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TIME SERIES TRENDS OF STREAMFLOW AND RAINFALL IN THE SANTO ANTÔNIO RIVER BASIN, BRAZIL

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KEYWORDS

stationarity, Run test, Mann Kendall test, Pettitt test.

ABSTRACT

Detecting trends in streamflow and rainfall series can have great significance for proper water resource management. Thus, the objective of this study was to analyze the trends of historical streamflow and rainfall series using nonparametric statistical tests. A historical series of pluviometric and fluviometric gauges, which belong to the hydrometeorological network of the Brazilian Water National Agency in the Santo Antônio River Basin, Brazil, from 1985 to 2014 were used. By applying statistical tests, it was found that the time series are independent and random, and from the total 24 rainfall gauges evaluated, 12 presented nonstationary behavior, exhibiting mostly decreasing trends. Based on the six fluviometric gauges used for the annual streamflow series, only the annual data of one gauge tended to decrease to the minimum streamflow. However, for the monthly series, three gauges showed decreasing trends between July and September. This decrease in streamflow may be a consequence of rainfall reductions, high water demand, and changes in land use and cover.

INTRODUCTION

As water is a fundamental natural element for the existence of life on Earth, it is necessary to develop strategies for its resource management. For this, research is required to better understand the hydrological variables that interfere with water dynamics. In this sense, the streamflow of watercourses is characterized as one of the most important variables as it represents the support capacity of a water basin (Uliana et al., 2015).

Anthropic activities combined with climate change have contributed to changes in the hydrological cycle. Various authors have reported an increase in the frequency and severity of extreme hydroclimatic events, such as floods and droughts (Gupta & Jain, 2018; Leng et al., 2015; Liu et al., 2017). Water resource management systems worldwide face problems related to these events, and they are generally designed and operated with the hypothesis of stationarity (Jiang et al., 2015; Milly et al., 2008; Verdon-Kidd & Kiem, 2015).

Over the past two decades, there has been an increase in studies regarding regional and continental water cycle trends due to climate change and variability (Joseph et al., 2013). Several of these studies confirmed the nonstationary behavior of both rainfall and streamflow in various regions (Ishida et al., 2017; Joseph et al., 2013; Santos et al., 2016). Further, changes in flow regimes have been observed in several rivers around the world as a response to changes in the environment (Gao et al., 2012).

Changes in the temporal distribution of rainfall in a region may be related to both climate change and climate variability (Gao et al., 2018). Climate variability and change are caused by natural and anthropogenic processes that affect production and life processes (Marin & Nassif, 2013). Adnan & Atkinson (2011) and Kibria et al. (2016) pointed out that trends in historical streamflow data series are closely associated, either directly or indirectly, to land use and cover, and changes in rainfall behavior.

Analyzing the historical series of climate data can assist in the evaluation of hypotheses that consider the stationarity of future hydroclimatic conditions (Villarini et al., 2011). Meanwhile, a spatial analysis of trends enables the identification of places that have changes in a series behavior, and can estimate the possible damage to these changes in social, environmental, and economic activities,

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thereby helping guide decisions regarding the risk due to these changes (Joseph et al., 2013; Salviano et al., 2016).

For proper water resources management, the detection of streamflow and rainfall series trends is extremely important (Casavecchia et al., 2016). These trends can be evidenced from the use of nonparametric statistical tests (Uliana et al., 2015), including the Run, Mann-Kendall, and Pettitt (Back, 2001; Gonçalves & Back, 2018) tests, which are most commonly used for this purpose.

Due to the social and economic relevance of the Santo Antônio River Basin, which is located in the southeastern region of Brazil, it is important to understand trends in its streamflow and rainfall series. Thus, the objective of this study is to analyze historical series trends of streamflow and rainfall through nonparametric statistical tests. The results will contribute to studies associated with hydrological modeling and water resource management.

MATERIAL AND METHODS

Study Area

The study area comprises the Santo Antônio River Basin in Minas Gerais, which is an important subbasin of the Doce River (Figure 1), and exists completely in the state of Minas Gerais, Brazil. Via the hydrographic division established by the State, the Santo Antônio River Basin constitutes the DO3 Water Resources Management Unit (UGRH - DO3 - Santo Antônio).

