950	0.54	0.9263	13.3 ± 4.6	13.2 ± 5.6	9.0 ± 3.0	7.1 ± 3.7
	4D001	3394	0.58	0.9243	12.8 ± 4.0	12.6 ± 5.8	8.8 ± 2.9	6.9 ± 4.1
Camanducaia	3D002	387	0.61	0.9316	14.1 ± 4.0	15.9 ± 6.9	8.7 ± 3.8	8.4 ± 4.2
	3D001	928	0.62	0.9407	16.3 ± 5.0	13.7 ± 6.2	6.9 ± 2.3	6.4 ± 3.5
Capivari	6242	697	0.55	0.9264	13.0 ± 3.2	8.4 ± 3.8	2.5 ± 1.1	3.3 ± 2.2
Corumbataí	4D023	59	0.84	0.9213	12.2 ± 3.6	17.0 ± 3.5	NA	13.7 ± 5.7
	4D021	1581	0.64	0.9527	20.6 ± 11.4	15.4 ± 8.4	6.7 ± 2.3	5.1 ± 3.4
Jacaré-Guaçu	5C013	1867	0.78	0.9637	15.9 ± 16.3	9.3 ± 5.1	8.4 ± 3.2	8.5 ± 2.8
Boa Esperança	5C027	190	0.82	0.9314	14.1 ± 4.1	11.7 ± 3.4	NA	6.8 ± 3.1
Itaquerê	5C029	334	0.67	0.9323	14.2 ± 3.5	10.5 ± 3.5	NA	9.0 ± 5.8
São João	5C028	338	0.71	0.9342	14.7 ± 3.3	10.5 ± 3.5	NA	6.1 ± 3.3
Jacaré-Pepira	5D028	442	0.69	0.9392	15.9 ± 5.1	17.0 ± 6.9	NA	6.4 ± 3.6
Jaú	5D029	417	0.67	0.9235	12.5 ± 3.8	13.9 ± 5.0	NA	9.2 ± 4.0

NA: not available; *c*: recession constant; BFI_{max}: maximum baseflow index; *S*: minimum storage; Q_{bf}: average baseflow; *k*: characteristic recession time.

Sánchez-Murillo et al., 2015). The method consists of a graphical analysis of the decline of the discharge ($-dQ/dt$ [L T^{-2}]) in relation to the discharge (Q [L T^{-3}]) on a logarithmic scale, and reproduces the dependence of the baseflow in relation to aquifer storage. The value of the intercept (a) is related to the characteristic time of the recession of the basin ($k = a^{-1}$).

The recession analysis was applied according to the method described by Sánchez-Murillo et al. (2015), who sorted the data to select the most representative values for the recession analysis and used the linear adjustment by different regression methods to evaluate different recession behaviors by adjusting the parameters of the lines (intercept a and slope b). The use of a set of regression methods allows better adjustments to the data distribution and allows to identify the behavior of the recession, bypassing possible problems in the data series or different natural behaviors.

Finally, the parameters c and BFI_{max} were used to determine the daily baseflow (b_i) in relation to the streamflow on the current day (Q_t) and the baseflow of the previous day (b_{i-1}):

$$b_i = \frac{(1 - BFI_{max})\, c\, b_{i-1} + (1 - c) + BFI_{max}\, Q_t}{1 - c\, BFI_{max}} \tag{3}$$

BFI was calculated to analyze the contribution of the baseflow, using the results of the hydrograph separation. The *BFI* is defined by the ratio of the total baseflow (b_i) and the total streamflow (Q_t)

$$BFI = \frac{\sum_{i=1}^{N} b_i}{\sum_{i=1}^{N} Q_t} \tag{4}$$

The hydrograph separation procedure was performed only with data prior to the construction of dams and used the R software (R CoreTeam, 2019) using the FlowScreen package (Dierauer & Whitfield, 2018).

Minimum storage (S)

Physical considerations based on groundwater hydraulic theory suggest that the storage of groundwater in a basin can be approximated as a function of the flow rate at the outlet of the basin (Brutsaert, 2008; Brutsaert & Nieber, 1977). Thus, flows from the dry period can be conveniently converted into minimum annual storage (S) using the k (characteristic recession time) values in relation to the recession's superficial flow rate (Q_7, the lowest annual flow in seven consecutive days) per unit area (A [LT^{-1}]):

$$S = k\left(\frac{Q_7}{A}\right) \tag{5}$$

Statistical analysis

Three nonparametric statistical tests were used to assess trends in the time series of rainfall and minimum storage (S), which is a way of assessing the degree of anthropogenic interference in the basins (Brutsaert, 2005, 2012; Smakhtin, 2001). The statistical analysis of annual rainfall was performed with all data from 1950 to 2017 and the stream gauging data were analyzed from 1945 to 2017. Stations with shorter time series were analyzed completely.

The selected tests were (1) the Mann-Kendall test to assess the trend in the data, (2) the distribution-free CUSUM to evaluate the variation of the average between two time periods, and (3) the Rank Sum test to verify the change in the median. We used Trend Version 1.2 software, developed by CRC for Catchment Hydrology in Australia (Chiew & Siriwardena, 2005). In addition, graphic variations in the specific discharge (discharge per unit area of an upstream watershed – $Ls^{-1}\,km^{-2}$) were evaluated to visualize the smoothed trends in streamflow.

Standardized Precipitation Index (SPI)

The Standardized Precipitation Index (Mckee et al., 1993) was used to characterize drought at various time scales, recognized as the standard index for quantifying and reporting extreme precipitation events and the effects on groundwater storage and reservoirs (Keyantash, 2018; WMO, 2012).

Precipitation data are typically fitted to a Gamma or Pearson Type III distribution and then transformed into a normal distribution. The transformed data are then used to calculate the SPI value, defined as the standardized precipitation anomaly:

$$SPI = \frac{(P - P^*)}{\sigma_p} \tag{6}$$

where P represents precipitation, P^* the average precipitation and σ_p the standard deviation of precipitation. SPI values can be interpreted as the number of standard deviations by which the observed anomaly deviates from the long-term mean on different monthly scales (Keyantash, 2018; WMO, 2012).

