

# Long-term rainfall trends in Serra da Mantiqueira Environmental Protection Area, southeast Brazil

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**Abstract** The Serra da Mantiqueira Environmental Protection Area (SMEPA) is one of the most important and unique Brazilian conservation units of the Atlantic Forest biome, located in the eponymous relief unit. Although the environmental and water resources relevance of the SMEPA is widely known, it lacks specific studies about the hydrological behavior of the region. This paper aims to contribute to the understanding of the rainfall behavior over the SMEPA, by detecting monotonic trends of total annual and seasonal rainfalls. The study was performed by applying the Mann–Kendall test to 37 years series from 23 rainfall stations located within and around the SMEPA. No trends were detected in total annual and spring seasonal rainfall. Few stations (one during summer, two during autumn and two during winter) presented statistically significant trends, indicating that there is no regional trend over the SMEPA region. The isolated significant trends detected suggest the existence of sites with distinct rainfall behavior in the mesoscale.

**Keywords** Serra da Mantiqueira Range · Precipitation · Hydrological variability · Mann–Kendall test

## Introduction

The Serra da Mantiqueira Range (SM) is a major Brazilian relief unit, located between the states of São Paulo (SP),

Minas Gerais (MG) and Rio de Janeiro (RJ). The fourth (Pedra da Mina, 2,798 m) and fifth (Pico das Agulhas Negras, 2,791 m) highest peaks of Brazil are located within the SM, attributing unique physical and environmental characteristics to the region. The Serra da Mantiqueira Environmental Protection Area (SMEPA) was created in 1985 through Brazilian Decree 91.304 (Brazil 1985), as a governmental effort to protect one of the most important national Atlantic Forest Biodiversity Hotspot and wildlife corridors, distributed over 4.218 km<sup>2</sup>. Le Saout et al. (2013) classified the SMEPA as one of the world's most irreplaceable protected areas for the conservation of amphibian, bird and mammal species. The environmental relevance of SM was also highlighted by Becker et al. (2013), who compared the SM with the North American Adirondack Mountains, due to their ecological and conservational contexts. Besides that, both mountain ranges are located between large metropolitan regions (MRs), with significant urban and economic pressures in their vicinities [the SM is located between the MRs of São Paulo and Rio de Janeiro, while the Adirondack Mountains are located between New York and Albany (USA)].

The relevance of Serra da Mantiqueira Range in terms of water resources has been recognized for a long time. The term “Mantiqueira” means “mountain that cries” in native indigenous language, due to the large number of springs, streams and waterfalls within the area. The SMEPA is located along the topographical divisor of two major Brazilian basins, the Paraíba do Sul River Basin (BRPS) and the Grande River Basin (BRG). The streams that flow through SM hills in both basins are water sources for various municipalities in the south of MG State and in the Paraíba do Sul River Valley, in SP and RJ states. The BRPS is one of the richest and most developed regions of Brazil, accounting for about 12 % of its gross domestic

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product (GDP) (CEIVAP 2013). Besides providing water for use in its own valley, the Paraíba do Sul River is responsible for the water supply of part of the Rio de Janeiro Metropolitan Region, which occurs through water transposition (by pumping stations) to Guandu River Basin (LABHID 2006). About the Grande River Basin, beyond the traditional uses of water (public supply, agriculture and livestock), its importance in the national energetic scenario must be emphasized. The BRG presents a cascade of hydropower plants with an installed capacity of 4,514 MW, only in its stretch upstream the confluence of the Grande River with the Pardo River (ONS 2013). The headwaters of the main tributaries of the Rio Grande (Sapucaí River, Verde River and the Grande River itself) in this stretch are located in the SM, which reinforces the relevance of the study area in the Brazilian water resources scenario.

Studies on hydrological trends have been conducted for decades, initially directed toward the analysis of the effect of human activities on watersheds over several variables, such as streamflow, rainfall, groundwater level and evapotranspiration. Recently, this kind of study has become even more relevant due to global climate change projections. According to Bates et al. (2008), there is abundant evidence that water resources are vulnerable and that they will be strongly impacted by climate change, resulting in a variety of consequences for humanity and ecosystems. The climate prediction models currently considered by the International Panel for Climate Change (Bates et al. 2008) allows estimating changes in hydrological process due to global warming in different regions of the world. Nevertheless, several studies (e.g., Vilanova 2014a, b; Martino et al. 2013; Gocic and Trajkovic 2013; Gebremicael et al. 2013; Panda et al. 2013; Shi et al. 2013; Bao et al. 2012; Joseph et al. 2012; Ríó et al. 2011; Cannarozzo et al. 2006) have investigated hydrological trends in a smaller scale (regional or watershed scale), allowing a better understanding of its variability as a function of not only the climate, but also anthropogenic changes on the watersheds. Many of these works analyzed hydrological trends in regions with special relevance in terms of water resources, environment and human development, such as the SMEPA. In the case of SMEPA, the hydrological variability and trends can result not only in changes of water availability for multiple uses, but also in other consequences for humans (such as increased flood and drought frequency and magnitude) and for the singular ecosystems of the SM, causing loss of biodiversity and deterioration of the environmental quality of the region. Vilanova (2014a), for example, did not detect long-term trends (from 1980 to 2009) in regional mean annual streamflow of SMEPA, but detected reduction trends in this variable during a shorter period (1980–1998).

The importance and unique characteristics of SM and SMEPA motivated the present work, since the understanding of its rainfall behavior is critical to their proper environmental and water resources management and planning. Besides allowing the establishment of appropriate public policies and management plans for the protection area, this understanding can provide the basis for several other researches, not only in the area of water resources, but also, for example, in the areas of ecology, biology and environmental management.