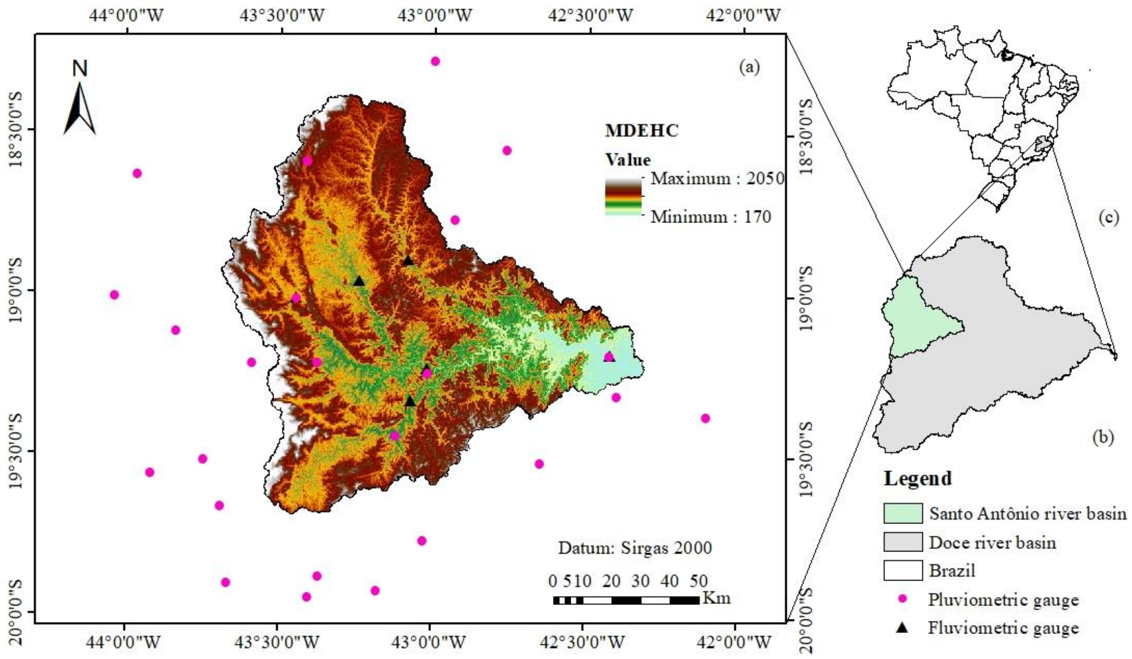

FIGURE 1. Santo Antônio River Basin (a) with fluviometric and pluviometric gauges of influence, and its location in (b) the Doce Rriver basin and (c) Brazil.

The Santo Antônio River begins in the Serra do Espinhaço in the municipality of Conceição do Mato Dentro and has a total length of 280 km. UGRH DO3 has 29 municipalities with 182,000 inhabitants. The basin is located in the Doce River Valley region, covering a drainage area of approximately 10,429 km², wherein its main watercourses are the Santo Antônio, Guanhães, Peixe, Tanque, and Preto do Itambé rivers (IGAM, 2010). In this basin, two biomes exist, the Atlantic Forest (87%), which is the predominant biome, and a small area of Cerrado (13%).

In relation to the economic activity developed in the basin, the service sector is significant, accounting for 44% of the gross domestic product (GDP), followed by the industrial sector. Other important activities include the extraction of iron ore by the Vale do Rio Doce Company and cellulose industries. In the agricultural sector, the main activities include cattle raising and sugar cane, coffee, and corn production (IGAM, 2010).

According to the Köppen climate classification described by Alvares et al. (2013), the study area has a predominance of Aw, CWa, and CWb climates. The monsoon-influenced humid subtropical climate (Cwa) is found at altitudes above the Aw (tropical dry season climate) and below the Cwb (monsoon-influenced temperate oceanic climate). This is typical of southeastern Brazil, especially in the Minas Gerais State, and is characterized by a humid temperate climate with dry winters and hot summers. The temperature in the colder months varies between -3 °Cº and 18 °C, while in the warmer months the average is 22 °C.

In a study on the mean rainfall of the Rio Doce basin analysis units based on the period from 1985 to 2015, Lima et al. (2019) found that the Santo Antônio River Basin is one of the largest sub-basins in the Rio Doce River basin, with a mean annual rainfall of 1,314.2 mm.

Collection and treatment of the Hydrological database

The database containing the historical series of streamflow and rainfall of the Santo Antônio River Basin from 1985 to 2014 was obtained from the Hydrological Information System (Hidroweb) of the Brazilian Water National Agency (ANA), and is available at http://www.snirh.gov.br/hidroweb/publico/medicoes_histori cas_abas.jsf.