The SPI was used to characterize changes in the pattern of rainfall in the study area between the years 1950–2017 from the data of the rain gauging stations using the SPEI package (Berguería, 2017) using R (R CoreTeam, 2019). It was also applied with GPM IMERG v6 spatial precipitation data series from 2001 to 2019, using the code Climate and Drought Indices (NIDIS, 2020).

Results

Hydrological analyses

The seasonal behavior of rain is similar in the study area, with slightly higher annual volumes at the PCJ unit. The evaluation of the historical monthly precipitation average (Figure 5(c,d)) indicates the existence of two periods: the humid period occurs from October to March, with average rain between 100 and 300 mm, with the months with the largest amount of rain being December, January and February. The dry period, from April to September, is characterized by rainfall below 100 mm, the months of July, August and September are the driest and often do not register any rain event.

The monthly specific discharge (discharge per unit area of an upstream watershed, $Ls^{-1}\,km^{-2}$) in the hydrogeological domains varied from 8.4 to 15.9 $Ls^{-1}\,km^{-2}$ in the crystalline domains and from 10.5 to 17 $Ls^{-1}\,km^{-2}$ in the sedimentary domains. The ratio of the flow duration curve ((Q_{90}/Q_{50})) in the crystalline domain has the lowest values of 0.37–0.49 and in the sedimentary basin values range from 0.50 to 0.75 (Supplementary Table 2).

The flow duration curves in the crystalline domain show greater variability between the streamflow in the wet period (Q_{10}) and dry period (Q_{90}). In the sedimentary domain, the seasonal variation is not as pronounced and reveals higher streamflow than in the crystalline domain in the dry period (**Figure 4**).

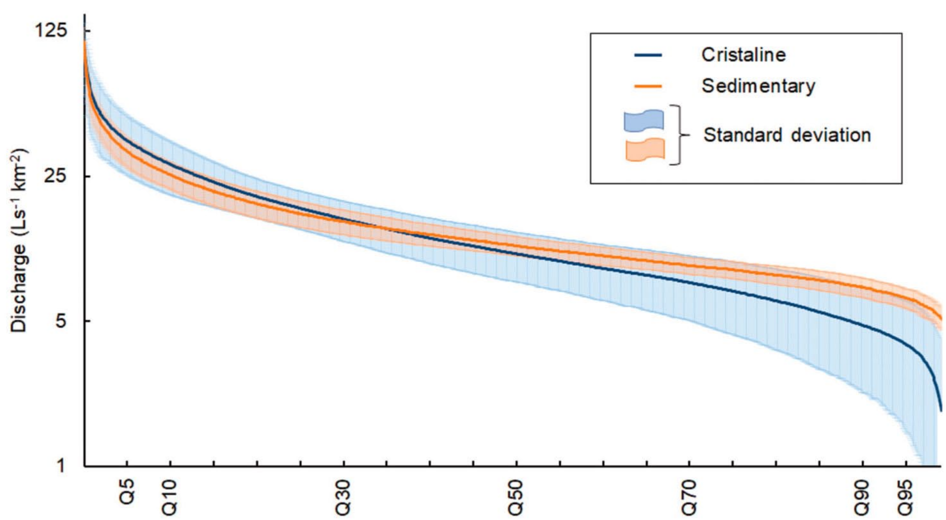

Figure 4. Flow duration curves ($Ls^{-1}\,km^{-2}$) for the river gauging stations in the crystalline and sedimentary domains, with standard deviation of streamflow behavior.

Hydrograph separation and recession analysis

The values of BFI_{max} (maximum baseflow index) ranged from 0.54 to 0.84 with average values of 0.58 and 0.72 for the crystalline and sedimentary domains, respectively. The *k* ranged from 12.2 to 20.6 days with an average of 14.25 ± 1.44 days for the crystalline domain and 16.44 ± 5.03 days for the sedimentary domain. And the *S* ranged from 3.3 to 13.7, with an average of 6.74 ± 1.25 and 7.88 ± 3.44 for the crystalline and sedimentary domains, respectively (Table 2).

The composition proportion of the average monthly streamflow separated by domain and source (baseflow and runoff) for each month (Ls^{-1} km^{-2}, **Figure 5**), follows the precipitation response in the seasonal transitions in both domains. There is a high seasonality in the volume of baseflow and runoff in the crystalline domain. In the basins overlying sedimentary aquifers, there is an attenuation of responses in seasonal transitions and the volumes of groundwater discharge (i.e. baseflow) are greater than in the crystalline domain, especially in the dry period. The proportions of baseflow in the dry period are greater in the sedimentary domain than in the crystalline, respectively 9.11 ± 3.08 Ls^{-1} km^{-2} vs. 6.00 ± 2.21 Ls^{-1} km^{-2}.