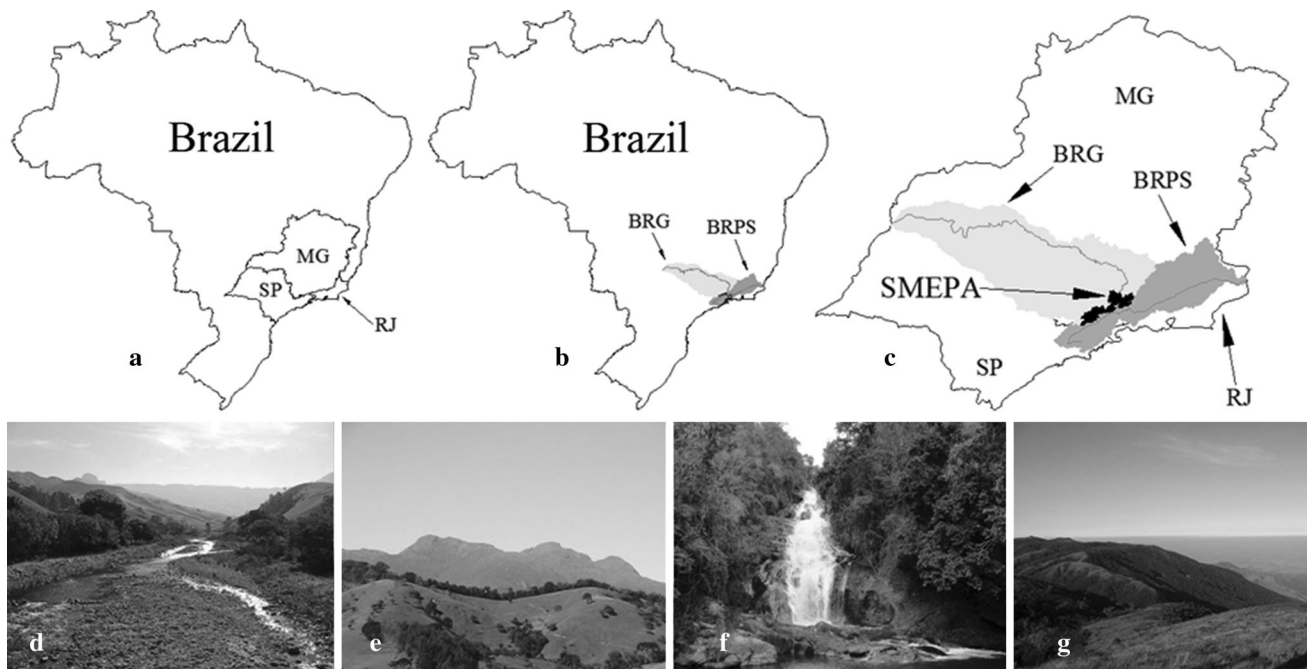
This work aims to detect monotonic trends (trends in one direction, increase or decrease) in time series of total annual and seasonal rainfall over and around the SMEPA. The results of the study allows to conclude if the rainfall of the SMEPA region is decreasing or increasing, which is an important contribution to regional and national water resources and environmental planning, management and research initiatives. Trend detection was performed by the Mann–Kendall test, one of the main methods for trend detection in hydrological series (the test is extensively present in the literature for rainfall time series analysis, for example: Vilanova 2014a, b; Martino et al. 2013; Gocic and Trajkovic 2013; Gebremicael et al. 2013; Panda et al. 2013; Shi et al. 2013; Bao et al. 2012; Joseph et al. 2012; Ríó et al. 2011; Cannarozzo et al. 2006).

## Materials and methods

### Characterization of SMEPA

The SMEPA is located in southeastern Brazil, in the border of SP, MG and RJ states (Fig. 1a), and longitudinally oriented in the southwest–northeast direction. The watersheds located in its northwest face are within the Grande River Basin, while the southeast face watersheds are included in the Paraíba do Sul River Basin (Fig. 1b). The location of SMEPA in relation to these states and basins can be seen in Fig. 1c. The climate is predominantly mild tropical mesothermal, with portions of median tropical and mild temperate mesothermal in the higher parts of the area IBGE (2002).

The SMEPA is part of the Atlantic Forest biome, presenting native vegetation of tropical dense and mixed rain forest, besides montane and upper montane rain forest (Fig. 1f, g) (IBGE 2004). Some higher areas of SM range presents fragments of altitude fields (Fig. 1g). Regarding the land use and occupation of the SMEPA, despite its creation dates of 1985, the management plan for the area has not yet been implemented, which can explain the variety of land uses in the area. The SM range presents a mosaic of native vegetation and different land coverage mainly in its borders and lower areas. This mosaic includes



**Fig. 1** Location of SMEPA: political division of SP, MG and RJ states within Brazil (a), BRG and BRPS basins within Brazil (b) and position of SMEPA within the states and basins (c). Below the maps,

some typical landscapes of SMEPA in Guaratinguetá-SP (d), Marmelópolis-MG (e and f) and Campos do Jordão-SP (g)

pasture, agriculture (Fig. 1d, e) and some isolated reforestation areas, in which forest production occurs. Some small urban areas (e.g., Wenceslau Braz/MG and Alagoa/MG) are also located within the SMEPA.

**Rainfall data and stations**

Series of total daily rainfall were used to calculate the total monthly rainfall. After that, these total monthly rainfall series were used to calculate the total annual and total seasonal rainfalls. These series were obtained from the database of the National Water Agency of Brazil (ANA), HIDROWEB (<http://hidroweb.ana.gov.br/>). The monthly rainfalls from months that presented daily data gaps were filled through linear regression that considered the monthly rainfall series of the considered station and nearby (auxiliary) stations. The auxiliary stations were selected using a correlation matrix between monthly series. This selection followed a priority order, according to the highest coefficients of correlation. This procedure resulted in high coefficients of determination ( $R^2$ ) of the linear regressions, indicating the quality of the adjustment and data fulfillment. All stations used presented integrity (ratio between the number of months with complete daily records and total months over the study period) of more than 91 % (Table 1). The average integrity of all stations used is 96.8 %. Considering the spatially distributed nature of rainfall, stations were selected not only over the SMEPA,