Six fluviometric gauges located in the basin (Table 1) and 24 rainfall gauges (Table 2) were used. To define the rainfall gauges, a 40 km buffer was used to cover the basin area under study as well as the surrounding areas.

TABLE 1. Fluviometric gauges used.

Gauge code	Gauge name	Years and level of consistency	
		Non-consistent	Consistent
56750000	Conceição do Mato Dentro	2015-2015	1945-2014
56765000	Dom Joaquim	2015-2017	1945-2014
56775000	Ferros	-	1940-2014
56787000	Fazenda Barraca	2015-2015	1965-2014
56800000	Senhora do Porto	2015-2015	1945-2014
56825000	Naque Velho	2015-2017	1974-2014

TABLE 2. Pluviometric gauges used.

Gauge code	Gauge name	Years and level of consistency	
		Non-consistent	Consistent
01842007	Guanhães*	2006-2018	1945-2005
01842020	São João Evangelista*	2006-2018	1984-2005
01843000	Usina Parauna*	2006-2018	1941-2005
01843011	Serro	2005-2018	1984-2004
01843012	Rio Vermelho*	2006-2018	1984-2005
01942008	Dom Cavati*	2003-2018	1969-2002
01942029	Mario de Carvalho*	2006-2018	1986-2005
01942030	Cenibra / Belo Oriente*	2006-2018	1986-2005
01942032	Naque Velho	2006-2018	1986-2005
01943001	Rio Piracicaba*	2006-2018	1940-2005
01943002	Conceição do Mato Dentro	2006-2018	1941-2005
01943003	Ferros	2006-2018	1941-2005
01943004	Jaboticatubas*	2006-2018	1941-2005
01943007	Santa Bárbara*	2006-2018	1941-2005
01943008	Santa Maria do Itabira	2006-2018	1941-2005
01943010	Caeté*	2006-2018	1941-2005
01943023	Taquaraçu*	2006-2018	1942-2005
01943025	Morro do Pilar	2006-2018	1945-2005
01943027	Usina Peti*	2006-2018	1946-2005
01943035	Vau da Lagoa*	2006-2018	1955-2005
01943042	Fazenda Caraíbas*	2006-2018	1974-2005
01943049	Ponte Raul Soares*	2006-2018	1973-2005
01943100	Nova Era Telemétrica*	2004-2018	2003-2003
01944020	Pirapama*	2006-2018	1958-2005

* Gauges located outside the study area boundary.

For the fluviometric gauges, the data used were already consistent. However, for the rainfall gauges, consistent data were used until 2004, with the exception of the Dom Cavati, Nova Era Telemétrica, and Serro gauges, which presented consistent data only until 2002, 2003, and 2004, respectively. For the remaining years, non-consistent rainfall data (raw data) were used.

Herein, the decision to work with the complete series (consistent and non-consistent data) was made because the use of non-consistent data is necessary to obtain more recent and long historical series, which are particularly important for applying trend tests. In shorter series, the natural fluctuations of the hydrological data can be attributed to stationary behavior (Aires et al., 2019).

For the rainfall series, the filling missing data process was performed monthly using the regional weighting method, which is based on linear regressions (Equation 1). To apply this method, the four nearest support gauges without missing data in the same period of the gauge that needed filling were considered. This was applied as a criterion in the choice of the support gauges with a determination coefficient (r^2) greater than or equal to 0.7 between the gauge with missing data and the selected support gauge for filling purposes (Junqueira et al., 2018). In order to fill the missing data from the fluviometric gauges, a simple linear regression method was employed that considered only one support gauge closer upstream or downstream to the gauge with missing data, as recommended by Bier & Ferraz (2017).

$$P = \frac{\sum P_i . r_i}{\sum r_i} \quad (1)$$

Where,

P - estimated rainfall for the period with missing data, mm;

P_i - rainfall at neighboring gauges, known data, mm,

r_i - linear regression coefficient between gauge i and gauge with missing data.

To verify the accuracy of the non-consistent data that were filled in, the double mass curve method was used, wherein the obtained analyses identified data homogeneity.

The basin study area was divided according to the drainage areas upstream of each of the six fluviometric gauges (Figure 2). The region that encompasses the mouth of the basin, with an area equivalent to 242.6 km², was not considered as it did not have a fluviometric gauge.