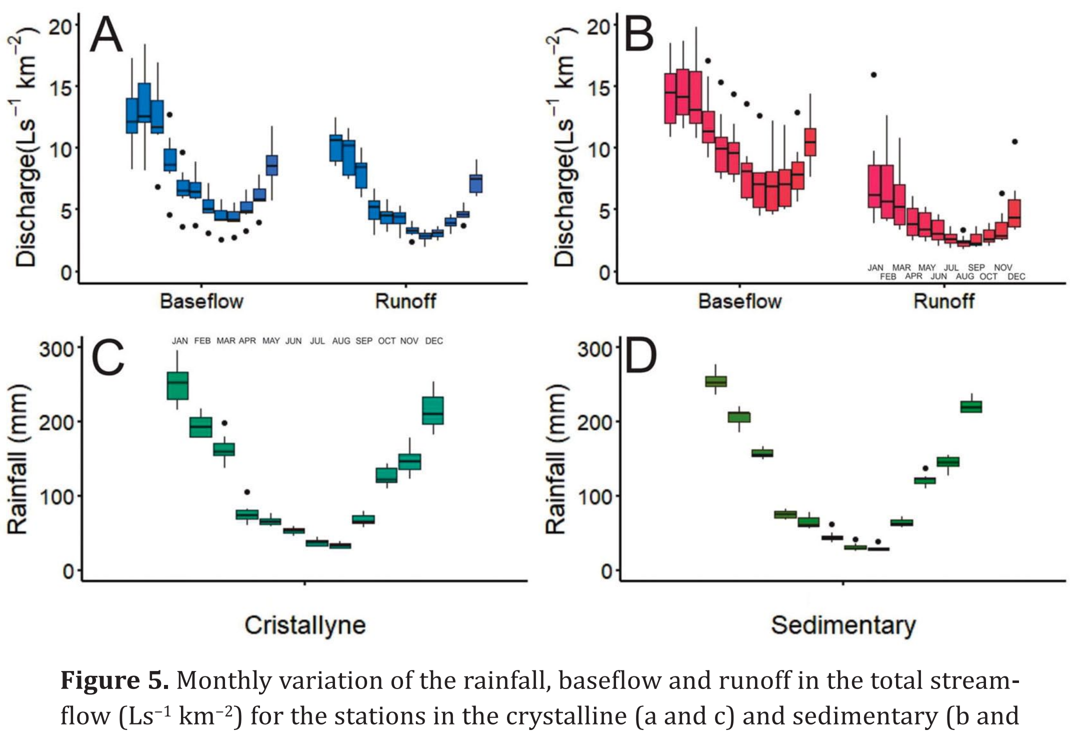

Figure 5. Monthly variation of the rainfall, baseflow and runoff in the total streamflow (Ls^{-1} km^{-2}) for the stations in the crystalline (a and c) and sedimentary (b and d) domains.

BFI has a characteristic division by hydrogeological domain. In basins with a predominance of sedimentary aquifers, the *BFI* is above average (0.66), except for station 4D021 (**Figure 6**(d)). *BFI* has significant correlations (significance at 95 and 99% C.L.) with the surface slope and the contributing area of the stations. The smallest slopes (up to 10%) have a *BFI* greater than 0.60 and the largest surface slopes (above 15%) have a lower *BFI* (Figure 6(b,c)). Additionally, *BFI* have a weak to moderate correlation with the percentage of second-order rivers (Figures 6(a)).

In the PCJ unit, the soils are essentially loam to clay with low variation, high percentages of urbanization and forest cover, and slopes greater than 7%. While the TJ unit presents great variability in soil textures ranging from very clayey to sandy greater occupation of agricultural activities, and slope predominantly between 3 and 7% to greater than 7% (Figure 6(e–g)).

Trends in hydrological data

The Mann-Kendall test detected a trend in minimum annual storage (*S*) for twelve of the river gauging stations. The distribution-free Cusum test identified six stations with changes in mean over the monitoring period, and Rank Sum test identified changes in the median for nine stations. All variations indicate reductions in *S* (Supplementary Table 3), with the exceptions of stations 6242 and 4D021, which had increases in *S*.

The nonparametric tests, applied to the long-term rainfall record (1950–2017), show a trend in the data for four precipitation stations, three with changes in the mean and three with changes in the median (Supplementary Table 4).

Standardized precipitation index

The analysis of the SPI from long-term data (1950–2017) reveals that most rainfall historical variations are within the normal range (−1 to 1; **Figure 7**). Periods of severe to extremely drought are identified in the 1950s, 1960s, 1970s and 2010s, and periods of wet to extremely wet in the 1980s and 1990s. In the SPI from short-term, GPM data from 2001 to 2019, show a wet period from 2009 to 2012 and a period of droughts from 2014 to 2019 (Figure 7).