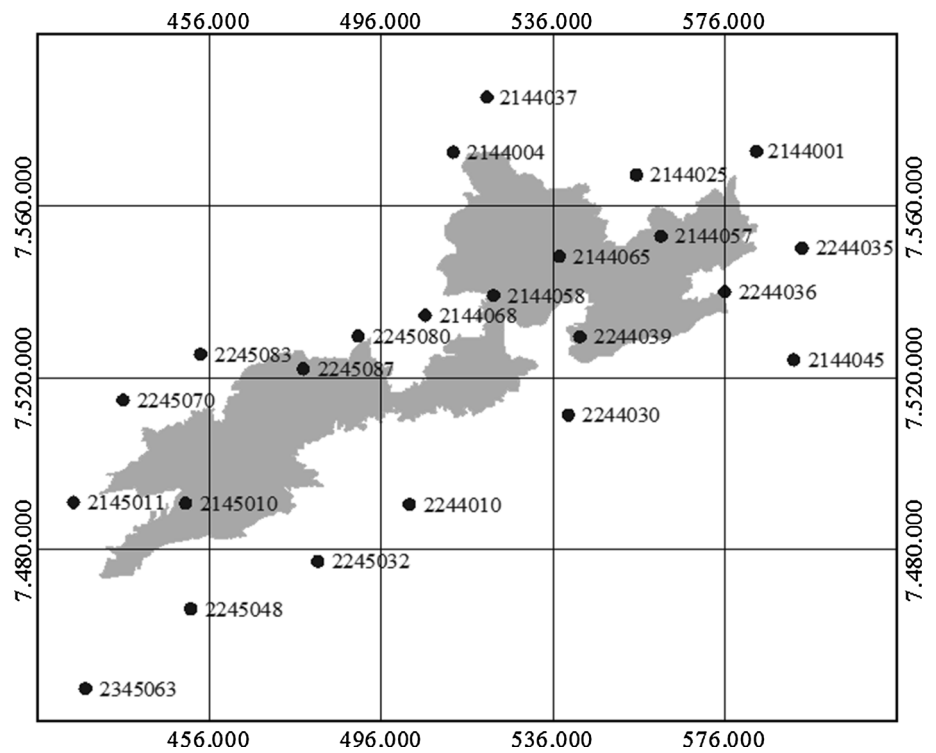
but also in its vicinities (Fig. 2). Table 1 presents the main characteristics of the selected stations.

The typical hydrological year in southeastern Brazil was considered to calculate the annual and seasonal rainfalls, and all series were analyzed between October 1975 and September 2012. This period was chosen because of the greater availability of data from the rainfall stations of the region. Larger periods (considering older rainfall data) could not be considered due to (1) the inexistence of data in many stations and (2) the occurrence of many data gaps in older periods. The chosen period (1975–2012) presented both few data gaps and simultaneous measurement periods between the considered stations. The total annual rainfalls were calculated with data from the months of October to September of the following year. The total seasonal rainfalls for spring, summer, autumn and winter were calculated, respectively, with data for the months October to December, January to March, April to June and July to September. Table 2 presents the main characteristics of rainfall of the selected stations, for each period of analysis—mean, skewness (Ske.) and coefficient of variation (CV).

According to Table 2, the total annual rainfall in the region of SMEPA varies from 1,209 mm at station 2245011, located in the extreme west of the region (in São Bento do Sapucaí/SP), to 2,500 mm at station 2244039, located in Resende/RJ. This station presented the most elevated rainfall both in annual and seasonal series. Some peculiarities of station 2244039 are its altitude (1,460 m),

**Table 1** Characteristics of the selected stations

Station	WGS84 coordinates		Altitude [m]	Municipality/state	Integrity (%)
	Lat.	Lon.			
2144001	−21:56:50	−44:11:38	1,075	Bom Jardim de Minas/MG	95.9
2144004	−21:57:04	−44:52:34	880	Baependi/MG	96.4
2144025	−21:59:53	−44:27:49	1,087	Carvalhos/MG	94.7
2144037	−21:50:07	−44:48:03	1,117	Cruzília/MG	97.5
2244010	−22:41:31	−44:58:30	550	Cachoeira Paulista/SP	96.0
2244030	−22:30:12	−44:36:56	440	Resende/RJ	95.7
2244035	−22:09:02	−44:5:24	530	Santa Rita do Jacutinga/MG	99.7
2244036	−22:14:35	−44:15:49	550	Passa Vinte/MG	98.5
2244039	−22:20:21	−44:35:26	1,460	Resende/RJ	99.5
2244045	−22:23:08	−44:06:27	400	Barra Mansa/RJ	99.8
2244057	−22:07:37	−44:24:30	1,153	Bocaina de Minas/MG	95.8
2244058	−22:15:07	−44:29:39	1,070	Bocaina de Minas/MG	99.5
2244065	−22:10:12	−44:38:13	1,036	Alagoa/MG	98.1
2244068	−22:17:40	−44:56:21	886	Itanhandú/MG	98.4
2245010	−22:41:20	−45:28:53	1,501	Campos do Jordão/SP	94.3
2245011	−22:41:09	−45:44:07	895	São Bento do Sapucaí/SP	94.2
2245032	−22:48:44	−45:10:57	519	Guratinguetá/SP	100.0
2245048	−22:54:40	−45:28:13	524	Pindamonhangaba/SP	96.3
2245070	−22:28:17	−45:37:19	880	Brasópolis/MG	97.8
2245080	−22:20:17	−45:05:26	930	Virgínia/MG	93.0
2245083	−22:22:32	−45:26:49	845	Itajubá/MG	96.8
2245087	−22:24:25	−45:12:54	1,083	Delfim Moreira/MG	94.8
2345063	−23:04:40	−45:42:37	545	Caçapava/SP	93.7