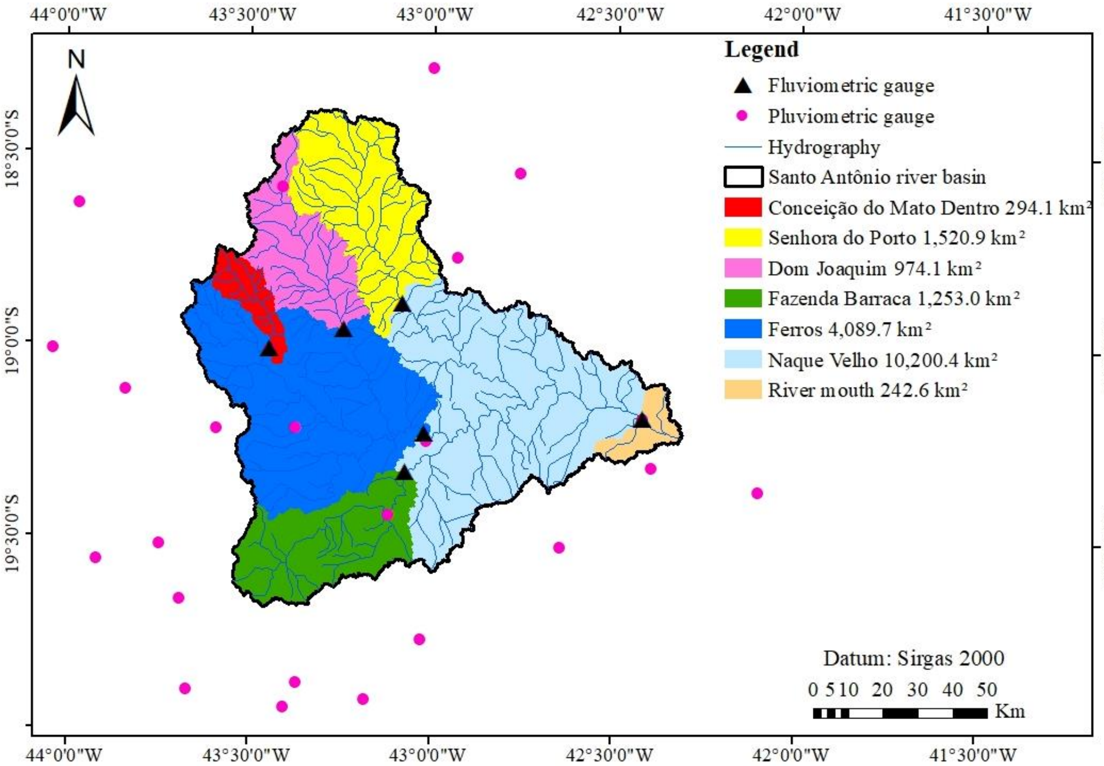

FIGURE 2. Fluviometric gauges and their respective drainage areas, and rainfall gauges used.

The annual and monthly streamflow rates used were the mean streamflow (Q_{mean}), maximum streamflow (Q_{max}), and mean minimum streamflow over seven days (Q_7). These streamflow rates were obtained with the aid of the Computational System for Hydrological Analysis Software (SisCAH). Meanwhile, the rainfall data rates used were the annual total rainfall (P_a), rainy semester rainfall (P_{sc}), rainy quarter rainfall (P_{tc}), rainy month rainfall (P_{mc}), dry semester rainfall (P_{ss}), dry quarter rainfall (P_{ts}), and dry month rainfall (P_{ms}).

The mean rainfall for each of the six drainage areas was calculated using the result of rainfall interpolation via the inverse distance weighting method (IDW). The weights were defined from the lowest values of the root of the mean square error and the mean absolute error.

The hydrological year used in this study was defined using the streamflow during low-flow conditions data, wherein an analysis of the months with Q_7 occurrence for the six fluviometric gauges was used. In addition, calculations were performed to obtain the monthly Q_7 for each fluviometric gauge as well as a monthly average of Q_7 for these gauges.