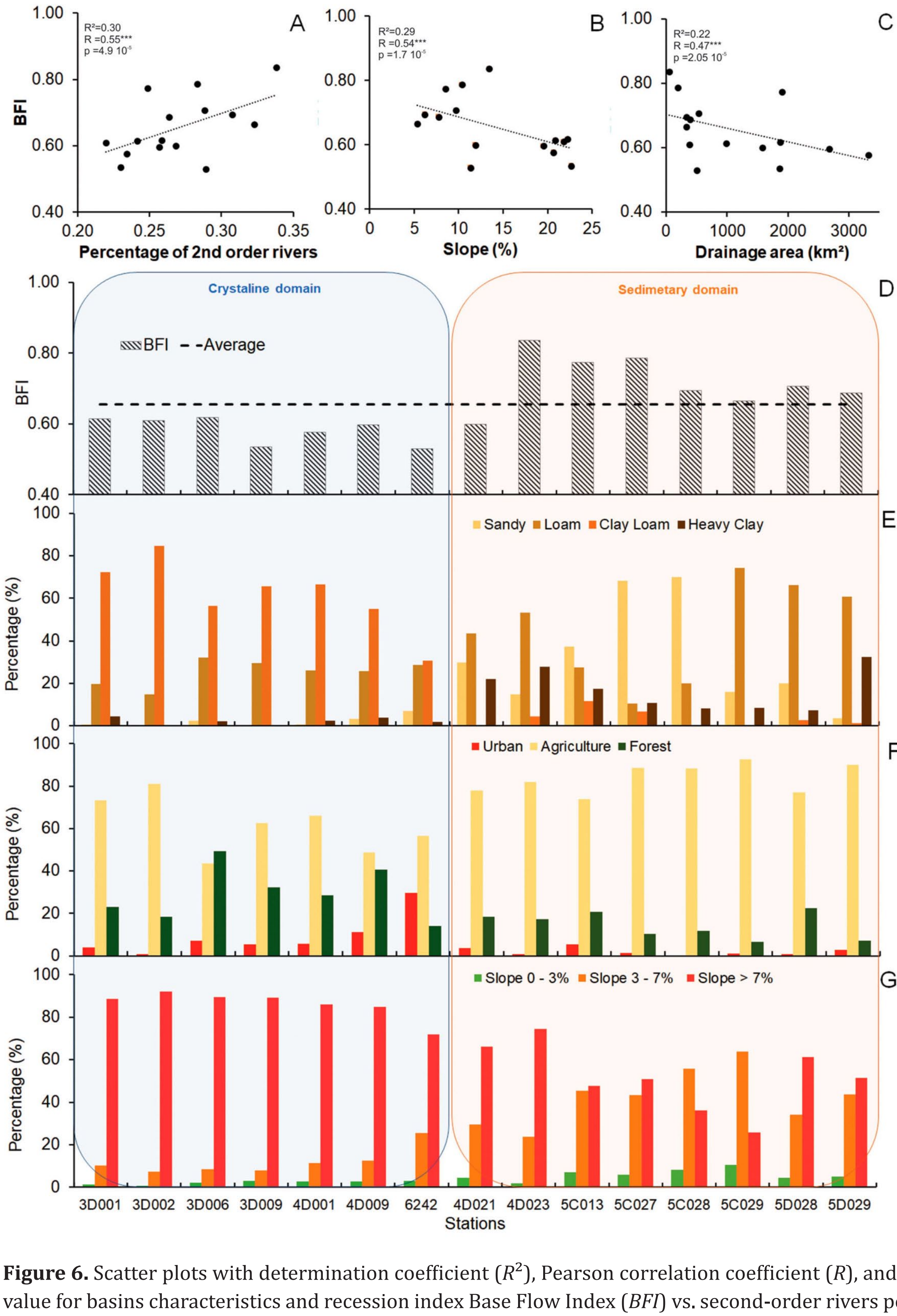

Figure 6. Scatter plots with determination coefficient (R^2), Pearson correlation coefficient (R), and p-value for basins characteristics and recession index Base Flow Index (*BFI*) vs. second-order rivers percentage, surface slope, and contribution area (a–c). *BFI* (d), soil texture (e), land cover (f), and slope percent (g) separated in hydrogeological domains (*** 99% significance level).

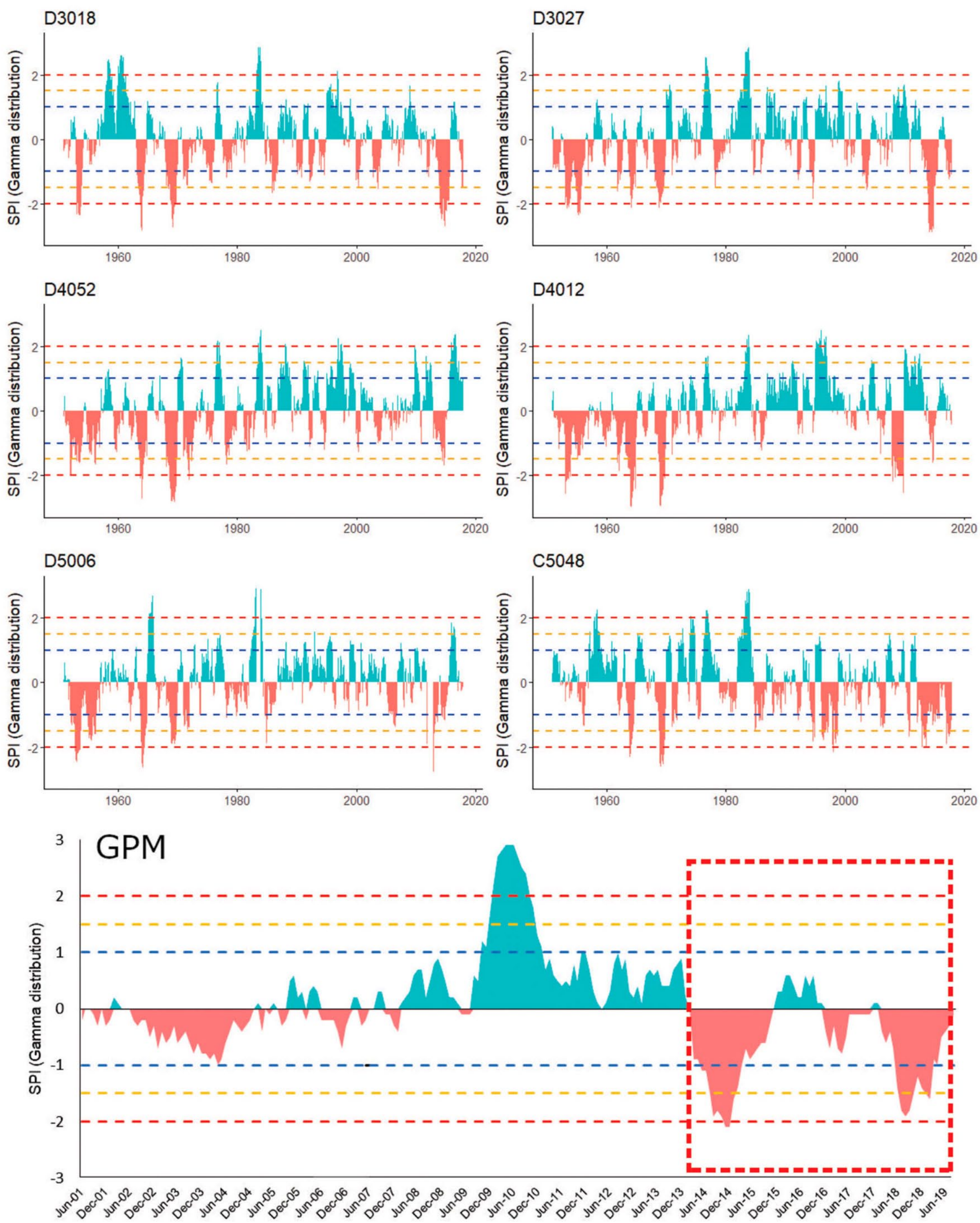

Figure 7. Standardized Precipitation Index (SPI, 12-months) for the period from 1950 to 2017 for rainfall gauging stations distributed by the study area and SPI calculated from 2001 to 2019 with spatial precipitation data from GPM IMERG v6. The rectangle highlights the time period with droughts from 2014 to 2019. The dotted lines are the normal range (1 to −1), moderate range (1.5 to −1.5) and severe range (> 2 or less <−2) (WMO 2012).

Climatic and anthropogenic effects on streamflow

The hydrological series with greater temporal coverage in the PCJ basin show important reductions in flows. In the Atibaia River (3D006 and 4D009), the reduction is continuous until the end of the series. In the Jaguari River (3D009 and 4D001), the reduction is more pronounced after 1980. The Capivari River (6242) shows an increase in the average monthly flow after 1980 (**Figure 8**).