**Fig. 2** Location of the selected rainfall stations in relation to SMEPA (grey area). Coordinates in UTM 23K

**Table 2** Rainfall characteristics of the selected stations, 1975–2012

Station	Annual			Spring			Summer			Autumn			Winter		
	Mean [mm]	Ske.	CV [1]	Mean [mm]	Ske.	CV [1]	Mean [mm]	Ske.	CV [1]	Mean [mm]	Ske.	CV [1]	Mean [mm]	Ske.	CV [1]
2144001	1,438	0.90	0.18	560	-0.18	0.28	620	-0.72	0.22	140	1.37	0.54	118	1.68	0.77
2144004	1,509	1.47	0.17	589	0.41	0.18	631	-0.39	0.24	159	0.89	0.51	129	1.47	0.71
2144025	1,591	1.34	0.22	611	0.21	0.24	699	0.02	0.28	148	2.29	0.65	134	1.46	0.67
2144037	1,535	1.57	0.16	607	0.67	0.21	660	-0.90	0.23	148	1.00	0.46	120	1.47	0.70
2244010	1,366	0.72	0.16	507	0.09	0.20	555	0.74	0.27	175	0.93	0.51	130	1.13	0.56
2244030	1,364	-0.30	0.16	489	0.59	0.24	594	0.38	0.27	151	1.60	0.51	130	0.82	0.55
2244035	1,736	1.26	0.24	647	1.39	0.33	799	0.35	0.29	171	1.95	0.64	120	1.40	0.75
2244036	1,794	0.08	0.23	661	-0.27	0.30	804	0.48	0.30	194	1.02	0.59	134	1.05	0.67
2244039	2,500	0.65	0.13	887	0.49	0.19	1126	0.32	0.25	274	1.28	0.38	214	1.08	0.45
2244045	1,756	0.16	0.16	599	0.97	0.27	813	0.41	0.28	198	1.22	0.50	145	0.67	0.51
2244057	1,932	0.20	0.22	738	0.52	0.29	856	0.27	0.27	186	0.93	0.59	151	1.45	0.76
2244058	2,126	0.35	0.13	792	0.53	0.17	939	0.10	0.24	223	1.31	0.42	172	0.62	0.47
2244065	1,789	0.90	0.15	682	0.42	0.21	785	-0.50	0.25	175	1.16	0.45	148	1.30	0.61
2244068	1,377	-0.12	0.25	518	-0.14	0.34	587	-0.01	0.26	143	1.19	0.56	130	1.55	0.74
2245010	1,805	-0.17	0.19	620	0.22	0.27	790	0.93	0.27	220	1.23	0.53	175	0.86	0.67
2245011	1,209	0.22	0.25	438	0.43	0.29	487	-0.22	0.32	154	1.12	0.61	131	0.53	0.56
2245032	1,458	0.09	0.21	505	0.69	0.26	620	-0.24	0.31	184	1.89	0.64	149	0.89	0.60
2245048	1,226	-0.35	0.27	402	-0.83	0.29	522	0.28	0.35	173	1.90	0.62	128	1.75	0.68
2245070	1,459	0.79	0.20	535	-0.13	0.24	588	-0.04	0.25	190	1.07	0.50	146	1.33	0.62
2245080	2,039	2.75	0.37	763	2.56	0.42	855	0.95	0.29	239	4.60	1.07	182	2.93	0.88
2245083	1,446	0.54	0.17	533	-0.05	0.21	581	-0.16	0.24	179	1.34	0.54	152	1.16	0.62
2245087	1,588	0.95	0.16	592	0.27	0.22	648	-0.43	0.23	193	1.41	0.50	156	1.90	0.66
2345063	1,306	0.83	0.15	414	0.14	0.25	565	0.93	0.27	187	1.66	0.55	141	1.69	0.62
Min.	1209	-0.35	0.13	402	-0.83	0.17	487	-0.90	0.22	140	0.89	0.38	118	0.53	0.45
Mean	1,624		0.20	595		0.26	701		0.27	183		0.56	145		0.64
Max.	2,500	2.75	0.37	887	2.56	0.42	1,126	0.95	0.35	274	4.60	1.07	214	2.93	0.88

the second highest among the stations considered, and its location at the base of Itatiaia National Park, in which is located the Agulhas Negras Peak (fifth highest point of Brazil). The coefficients of variation in Table 2 show that the greater spatial variability of rainfall in the region occurs in the dry season (autumn and winter). During this period, the lowest rainfall occurs in the station 2144001, located at the east of SMEPA. Station 2245080 presented the highest values of skewness, both in annual and seasonal terms. This result suggests that the total rainfall of the station does not fit the normal distribution, given its symmetry. No other station presented a skewness pattern as defined for station 2245080.

**Mann–Kendall test**

The theoretical basis of the Mann–Kendall was proposed by Mann (1945) and Kendall (1975). The test checks for monotonic trends (increase or decrease) in time series

(Hipel and Mcleod 1994), being a non-parametric and rank-based method (Xu et al. 2010). Equation (1) calculates the Mann–Kendall test statistic, considering the null hypothesis ( $H_0$ ) that the data comes from a population whose random variables are independent and identically distributed, while the alternative hypothesis ( $H_1$ ) represents the existence of a monotonic trend (Hipel and Mcleod 1994). In the case studied,  $H_0$  means that the rainfall (annual or sazonal) presents no significant increases or decreases over the periods considered. In Eqs. (1) and (2),  $S$  is the Mann–Kendall test statistic,  $n$  is the size of the sample (number of years in the period of analysis) and  $sgn$  is the signal of the difference of subsequent rainfalls. In Eqs. (3) and (4),  $E[S]$  is the mean of  $S$ ,  $Var[S]$  is the variance of  $S$ ,  $p$  is the number of tied groups (sets of data from the sample that have the same value) and  $t_j$  is the number of data of the  $j$  order tied group.  $Z$  [Eq. (5)] represents the test statistic for samples with  $n > 10$ , which approximates to the normal distribution.

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^n \operatorname{sgn}(x_j - x_k) \quad (1)$$

$$\operatorname{sgn}(x) = \begin{cases} +1, & x > 0 \\ 0, & x = 0 \\ -1, & x < 0 \end{cases} \quad (2)$$

$$E[S] = 0 \quad (3)$$

$$\operatorname{Var}[S] = \frac{\left\{ n(n-1)(2n+5) - \sum_{j=1}^p t_j(t_j-1)(2t_j+5) \right\}}{18} \quad (4)$$

$$Z = \begin{cases} \frac{S-1}{[\operatorname{Var}(S)]^{\frac{1}{2}}}, & \text{for } S > 0 \\ 0, & \text{for } S = 0 \\ \frac{S+1}{[\operatorname{Var}(S)]^{\frac{1}{2}}}, & \text{for } S < 0 \end{cases} \quad (5)$$

The Mann–Kendall test assumes that the data set is independent, meaning that there is no short-term serial correlation between observations (Helsel et al. 2006). Once serial autocorrelation is detected in the series, procedures such as pre-whiten (Bayazit and Önöz 2007) may be used to eliminate it. In this work, the detection of serial autocorrelation was performed by calculating the autocorrelation function (ACF) for the stations series, which were analyzed for the lag 1. The serial autocorrelation occurs when the correlation coefficient is statistically significant at a 5 % level (Burn et al. 2004; Wilson et al. 2010). When autocorrelation was detected, it was removed using the pre-whiten approach, as described by Gocic and Trajkovic (2013) and Hartmann and Andresky (2013).

The Mann–Kendall tests were performed computationally, using the program developed by United States Geologic Survey (USGS) (Helsel et al. 2006). The program calculates the test statistics  $S$  and  $Z$ , the Kendall  $\tau$  coefficient and the  $p$  value (analyzed considering the significance  $\alpha = 0.05$ ).