Stationarity analysis of historical streamflow and rainfall series

A trend analysis was performed to evaluate the behavior of streamflow and rainfall in each of the drainage areas. The Run test (Thom, 1966) was applied to evaluate the randomness of the series. Then, the Mann-Kendall test (Mann, 1945; Kendall, 1975) was applied to assess whether the streamflow and rainfall data series showed a statistically significant temporal change trend, and if this trend was increasing or decreasing. This test was applied in order to check the null hypothesis (the absence of trend), which must be rejected in order to have a trend in the data series. Finally, Pettitt's test (Pettitt, 1979) was adopted to confirm the stationarity of the historical series and to locate the point where the change occurred in the nonstationary cases. The nonparametric Mann Kendall and Pettitt tests were applied considering a significance level of 5% (Mudbhatkal et al., 2017).

The calculations associated with all of the trend tests were developed in the R environment (R Core Team, 2018), using the packages: “randtests” function “runs.test”, “Kendall” function “MannKendall”, and “trend” function “pettitt.test”.

RESULTS AND DISCUSSION

By analyzing the Q_7 occurrence data for the historical series of the base period of the fluviometric gauges, it was found that the highest incidence occurred in September and October. However, isolated occurrences were observed in several other months. Thus, the hydrological year for the Santo Antônio River Basin was defined to occur from November to October, with a rainy semester occurring from November to April and a dry semester from May to October. The rainy quarter was defined as the three rainiest months, from November to January, and the dry quarter was comprised of the months with the lowest rainfall rates from May to July.

By applying the Run test to the annual and monthly streamflow and annual rainfall data series, it was found that the time series are independent and random. With the application of the Mann-Kendall and Pettitt tests, the data of the mean rainfall interpolated data for Pa, Psc, Ptc, Pmc, Pss, Pts, and Pms for each of the six drainage areas, calculated via the IDW method, verified a stationary behavior. Conversely, analyzing the data from each of the 24 rainfall stations, 12 exhibited non-stationary behavior (Table 3).

TABLE 3. Gauges that presented a trend in the annual series of rainfall and their respective year of change.

Gauge	Variable	Trend	Year of change
01843012	P_{ms}	Increase	1998
01942029	P_{ts}	Decrease	1994
01943004	P_{ss}	Decrease	1997
	P_{ts}	Decrease	2005
01943027	P_{ms}	Decrease	1993
01943100	P_{ts}	Decrease	1994
	P_{ms}	Decrease	2002
01942030	P_{ms}	Decrease	1993
01943002	P_{ms}	Decrease	1992
01943008	P_{ms}	Decrease	2005
01943049	P_{ss}	Decrease	1998
01944020	P_a	Decrease	1996
	P_{sc}	Decrease	1996
	P_{ss}	Decrease	1998
01943007	P_a	Increase	1995
	P_{sc}	Increase	1995
01942008	P_{mc}	Increase	1991

Data from gauge 01943004 showed decreasing trends in P_{ts} and P_{ss}. In addition, gauge 01943100 showed nonstationary behavior with decreasing trends in the P_{ts} and P_{ms} regimes. Gauge 01944020 revealed nonstationary behavior with decreasing trends in P_a, P_{sc}, and P_{ss}. Finally, gauge 01943007 showed nonstationary behavior with increasing trends in the P_a and P_{sc} regimes.

The period of occurrence of changes in the behavior of the rainfall series is mostly distinct (Table 3). Gauges 01943027 and 01942030 have similar years of change for P_{ms} (1993), while gauges 01943100 and 01942029 have similar years of change for P_{ts} (1994), and gauges 01943049 and 01944020 have similar years of change for P_{ss} (1998).

Trends in the rainfall series were mostly concentrated during the driest periods. According to a study by Santos et al. (2016) in the Pardo river basin, located between the states of São Paulo and Minas Gerais, no significant trend in rainfall during the rainy season was found, which is consistent with the findings herein.

Although precipitation has a strong influence on streamflow, this influence is generally reduced during the driest period of the year as this is when the most precipitation is retained in the unsaturated zone of the soil, thereby reducing recharge (Novaes et al., 2009).

Analyzing the annual streamflow data, only gauge 56800000 showed a nonstationary behavior for Q_7, with a decreasing trend, wherein its year of change was 1996 (Figure 3). For the annual streamflow data Q_{mean} and Q_{max}, none of the fluviometric gauges showed nonstationary behavior.