The Camanducaia river basin (3D001 and 3D002) is a reference basin because it is not subjected to major pumping (Figures 2 and 3). In this basin, only fluctuations in precipitation are identified, with the effect of reducing flows after the year 2000 (Figure 8) due to occurrence of moderate to severe droughts from 2014 to 2019 (Figure 7). In addition, the non-parametric tests do not suggest trends in station 3D002 (Table 5).

In stations with shorter time series since 1980 (year of construction of the dams), there are no major changes in the temporal pattern. In general, the statistical tests did not identify changes in the averages. The decreasing trend can be associated with decreased flow in the beginning of the monitoring period in the 1980s when precipitation was greater than average (Supplementary Table 3).

Except the station located at the mouth of Corumbataí (4D021), which shows an increase in specific discharge at the end of the series, the other stations show oscillations related to the rainfall pattern (4D023, 5D028, and 5D029) and other ones show significant oscillation in the 1980s after which they remain relatively stable. Jau and Jacaré- Pepira river basins have a more pronounced effect of reductions of rainfall since 2010 (**Figure 9**).

Discussion

The basins draining the formations over the crystalline domain have fast recharge and discharge processes, with a short storage period. This seasonality is noted in the comparison between the trend of the temporal pattern of rainfall and the baseflow (Figures 5(a,c)). On the other hand, the basins on sedimentary rocks, with emphasis on the Guarani and Bauru aquifer systems, present greater seasonal stability in the discharge of groundwater and contribute to a greater volume of streamflow, another highlight is the good distribution of water surpluses throughout the year due to the greater storage capacity of these aquifers (Figure 5(b)).

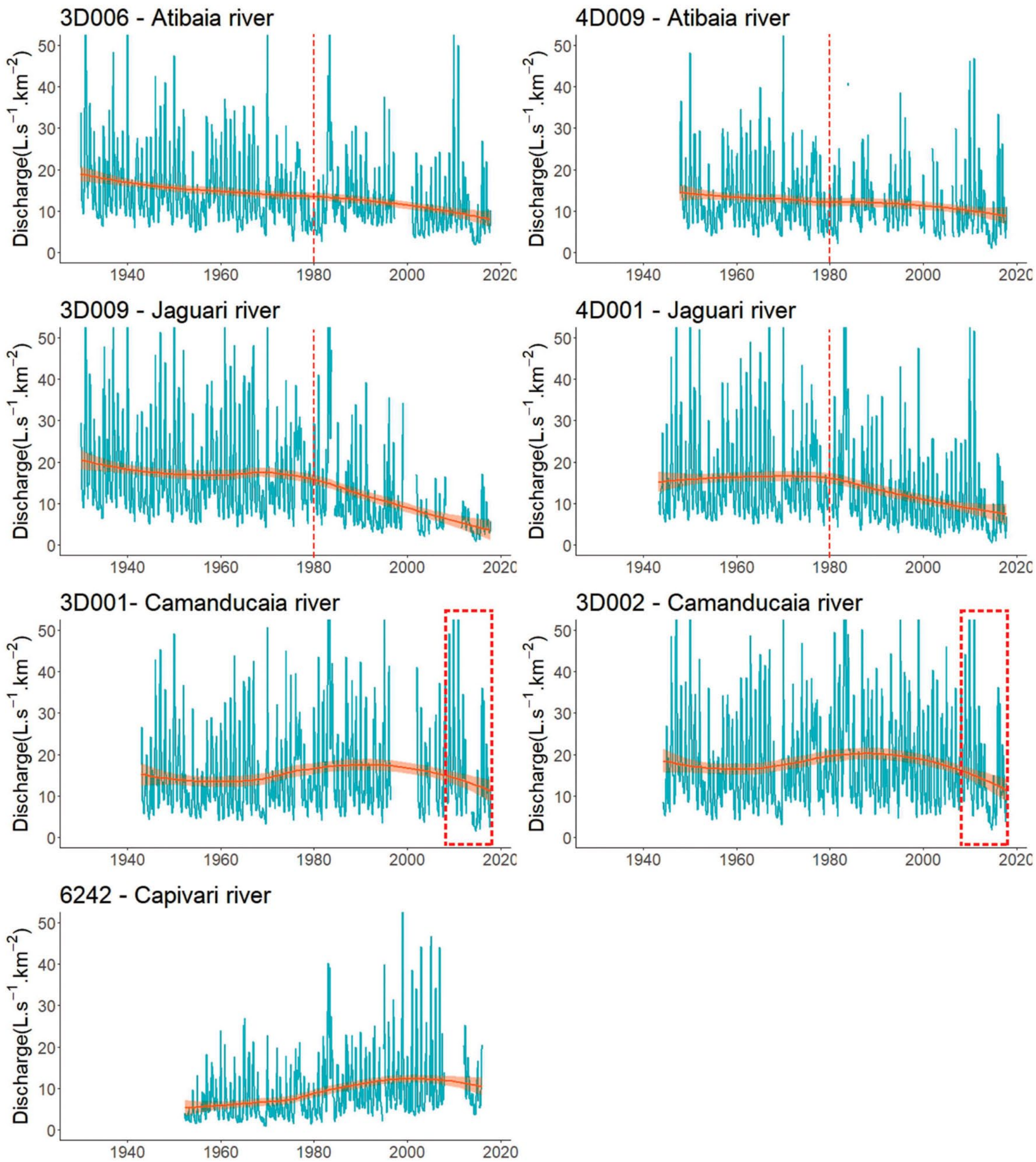

Figure 8. Specific discharge (Ls^{-1} km^{-2}) and smoothed trend line (loess method) for river gauging stations with longer series located in the PCJ basins. The dotted line (1980) represents the period of dam construction to Cantareira system and rectangle the drought period (2014–2019) identified in short-term SPI.