The slope of trend line is defined by the Theil–Sen slope estimator ( $\beta$ ) (Theil 1950; Sen 1968), calculated with Eq. (6). In Eq. (6),  $x$  is the value of rainfall and the indexes  $j$  and  $i$  are times within the time series.  $\beta$  corresponds to the magnitude of the trend, in  $\text{mm year}^{-1}$ .

$$\beta = \operatorname{median} \left( \frac{x_j - x_i}{j - i} \right) \text{ for all } i < j < n. \quad (6)$$

## Results

Table 3 presents the results of autocorrelation analysis of the rainfall series.

**Table 3** Autocorrelation coefficients (ACC) of the rainfall series

Station	Annual	Spring	Summer	Autumn	Winter
2144001	0.146	<b>0.383</b>	−0.188	−0.044	−0.079
2,144,004	0.016	0.260	−0.231	0.046	−0.066
2,144,025	<b>0.361</b>	0.403	0.022	0.149	0.030
2,144,037	−0.208	0.053	−0.174	0.043	−0.036
2,244,010	0.053	0.283	−0.196	0.162	0.002
2,244,030	−0.066	−0.117	−0.218	0.192	−0.101
2,244,035	0.022	0.270	−0.296	−0.002	−0.110
2,244,036	<b>0.386</b>	0.321	0.002	0.302	−0.061
2244039	0.075	−0.290	−0.183	−0.130	−0.053
2244045	0.213	<b>0.348</b>	−0.064	0.136	−0.014
2244057	0.142	0.046	−0.073	0.049	−0.111
2244058	0.108	0.202	−0.297	0.140	−0.100
2244065	0.209	0.237	−0.225	0.088	−0.153
2244068	0.273	0.225	−0.119	0.057	0.032
2245010	0.113	0.229	−0.074	0.134	−0.083
2245011	<b>0.407</b>	0.320	0.149	0.238	0.089
2245032	0.196	−0.002	−0.063	0.119	−0.144
2245048	<b>0.543</b>	<b>0.557</b>	0.276	0.248	−0.020
2245070	0.020	0.192	−0.134	0.027	−0.021
2245080	<b>0.560</b>	<b>0.451</b>	0.206	0.090	0.074
2245083	0.113	−0.048	−0.081	0.148	−0.045
2245087	−0.176	−0.070	0.068	0.030	−0.095
2345063	−0.231	0.112	−0.075	0.116	−0.137

Bold values indicate the presence of lag 1 serial autocorrelation. 95 % confidence bounds =  $\pm 0.329$

Table 3 shows that few annual and spring series (stations 2144001, 2245011, 2244036, 2244045, 2245011, 2245048 and 2245080) presented in lag 1 autocorrelation and were pre-whitened before the trend analysis.

Tables 4 and 5 present, respectively, the Mann–Kendall test results for annual and seasonal series. Figure 3 presents the geographical location and the significant trend values of the seasonal series.

According to results from Table 4, no statistically significant trends were detected in the total annual rainfall of SMEPA. The mean and standard deviation of the percentage of trends in relation to the means demonstrate that the total annual rainfalls in the SMEPA region remained fairly constant during the studied period.

The analysis of Table 5 and Fig. 3 shows that most of the stations considered in the study did not present statistically significant trends for its seasonal rainfall series during 1975–2012.

The mean trends of all stations during the wet period (spring:  $0.03 \text{ mm year}^{-1}$  and summer:  $1.15 \text{ mm year}^{-1}$ ) are positive, while dry period mean trends are negative (autumn:  $-1.41 \text{ mm year}^{-1}$  and winter:  $1.48 \text{ mm year}^{-1}$ ).



**Table 4** Mann–Kendall test results for total annual rainfalls, 1975–2012

Station	Annual					
	$\tau$	$S$	$Z$	$p$ value	$\beta$	$m$ (%)
2144001	0.173	115	1.491	0.136	6.5	0.45
2144004	-0.159	-106	-1.373	0.170	-5.0	-0.33
2144025	-0.098	-62	-0.831	0.406	-4.7	-0.30
2144037	0.014	9	0.105	0.917	0.4	0.03
2244010	0.051	34	0.432	0.666	1.1	0.08
2244030	-0.221	-147	-1.910	0.056	-6.7	-0.49
2244035	0.060	40	0.510	0.610	2.5	0.14
2244036	0.038	24	0.313	0.754	2.1	0.12
2244039	0.066	44	0.562	0.574	3.0	0.12
2244045	-0.014	-9	-0.105	0.917	-0.4	-0.02
2244057	0.114	76	0.981	0.327	5.7	0.29
2244058	0.080	53	0.680	0.496	3.6	0.17
2244065	-0.111	-74	-0.955	0.340	-3.5	-0.20
2244068	-0.077	-51	-0.654	0.513	-3.7	-0.27
2245010	0.029	19	0.235	0.814	1.1	0.06
2245011	-0.003	-2	-0.014	0.989	-0.2	-0.01
2245032	0.069	46	0.589	0.556	3.0	0.21
2245048	0.070	44	0.586	0.558	2.5	0.20
2245070	0.048	32	0.406	0.685	1.8	0.12
2245080	-0.086	-54	-0.722	0.470	-5.6	-0.27
2245083	-0.218	-145	-1.884	0.060	-6.1	-0.42
2245087	0.063	42	0.536	0.592	2.6	0.16
2345063	-0.021	-14	-0.170	0.865	-0.5	-0.04
<b>Mean</b>					<b>-0.03</b>	<b>-0.01</b>
<b>Standard deviation</b>					<b>3.82</b>	<b>0.24</b>

Bold values indicate the presence of statistically significant trends at 5 % significance level

According to the standard deviations from Table 5, the wet period presented a higher dispersion of the mean trends in relation to their means.

No statistically significant trends were detected during spring. During summer, only station 2144001 presented a statistically significant trend, with an annual increase of the 0.61 % of seasonal rainfall in relation to its mean.

Stations 2245011 and 2245080 presented an annual decrease of autumn rainfalls of -1.79 % and -1.54 % in relation to their means, respectively. During winter, stations 2144004 and 2245080 presented statistically significant negative trends (-1.48 and -2.20 % in relation to their means, respectively). According to the mean and standard deviation of percentage trend in relation to the means, winter is the season with higher variability of total season rainfall (mean reduction of 1.0 % in relation to the mean with a standard deviation of 0,56 %).

None of the stations located in the south face of SM Range, in the Paraíba do Sul River Basin, presented statistically significant long-term rainfall trends, which is

consistent with the findings of Marengo and Alves (2005). The authors evaluated hydrological trends throughout the BRPS and did not detect statistically significant trends in BRPS until the year of 2000.