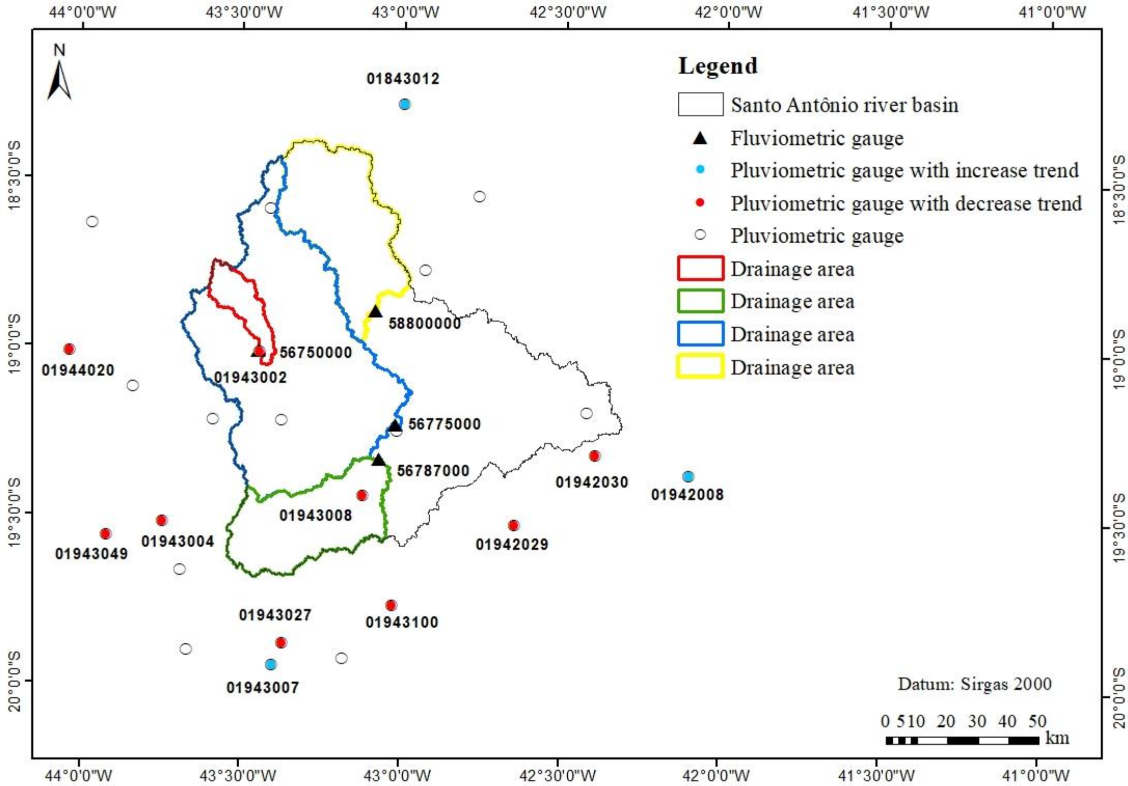

FIGURE 3. Drainage areas of the 56800000 (yellow), 56750000 (red), 56775000 (blue), and 56787000 (green) streamflow gauges, and the rainfall gauges used in the study.

Analyzing the streamflow data of guage 56800000, a decreasing trend of Q_7 was verified in 1996. Rainfall gauges closest to its drainage area are 01842007, 01843012, 01843011, 01842020, and 01943002. However, only data from gauges 01943002 and 01843012 showed a significant trend. Gauge 01943002 presented nonstationary behavior with a decreasing trend in P_{ms}, while gauge 01943012 presented an increasing trend for P_{ms}.

The decreasing trend of Q_7 for gauge 56800000 is possibly unrelated to the decreasing trend in rainfall observed in gauge 01943002 that occurred for P_{ms} in 1992. Besides the reduction trend observed in the driest month, the region of influence of this season in the drainage area is small.

Analyzing the monthly streamflow series, it was observed that the Q_7 data in all of the gauges showed stationary behavior. However, the Q_{mean} and Q_{max} data, in some months, revealed nonstationary behavior, with a decreasing trend (Table 4).

TABLE 4. Fluviometric gauges that presented a trend in the monthly series of streamflow and their respective year of change.