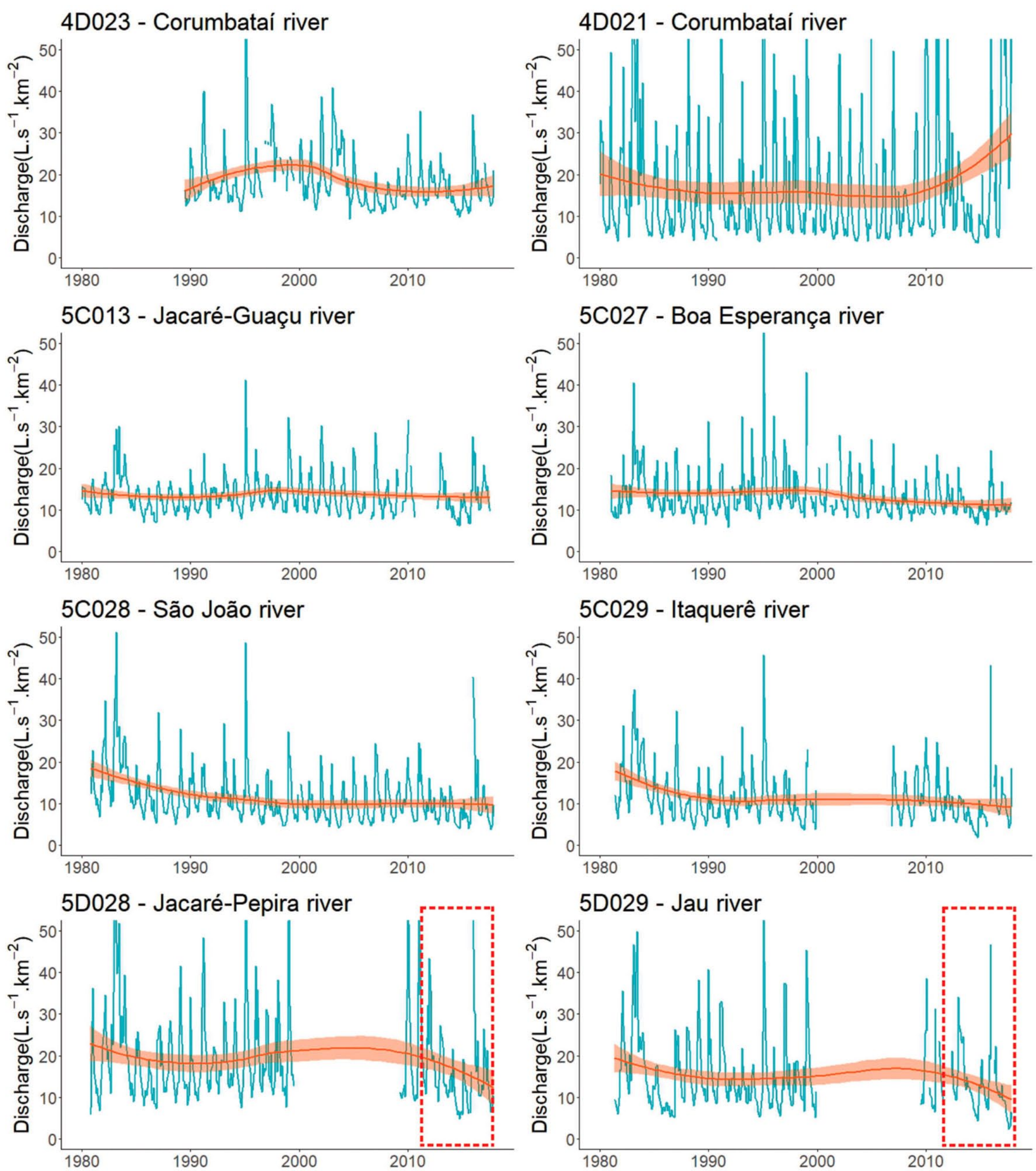

Figure 9. Specific discharge (Ls−1 km−2) and smoothed trend line (loess method) for river gauging stations from 1980, located in the PCJ (Corumbataí) and TJ basins. The rectangle shows the drought period (2014–2019) identified in short-term SPI.

Based on these findings, we can say that the water resilience of the basins of the crystalline domain depends on the regular rainfall regime and any change in the patterns of this variable implies reductions in their streamflow. While the basins of the sedimentary domain depend more on the recharge and storage processes and have less pronounced impacts in the face of observed climatic variations.

The analysis of the BFI and hydrograph separation confirm the behavior showed on flow duration curves and curve ratios, that identified the major contribution of baseflow in the sedimentary domain basins (Figure 4 and Supplementary Table 2). The results of the Q_{90}/Q_{50} ratio associated with *BFI* reveal that the contribution of groundwater discharges can vary between 40% and 75% of the streamflow in all basins analyzed.

At station 4D021, *BFI* is below average for the sedimentary domain and the flow duration curve presents a behavior different in relation to other stations, it is in the sedimentary domain but acts more like the basins in the crystalline domain. The basin combines the headwater discharges from the Guarani aquifer and downstream discharge from the Tubarão aquifer, in addition to the areas of the Passa Dois aquiclude (Figures 1 and 6(d)).

The characteristics of soils, land cover and slopes have different distributions among the hydrogeological domains (Figure 6). The soils and slopes are directly related to the geological formations, such as the predominance of sandy soils and slopes between 3% and 7% in the sedimentary domain and clayey soils and slopes above 7% in the crystalline domain. These factors contribute to the behavior of the hydrological variables analyzed, influencing the baseflow dynamics (BFI) and the recession flow characteristics (S and k). In the statistical tests, this relationship was not significant, there is a coincidence between the separation between domains, the types of soils and slope characteristics.

Non-parametric statistical analysis reveals a trend in S, and significant changes in means and medians (Supplementary Table 3), and reduction in streamflow (Figure 8), mainly in the PCJ unit. This behavior is also observed in the variation of S before and after 1980 (Table 2), the S has a marked reduction in the basins of the Jaguari and Atibaia rivers. These analyses highlight the negative effects of human action in changing the hydrologic behavior of the basins in combination with the variation in precipitation patterns (Figures 7 and 8). A contrast to the low reduction in the Camanducaia basin, which shows less effect of human activities, but a reduction in rainfall effect.