Table 6 presents the correlation coefficients of the stations that presented statistically significant trends and the nearest ones that did not present trends.

As can be seen in Table 6, station 2144001 presents a strong correlation with station 2244057 during summer. Both stations presented positive trends (although station 2244057’s trend is not significant for  $\alpha = 0.05$ ). On the other hand, the correlations between stations 2144001, 2244025 and 2244035 are moderate, and these stations presented no significant negative trends. This is an interesting finding that indicates the existence of an area between stations 2144001 and 2244057 with similar rainfall patterns, dividing other distinct rainfall regions in which stations 2244025 and 2244035 are located, as can be seen in Fig. 2.

Considering the autumn series, station 2245011 is strongly correlated with stations 2245010 and 2245070, but

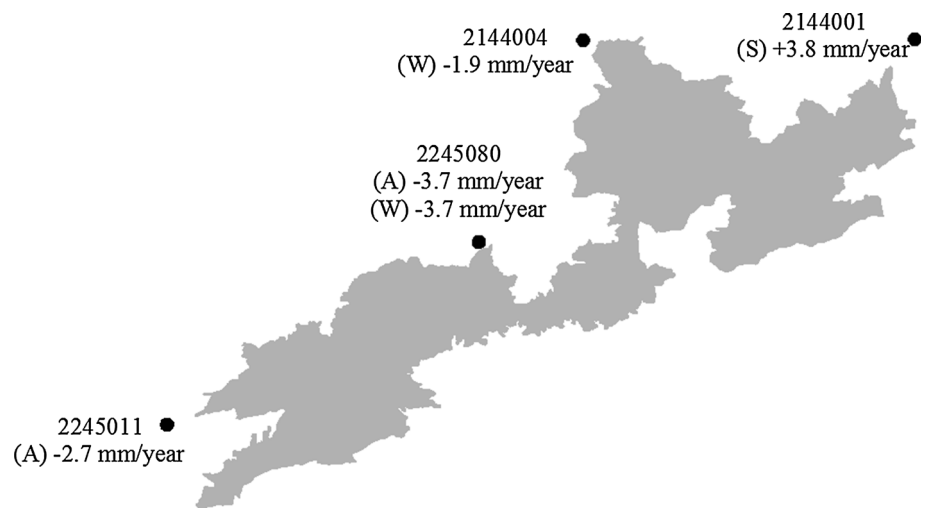
**Table 5** Mann–Kendall tests results for total seasonal rainfalls, 1975–2012

Station	Spring						Summer						Autumn						Winter					
	$\tau$	S	Z	p value	$\beta$	m (%)	$\tau$	S	Z	p value	$\beta$	m (%)	$\tau$	S	Z	p value	$\beta$	m (%)	$\tau$	S	Z	p value	$\beta$	m (%)
2144001	0.168	106	1.430	0.153	3.5	0.62	<b>0.24</b>	<b>160</b>	<b>2.08</b>	<b>0.038</b>	<b>3.8</b>	<b>0.61</b>	-0.116	-77	-0.994	0.320	-1.3	-0.95	-0.045	-30	-0.379	0.704	-0.5	-0.45
2144004	-0.072	-48	-0.615	0.539	-1.1	-0.18	-0.068	-45	-0.576	0.565	-1.2	-0.19	-0.153	-102	-1.321	0.186	-1.5	-0.94	<b>-0.230</b>	<b>-153</b>	<b>-1.989</b>	<b>0.047</b>	<b>-1.9</b>	<b>-1.48</b>
2144025	-0.083	-52	-0.695	0.487	-2.2	-0.36	-0.05	-33	-0.419	0.676	-1.6	-0.23	-0.188	-125	-1.622	0.105	-2.1	-1.40	-0.218	-145	-1.884	0.060	-2.3	-1.76
2144037	-0.132	-88	-1.138	0.255	-2.2	-0.36	0.141	94	1.217	0.224	3.4	0.51	-0.108	-72	-0.929	0.353	-0.8	-0.51	-0.213	-142	-1.844	0.065	-1.9	-1.61
2244010	0.032	21	0.262	0.794	0.6	0.12	0.149	99	1.282	0.200	2.9	0.53	-0.072	-48	-0.615	0.539	-0.7	-0.39	-0.137	-91	-1.177	0.239	-1.0	-0.77
2244030	-0.209	-139	-1.805	0.071	-3.4	-0.69	-0.045	-30	-0.379	0.705	-1.5	-0.25	-0.134	-89	-1.151	0.250	-1.2	-0.82	-0.129	-86	-1.112	0.266	-1.3	-1.01
2244035	0.081	54	0.693	0.488	2.3	0.36	-0.033	-22	-0.275	0.784	-0.9	-0.11	-0.116	-77	-0.994	0.320	-1.5	-0.88	-0.069	-46	-0.589	0.556	-1.0	-0.86
2244036	-0.084	-56	-0.719	0.472	-2.5	-0.37	-0.062	-41	-0.523	0.601	-1.5	-0.19	-0.078	-52	-0.667	0.505	-1.2	-0.64	-0.074	-49	-0.628	0.530	-0.9	-0.64
2244039	0.119	79	1.020	0.308	2.9	0.33	0.008	5	0.052	0.958	0.1	0.01	0.128	85	1.099	0.272	1.4	0.52	-0.138	-92	-1.191	0.234	-1.5	-0.68
2244045	0.010	6	0.068	0.946	0.2	0.03	0.042	28	0.353	0.724	0.9	0.11	-0.113	-75	-0.968	0.333	-1.5	-0.75	-0.210	-140	-1.819	0.069	-2.2	-1.52
2244057	0.149	99	1.282	0.200	4.6	0.62	0.161	107	1.386	0.166	6.4	0.74	-0.116	-77	-0.994	0.320	-1.3	-0.71	-0.129	-86	-1.112	0.266	-1.4	-0.94
2244058	0.063	42	0.536	0.592	1.3	0.17	0.042	28	0.353	0.724	1.5	0.16	-0.062	-41	-0.523	0.601	-0.5	-0.24	-0.183	-122	-1.583	0.114	-2.3	-1.37
2244065	0.024	16	0.196	0.845	0.5	0.08	-0.036	-24	-0.301	0.764	-1.0	-0.13	-0.221	-147	-1.91	0.056	-2.1	-1.20	-0.120	-80	-1.033	0.301	-1.5	-1.00
2244068	-0.098	-65	-0.837	0.403	-2.5	-0.49	0.078	52	0.667	0.505	1.5	0.25	-0.134	-89	-1.151	0.250	-1.4	-0.95	-0.150	-100	-1.295	0.195	-1.7	-1.29
2245010	0.057	38	0.484	0.628	1.5	0.23	0.075	50	0.641	0.522	3.1	0.39	-0.167	-111	-1.439	0.150	-2.4	-1.07	-0.089	-59	-0.759	0.448	-1.5	-0.87
2245011	-0.095	-63	-0.811	0.417	-1.5	-0.35	0.084	56	0.719	0.472	2.2	0.46	<b>-0.269</b>	<b>-179</b>	<b>-2.329</b>	<b>0.020</b>	<b>-2.7</b>	<b>-1.79</b>	-0.018	-12	-0.144	0.886	-0.2	-0.18
2245032	0.182	121	1.570	0.117	3.2	0.64	0.093	62	0.798	0.425	3.2	0.51	-0.138	-92	-1.19	0.234	-1.1	-0.62	-0.146	-97	-1.256	0.209	-1.6	-1.06
2245048	0.132	83	1.117	0.264	2.2	0.54	0.114	76	0.981	0.327	2.1	0.40	-0.08	-53	-0.68	0.496	-1.0	-0.58	0.087	58	0.746	0.456	0.9	0.70
2245070	-0.024	-16	-0.196	0.845	-0.3	-0.06	0.081	54	0.693	0.488	1.7	0.30	-0.071	-47	-0.602	0.547	-0.8	-0.41	-0.099	-66	-0.850	0.395	-1.4	-0.93
2245080	-0.127	-80	-1.077	0.282	-3.0	-0.39	-0.158	-105	-1.36	0.174	-5.4	-0.63	<b>-0.242</b>	<b>-161</b>	<b>-2.093</b>	<b>0.036</b>	<b>-3.7</b>	<b>-1.54</b>	<b>-0.261</b>	<b>-174</b>	<b>-2.263</b>	<b>0.024</b>	<b>-3.7</b>	<b>-2.02</b>
2245083	-0.128	-85	-1.099	0.272	-2.2	-0.42	0.011	7	0.078	0.937	0.3	0.06	-0.179	-119	-1.543	0.123	-2.0	-1.11	-0.180	-120	-1.557	0.120	-1.9	-1.24
2245087	0.023	15	0.183	0.855	0.2	0.04	0.225	150	1.949	0.051	3.6	0.56	-0.111	-74	-0.955	0.339	-1.2	-0.61	-0.174	-116	-1.504	0.133	-1.6	-1.06
2345063	-0.087	-58	-0.746	0.456	-1.5	-0.36	0.197	131	1.7	0.089	3.0	0.53	-0.185	-123	-1.596	0.111	-1.9	-1.03	-0.140	-93	-1.204	0.229	-1.5	-1.05
<b>Mean</b>					<b>0.03</b>	<b>-0.01</b>					<b>1.15</b>	<b>0.19</b>					<b>-1.41</b>	<b>-0.81</b>					<b>-1.48</b>	<b>-1.00</b>
<b>SD</b>					<b>2.34</b>	<b>0.40</b>					<b>2.54</b>	<b>0.36</b>					<b>0.95</b>	<b>0.47</b>					<b>0.86</b>	<b>0.56</b>