Variable	Month	Gauge	Trend	Year of change
Q_{mean}	September	56750000	Decrease	1997
Q_{max}	July	56750000	Decrease	1995
	August	56750000	Decrease	1993
		56775000	Decrease	1993
		56787000	Decrease	2005
	September	56750000	Decrease	2002
		56787000	Decrease	2005

Changes in the streamflow series were observed at gauges 56775000, 56787000, and 56750000 (Figure 3) and occurred between July and September, which is the dry period of the year (Table 4). Streamflow data from gauge 56775000 presented nonstationary behavior with a decreasing trend for the monthly Q_{max} in August, with a year of change in 1993 (Table 4). The drainage area of this gauge may have been influenced by the rainfall trends of the gauges within the basin, 01943008 and 01943002, and outside the basin, 01944020, 01943049, and 01943004. Although these gauges tended to decrease, only gauge 01943002 tended to decrease prior to the Q_{max} reduction, whereas a decreasing trend in P_{ms} also occurred in 1992. This streamflow decreasing trend may be related to the previous reduction in rainfall as they occurred during the same period of the year.

For the streamflow data measured in the fluviometric gauge 56787000, it was observed that the behavior was nonstationary with a decreasing trend in the maximum monthly streamflow in August and September, 2005 (Table 4). The streamflow in this river section is influenced by rainfall that occurred in its drainage area, which was recorded at the rainfall gauge 01943008, as well as in the gauges that presented trends in the adjacent areas, 01943027, 01943004, 01943049, 01943007, and 01943100, wherein gauges 01943008 and 01943004 showed a decreasing trend in P_{ms} and P_{tc}, respectively, in 2005. Although the influence of rainfall on streamflow during the dry season is smaller, the Q_{max} reduction trend observed in August and September may be associated with the decreasing trend in rainfall as these variations occurred in the dry period of the same year.

Streamflow data measured at gauge 56750000 exhibited nonstationary behavior in some months, with a decreasing trend for the monthly Q_{mean} and Q_{max}. Regarding Q_{mean}, a reduction trend occurred in September, 1997, whereas for Q_{max}, there were decreasing trends in July, August, and September, in 1995, 1993, and 2002, respectively (Figure 3). The drainage area of this fluviometric gauge may have been influenced by the rainfall trends in gauges 01943002 and 01944020 (Figure 3). Although the data from both of these gauges showed a decreasing trend, only gauge 01943002 exhibited nonstationary behavior with a reduction in P_{ms} in 1992. This reduction in rainfall may be related to the streamflow reduction.

The detection of nonstationary behavior in any of the pluviometric and fluviometric gauges in the study area is in agreement with Ishida et al. (2017), Joseph et al. (2013), and Santos et al. (2016). These authors confirmed the nonstationary behavior of both rainfall and streamflow in various regions worldwide.

The observed changes in the monthly Q_{mean} and Q_{max} behaviors may be associated with changes in rainfall having some influence on drainage areas, whereas changes in the annual Q_7 are not directly associated with changes in rainfall behavior. According to Adnan & Atkinson (2011) and Kibria et al. (2016), the trends found in the historical streamflow series are closely related to the behavior, directly or indirectly, of the changes that occur in rainfall and in land use and cover. Thus, the observed changes herein are likely associated with rainfall changes, as well as increasing impermeabilization and compaction of soil, and higher water withdrawals in each of the studied drainage areas.

A study conducted in northern China by Zhang et al. (2011) found that there is a relationship between annual streamflow and precipitation, wherein the streamflow regime presented nonstationary behavior with a trend of reduction. These changes were influenced by anthropic activities and changes occurring in the rainfall regime.

As explained by Cecílio et al. (2018), the reduction in Q_7 affects the natural potential available for water supply for multiple users, while the Q_{mean} and Q_{max} influence the potential water availability of the basin, and the control of floods and the dimensioning of hydraulic works, respectively. Therefore, the reduction trends in the monthly Q_{mean} and Q_{max}, and the annual Q_7, observed herein should be considered during the planning and management of water resources in the basin under analysis to provide improved water security.

CONCLUSIONS

Statistical tests enabled the identification of significant trends in the annual rainfall and annual and monthly streamflow series as well as their years of change.

In the rainfall series, 50% of the historical series were identified to exhibit nonstationary behavior, wherein they mostly had a decreasing trend during the dry period. For the annual streamflow, only 1996 showed a decreasing trend in minimum streamflow. Trends found in the monthly streamflow series data were observed for mean streamflow and maximum streamflow in three gauges, wherein their occurrences were between July and September, which is during the dry period of the year.

The observed changes in streamflow rates are possibly associated with rainfall changes, increase in impermeabilization and compaction of soil, and higher water withdrawals in each of the drainage areas analyzed.

Thus, to provide improved water security for the studied water basin, the detection of changes in streamflow and precipitation must be considered during the planning and management of water resources.

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