In the TJ unit, the graphs show the variation caused by fluctuations in precipitation. Gauging stations along the Jacaré-Guaçu river and its tributaries suggest no significant variations in *S* and streamflow, while a negative trend is identified after 2010 for the Jau and Jacaré-Pepira rivers (Table 5 and Figure 9). In this unit, the streamflow and *S* are stable due to the great contribution of groundwater discharges to the streamflow (Figure 5). Deforestation and overexploitation of aquifers are known and presented in the water resources situation report (TJ, 2019). These are anthropogenic effects that concern water resources managers, however, they did not present negative effects in the dataset analyzed in this study (Figure 2).

The availability of underground water resources represents water security in scenarios of changes in rainfall patterns (Alley, 2016) and groundwater exploitation needs to be better monitored to maintain the resilience in the TJ unit.

Native vegetation plays a fundamental role in subsoil hydrological processes, controls infiltration and recharge processes (Doble & Crosbie, 2017) and, in the atmosphere, regulates humidity and directly affects temperature and rainfall (Keys et al., 2019). In addition, native vegetation regulates exchanges between the terrestrial and atmospheric compartments of the hydrological cycle (Anache et al., 2019). Thus, deforestation in the TJ unit (see Figure 2) due to the sugarcane agroindustry (the main crop in the TJ basin) is a concern because of effects on water resources (Hernandes et al., 2014; Scarpare et al., 2016).

The SPI results of the GPM data (2001–2019) are in accordance with recent studies that show the occurrence of droughts in the southeastern region of Brazil (2011–2019) and highlights the reduction of rainfall in the periods of 2014–2015 and 2017–2019 (Cunha et al., 2019; Marengo et al., 2015; Nobre et al., 2016). These droughts periods produced a more accentuated dropdown in the streamflow of the Jaguari and Atibaia basins due to the need for preserving the Cantareira reservoir levels to maintain the water supply.

The occurrence of severe droughts in recent years, coupled with reduced streamflow in the PCJ basin and low water quality in areas with high demand (CMR and SPMR) can accentuate the water crisis with important social and economic effects (Guzmám et al., 2017), as experienced in the years 2014 and 2015 (Coelho et al., n.d.; Marengo et al., 2015).

Water resilience under normal reservoir operating conditions can be lost in periods of drought. Recovery to normal condition may require potentially extreme measures, which has a negative impact on populations, economic activities and ecological functions. This demands cautious management of Cantareira system reservoirs (Coutinho et al., 2015).

The situation of changes in rainfall (see SPI results and streamflow plots) patterns was extremely impactful to the PCJ unit during the drought of 2014 and 2015. The use of surface water resources is above the natural capacity of the Capivari, Jundiaí and Atibaia basins (120%) and the groundwater use has increased from 17% to 46% from the allowable volume. Before this drought, the water transfers to the Cantareira System were an average of 30.9 $m^3\ s^{-1}$ and among the years 2015 and 2018 was reduced to 17.96 $m^3\ s^{-1}$, seriously affecting the MRSP's municipally (PCJ, 2018b). The return of water to maintain the ecological streamflow in the PCJ basins (instituted at 5 $m^3\ s^{-1}$; PCJ, 2018b) was reduced below half in the years 2015 and 2016. This situation caused negative effects on the aquatic fauna of the Piracicaba river basin (CETESB, 2018).

The present study shows that the maintenance of streamflow by the baseflow discharge in the PCJ basins, in the dry season, indicates a short time of water permanence in the basins (Figure 5) and requires more appropriate management actions for periods of reduced rainfall higher than the usual droughts. The results presented show that the basin management, in PCJ unit, enables the consumption to exceed water availability. The TJ basins have a greater contribution from groundwater and preserve the water resilience of the rivers, with some points of attention (Jau and Jacaré-Pepira rivers) and in areas with high deforestation rates and increased groundwater exploitation (Figures 2 and 9).

The negative effects identified in the streamflow and the regulation of the hydrological regime by the use of dams and the over-pumping in the PCJ basins and the groundwater extraction and deforestation in the TJ basins, can be considered as linear collapses of the hydrological system (gradual change that causes the collapse of a system, Falkenmark et al., 2019). However, there is the possibility of reversing the depletion of water sources and restoring water resilience, with reforestation measures, creation of protection/recovery measures for springs, reduction of water volumes transferred to the Cantareira System, and recovery of water quality in the main basins.

Current problems raised in this study (overexploitation of water availability and the response face the changes in rainfall pattern) reveal that the management model of the studied basins needs to be modified for a dynamic and adaptive system for the hydrological system resilience which assures the social and economic demands, without harming the ecological functions of basins (Clarvis et al., 2014).

New groundwater management strategies aimed at water security are needed to attend the most urgent demands in a scenario of changes in climate patterns, mainly, the efforts in the conflict reduction and maintenance of the sustainability of the basins These strategies can be directed towards the conjunctive water management of the groundwater and surface water resources. Focused on assessing and establishing limits for sustainable use; clearly define access, storage, and use rights; produce integrated plans; evaluate exchange and commercialization situation; carry out centralized management; stakeholder participation in decision making and; expand measurement and monitoring (Ross 2018)

Conclusions

This study presents hydrological analyses of the basins in the TJ and PCJ management units which demonstrate different natural behaviors. A key difference between the basins is the magnitude of groundwater discharge (i.e. baseflow) that maintains streamflow, especially during dry periods. The TJ basins have a natural capacity to maintain water reserves, in part due to groundwater recharge, which is more reliable in the face of changing in rainfall patterns. On the other hand, the PCJ basins present a more delicate situation due to the short time water remains in the aquifer systems, resulting in more drastic effects with reductions in rainfall.

The response to rainfall variability in the PCJ basins is more critical than in the TJ basins and requires changes in management plans. There is a need to change to a management adaptive model given how changes in rainfall patterns have affected the supply system of RMC and RMSP. The large water demand in PCJ basins has reduced streamflows and the water transfer model from the PCJ basins to the Cantareira system is not sustainable in the long term. Water pollution has also limited the availability of water.

The TJ region currently indicates limited impacts from anthropic action compared to PCJ basins or drastic effects of climatic variability on streamflow. Even with a certain abundance of available water resources, however, the management in the TJ basins must account for environmental change, and fluctuations in storage and consumption patterns. Adaptive management strategies are essential in anticipation of the reductions in rainfall, mainly due to the possible depletion of aquifers.