Bold values indicate the presence of statistically significant trends at 5 % significance level



**Fig. 3** Seasonal statistically significant trends in SMEPA. *S* summer, *A* autumn, *W* winter



**Table 6** Correlation between the stations that presented statistically significant trends and the nearest stations with no significant trends

Stations with significant trends		2144001	2144004	2245011	2245080	2245080
Season		Summer	Winter	Autumn	Autumn	Winter
Nearest stations (with no significant trends)	2144025	0.62	0.85	–	–	–
	2244035	0.66	–	–	–	–
	2244057	0.76	–	–	–	–
	2144037	–	0.96	–	–	–
	2244065	–	0.93	–	–	–
	2245010	–	–	0.83	–	–
	2245070	–	–	0.76	–	–
	2245068	–	–	–	0.69	0.83
	2245087	–	–	–	0.75	0.87

*p* values in Table 5 demonstrate that there are strong evidences to reject the existence of trends in these stations.

During winter, station 2144004 presented strong correlation with stations 2144025, 2144037 and 2244065. As can be seen in Table 5, all of these stations did not present significant negative trends for  $\alpha = 0.05$ . Nonetheless, *p* values in Table 5 show that evidences to reject the existence of trends in stations 2144037 and 2144025 are not strong, since their trends could be considered significant for  $\alpha = 0.10$ . This finding indicates the existence of another homogeneous rainfall pattern between these stations, although only station 2144004 presented a significant trend for  $\alpha = 0.05$ .

In the case of station 2245080 (winter), strong correlations were found with stations 2245068 and 2245087, but the trend's *p* values (Table 5) of these stations did not support the existence of trends in these stations. In this case, rainfall behavior of station 2245080 is very distinct compared to that of the nearest stations, even considering their geographical proximity (both stations are about 15 km from station 2245080). This finding suggests that

rainfall changes in station 2245080 occurred on a very small spatial scale.

An e-mail contact was made with the HIDROWEB/ANA, seeking information about possible events (e.g., replacement of the rain gauges or changes of the measurement systems) in the stations that presented statistically significant trends that could have influenced the rainfall time series and trends. According to the records of HIDROWEB, no significant event occurred at these stations during the analyzed period.

**Discussion**

The results of the present study demonstrate that there is no regional long-term rainfall trend in the SMEPA region. In a complementary way, the results suggest the existence of locations with singular rainfall patterns in mesoscale, since few isolated stations presented statistically significant rainfall trends. The variety of rainfall patterns along the SM range was approached by Modenesi-Gauttieri and

Nunes (1998), according to whom the summits of the SM present particular climatic characteristics related to the altitude and to its front position on the Atlantic seaboard of South America. Analyzing the results of the present work according to this statement of Modenesi-Gauttieri and Nunes (1998), the stations that presented significant trends are located in the borders of SM Range, in lower altitude sites. Besides that, all of these stations are located in the northwest face of the SM Range. Considering the position of these stations, the position of the SM makes it act as a barrier to the atmospheric circulation coming from the Atlantic Ocean. For Modenesi-Gauttieri and Nunes (1998), events like El Niño have no significant influence over the rainfall in the Itatiaia Region (northeast region of SM), while in the Campos do Jordão region (southwest region of SM), years over El Niño influence are characterized by positive anomalies or trends. The fact that stations that present significant trends are located near stations with no significant trends (all stations that present significant trends are located closer than 30 km from the stations that present no significant trends) suggests that there is no influence of periodic/cyclical events (such as El Niño or solar cycles that influence the climate in meso to synoptic scales) over these trends. If such events were influential over the detected rainfall trends, a regional influence (significant trends should be identified at various stations located near each other) would be expected.