The results point to different baseflow behaviors against the hydrogeological complexity, with greater variability and vulnerability in the crystalline domain against anthropic effects and the reduction of rainfall, with greater influence on the negative trend of the streamflow. While the sedimentary domain experiences smaller oscillations and the negative effects do not appear in all basins.

Hydrological characteristics in these basins are representative of other hydrological regions of the state of São Paulo and Paraná river basin (Brazil). The tools presented here can be used to plan actions to adapt water resource management according to hydrogeological framework. Findings from this study can be used for predicting the behavior of natural water resource resilience controlled by baseflow, and evaluate the possible impacts of change in climate patterns and human activities on water resources.

Some limitations were found in this study, such as more robust statistical analyses to correlate the environmental variables with the hydrological behavior of the basins. It is recommended that these tests be applied under different conditions of anthropic intervention and also considering another spatial scale or data set.

* * * * *

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Availability of data and material All data was obtained from public database, satellite data from NASA:

(a) precipitation from GPM (Global Precipitation Measurement) available at https://giovanni.gsfc.nasa.gov/giovanni/ and https://disc.gsfc.nasa.gov/

(b) altimetry from SRTM (Shuttle Radar Topography Mission) in https://earthexplorer.usgs.gov/

(c) gauging and rain stations data from Water and Energy Department of São Paulo State (DAEE) in http://www.hidrologia.daee.sp.gov.br/

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Table 1-SM. Identification of stream gauging and rain gauge stations used in the analysis of recession.

Domain	Unit	Basins	Gauging station	Monitoring Period	Rain gauge station	Monitoring Period
Crystalline	PCJ	Atibaia	3D006	1945-2017	D3046	1947-2017
			4D009	1947-2016	D4052	1942-2017
		Jaguari	3D009	1930-2017	D3046	1947-2017
			4D001	1943-2017	D4052	1942-2017
		Camanducaia	3D002	1944-2018	D3027	1942-2017
			3D001	1943-2018	D3042	1942-2017
		Capivari	6242*	1952-2016	E4015	1951-2017
Sedimentary	PCJ	Corumbataí	4D023	1989-2017	D4035	1937-2017
			4D021	1972-2017	D4012	1936-2017
	TJ	Jacaré-Guaçu	5C013	1969-2017	C5117	1931-2017
		Boa Esperança	5C027	1980-2017	C5117	1931-2017
		Itaquerê	5C029	1981-2017	C5048	1940-2017
		São João	5C028	1980-2017	C5048	1943-2017
		Jacaré-Pepira	5D028	1980-2017	D5006	1936-2017
		Jaú	5D029	1981-2017	D5084	1976-2017

Table 2-SM. River gauging stations streamflow characteristics, contribution area and flow duration curves.

Domains	Basins	Stations	Contribution Area	Q_{med}	Q_{50}	Q_{90}	$\frac{Q_{90}}{Q_{50}}$
			km²	Ls^{-1}km^{-2}			
Crystalline	Atibaia	3D006	1920	12.5	10.7	5.2	0.48
		4D009	2738	11.1	9.2	4.3	0.46
	Jaguari	3D009	1950	13.2	10.6	4.0	0.37
		4D001	3394	12.6	9.7	4.2	0.43
	Camanducaia	3D002	387	15.9	12.8	6.1	0.47
		3D001	928	13.7	10.4	5.1	0.49
	Capivari	6242	697	8.4	5.5	2.3	0.41
Sedimentary	Corumbataí	4D023	59	17.0	15.6	11.7	0.75
		4D021	1581	15.4	9.4	4.7	0.50
	Jacaré-Guaçu	5C013	1867	11.8	11.9	8.0	0.67
	Boa Esperança	5C027	190	11.7	10.8	7.8	0.72
	Itaquerê	5C029	334	10.5	9.1	5.0	0.47
	São João	5C028	338	10.5	8.9	5.3	0.50
	Jacaré-Pepira	5D028	442	17.0	15.2	8.7	0.57
	Jaú	5D029	417	13.9	11.4	6.2	0.54

Q_{med} = mean streamflow; Q_{50} *and* Q_{90} = flow duration indices used for low flow study; Q_{90}/Q_{50} = index representing the proportion of streamflow originating from groundwater stores.

Table 3-SM. Result of nonparametric statistical tests for annual minimum (S) storage.

Basins	Stations	Mann-Kendall	Cusum	Rank Sum
Atibaia	3D006	***↓	***	***
	4D009	***↓	***	***
Jaguari	3D009	***↓	***	***
	4D001	***↓	***	***
Camanducaia	3D002	NS	NS	NS
	3D001	***↓	NS	*
Capivari	6242	***↑	***	***
Corumbataí	4D023	NS	NS	NS
	4D021	** ↑	NS	*
Jacaré-Guaçu	5C013	NS	*	NS
Boa Esperança	5C027	* ↓	NS	NS
Itaquerê	5C029	** ↓	NS	NS
São João	5C028	***↓	NS	***
Jacaré-Pepira	5D028	** ↓	NS	*
Jaú	5D029	***↓	NS	**

Significance level (*** = 99%, ** = 95% and * = 90%) and non-significant (NS) test.
Reduction trend = ↓ and increasing trending = ↑

Table 4-SM. Results of non-parametric statistical tests for total annual precipitation.

Station	Mann-Kendall	Cusum	Rank Sum
D3018	NS	NS	NS
D3027	NS	NS	NS
D3035	* ↑	***	***
D3042	NS	NS	NS
D3046	NS	NS	NS
D4012	NS	NS	*
D4035	NS	NS	NS
D4044	NS	NS	NS
D4052	* ↑	NS	NS
D4068	NS	NS	NS
E3015	NS	NS	NS
E3099	** ↓	**	**
E4015	NS	NS	NS
C5117	NS	NS	NS
C5048	* ↓	*	NS
D5006	NS	NS	NS
D5047	NS	NS	NS
D5084	NS	NS	NS

Significance level (*** = 99%, ** = 95% and * = 90%) and non-significant (NS) test.
Reduction trend = ↓ and increasing trending = ↑