André et al. (2008) also reported differences between local rainfall patterns in the SMEPA region. According to these authors, the stations 2244039 and 2244045, considered in the present study, belong to different regions of homogeneous precipitation, despite their proximity (about 50 km distant from each other).

The literature and the present work findings suggest the establishment of areas with singular rainfall behavior throughout the SMEPA region and with significant differences in very small spatial scale (mesoscale). According to Holton (2004), possible mesoscale disturbances may originate from thermal and topographic sources, besides non-linear energy transfers and interactions between physical and dynamical cloud processes. Also according to Holton (2004), the atmospheric flow over large mountains (such as the SM range) can produce orographic disturbances with mesoscale range of 10 km to 100 km, governed by the wind and the static stability profiles, beyond the scale of the orography. The topographic influence of SM over regional rainfall has been analyzed, for example, by Melo Júnior et al. (2006) and André et al. (2008). Evidences of the existence of strong orographic influence of SM over the regional rainfall were also obtained in the present work. As previously mentioned, the station 2244039, located at the base of the Itatiaia Plateau, presents a higher mean annual rainfall (2,500 mm). This fact is consistent with the theory

presented by Barry and Chorley (2003), according to whom in tropical and subtropical regions the maximum precipitation in a mountain area occurs below the summits of the highest mountains. In this case, the station 2244039 is located at the base of Pico das Agulhas Negras Peak, the fifth highest point in Brazil. Other possible source of mesoscale disturbances in the SM region may be attributed to changes in land use and occupation, affecting the energy and moisture fluxes. The analysis of the causes of the rainfall trends detected is outside the scope of the present study and can be the object of future researches.

Station 2245080 proved to be the one with greater variability in the region, with statistically significant negative trends during autumn and winter. Some stations located near this station (closer than 20 km), such as 2245087 and 2244068, did not present significant trends. Besides that, the station's skewness demonstrates that its annual rainfall series distribution is not symmetric as expected for a normal distributed series.

All of these findings reinforce the hypothesis that the isolated rainfall trends detected in the present study are due to mesoscale processes. This is an interesting finding that highlights the importance of hydrological researches in the SMEPA. Although the region is densely monitored in terms of rainfall (as can be seen in Fig. 2), it is possible that different hydrological processes occur at a much smaller scale, in unmonitored areas, such as forest areas and peaks higher than 2,000 m. This opens possibilities and prospects for researches, involving high-resolution hydrometeorological monitoring of the area (e.g., by the installation of monitoring stations at specific points such as those mentioned) mainly in the higher sites of the Serra da Mantiqueira Range. The need for improvements of the hydrological monitoring systems of Serra da Mantiqueira Range was also observed by Vilanova (2014a), who identified 35 streamflow stations in the area of SMEPA, but only 4 of these presented historical series with sufficient extension and integrity for streamflow trends analysis.

In terms of water resources management, the negative rainfall trends detected during the dry period (autumn and winter) can result in a reduction of water availability for multiple uses in the watersheds located in the areas around stations 2245011 and 2245080. It is important to note that station 2245011 is the one that presented the lowest mean annual rainfall (1,209 mm) among those studied. An emblematic case of possible problems caused by reduced rainfall in the SM is the current scenario of water scarcity faced by the MR of São Paulo. Some watersheds that supply the main source of the city (Cantareira System), whose springs are in SM (near the southwest part of SMEPA), has shown very low rainfall totals in relation to its historical means since the beginning of 2014. This variation in the rainfall behavior in the region led the

storage levels of the Cantareira System to a critical condition, signaling even a scenario of water rationing in the MR of São Paulo.

As an environmental protection area, another relevant consequence of these negative trends for the SMEPA can be the increase in the frequency of fires in the region. This type of occurrence has been reported several times over the SM Range, caused mainly by the use of fire for the preparation of agricultural areas, besides accidents involving ecotourists. Biological and ecological responses can also be triggered by the reduction in rainfall during the dry period. Eller et al. (2013), for example, identified the mechanism of foliar water uptake (FWU) in the tree species *Drimys brasiliensis* during experiments conducted in the SM, in Campos do Jordão (near station 2245011). The FWU is a physiological response of these trees to periods of severe drought, through which fog water is removed by the leaves and partially distributed into the soil through the root system. Among the possible consequences of increased rainfall during the summer, as detected in station 2144001, are the increase in frequency and magnitude of floods and landslides, in addition to the increased rates of erosion in the watersheds. Moreover, this positive trend may, for example, favor the hydroelectric generation in BRG.

The results of the present work also highlight the environmental importance of SMEPA, since the borders of the protection area, where changes of land use and occupation are more intense, were more susceptible to hydrological (rainfall) changes. A similar rainfall trend behavior was identified by Vilanova (2014b), who analyzed rainfall trends in another important mountain environmental protection area located in southeast Brazil, the Serra do Mar State Park (SMSP). The author did not detect significant trends in a rainfall station located within the forestall area of the SMSP, but detected reduction trends in another rainfall station located 35 km away from the first one. The second station analyzed by Vilanova (2014b), which presented statistically significant trends, is also located in the border of the SMSP, surrounded by anthropogenic fields and agricultural areas.

### Conclusions

The results of this study allow to conclude that no regional changes occurred in total annual and seasonal rainfalls in the Serra da Mantiqueira Environmental Protection Area, during the period of 1975–2012. Few isolated stations analyzed, located in the vicinity of the north portion of SMEPA, presented local statistically significant seasonal trends, most of them negative. These findings suggest the establishment of singular mesoscale rainfall patterns in isolated locations around the SMEPA.

Despite its importance for Brazil, the Serra da Mantiqueira Range and the Serra da Mantiqueira Environmental Protection Area are little studied in terms of water resources. Most of the references and previous studies conducted in the region that were identified during the literature review are from the area of biology. The present work is a small, but important contribution to a better understanding of the hydrological behavior of this important natural area of Brazil and can motivate future water resources and hydrometeorological studies, besides serving as a reference for the environmental management and planning of the SMEPA.

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