Trend Analysis of Reference Evapotranspiration in the São Francisco River Basin, Brazil

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TREND ANALYSIS OF REFERENCE EVAPOTRANSPIRATION IN THE SÃO FRANCISCO RIVER BASIN, BRAZIL

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ABSTRACT: An important requisite in any water resources management program is the knowledge of the natural processes that regulate the hydrological cycle, especially for spatial and temporal analyses of these processes. This work aimed to explore spatial and temporal trends of reference evapotranspiration (ET_o), evaluate ET_o variation dynamics and quantify the contribution of each one of the meteorological variables in ET_o calculation in the São Francisco River basin. Daily data of maximum and minimum air temperature, mean relative air humidity, wind speed and net radiation from 101 weather stations, for the period from 1961 to 2015, were used and are part of the network of the National Institute of Meteorology (INMET). Climate trend analysis was performed using the non-parametric Mann-Kendall statistical test and the sensitivity analysis for the Penman-Monteith equation was carried out based on partial derivatives as a function of the key meteorological variables of ET_o (air temperature, net radiation, wind speed and actual water vapor pressure). A significant increase ($p < 0.01$) in vapor pressure deficit (VPD) associated with the increase in mean air temperature contributed to increments in ET_o along the studied period. The scenario in the entire São Francisco River basin is of increase in the values of the climatic variables, particularly evapotranspiration (85% of basin area with increments) and rainfall (52% of basin area with decrements). Results indicate an increase in ET_o variation rates of approximately 2.424 mm year⁻², on average, in the entire basin. The energy term represents higher weight in ET_o calculation in 81% of the basin territory.

Key Words: Climatology, climate changes, Mann-Kendall test

1 | INTRODUCTION

In the hydrological cycle, precipitation and evaporation are opposite pathways for water flow. At a regional scale, potential evapotranspiration (PET) (Thornthwaite, 1948) is the transfer rate of water vapor that would occur from a surface with unlimited water supply. Under given meteorological conditions, PET quantifies the atmospheric water demand, and the balance between precipitation and PET is an essential step in climate analysis with important applications in catchment hydrology, irrigation and drainage of agricultural lands, and management of reservoirs (Dingman, 2015).

The definition of a reference crop evapotranspiration (ET_0), as proposed by FAO (Doorenbos and Pruitt, 1977; Allen et al., 1998) fits the concept of PET with the exception that ET_0 refers to a specific type of surface with predefined characteristics. Broadly, average ET_0 can vary from 1 to 9 mm d⁻¹, with lower values (1 - 3 mm d⁻¹) found in cool agroclimatic zones (mean daily temperature, $T_a \sim 10$ °C) and higher values (6 - 9 mm d⁻¹) in warm zones ($T_a > 30$ °C) (Allen et al., 1998). Simpler models to simulate ET_0 are typically based on air temperature data only, such as the Thornthwaite (Thornthwaite, 1948) and Hargreaves-Samani methods (Hargreaves and Samani, 1985; Hargreaves and Allen, 2003), while more complex models (Penman-type equations) require the measurement of other meteorological variables (ASCE-EWRI, 2005) in addition to temperature.

Today, there is a consensus that the Earth's climate system is under unequivocal changes due mainly to anthropogenic activities starting from the mid-20th century (IPCC, 2013). Human influence has augmented CO₂ concentration and other greenhouse gases in the atmosphere, which is likely to cause, among other impacts, changes in global surface temperature to exceed 1.5 °C by the year 2100 (IPCC, 2013). Global warming impacts in some degree processes such as evaporation, cloudiness, incident solar radiation, atmospheric circulation, and precipitation (Moratíel et al., 2011). In searching for connections with the actual scenario of climate change and considering that evaporation in natural environments combines the effects of meteorological conditions and surface properties, many studies based on long-term weather data have focused on trends of pan evaporation E_p (Lawrimore and Peterson, 2000; Roderick et al., 2009; Yang and Yang, 2012; Talaei et al., 2014) and ET_0 (Gong et al., 2006; Tang et al., 2011; Irmak et al., 2012; Tabari et al., 2012; Vicente-Serrano et al., 2014; Li et al., 2015; Dadaser-Celik et al., 2016).

Globally, the sign and magnitude of trends in ET_o and associated variables have been diverse. For example, in China, Tang et al. (2011) reported a gradual decrease (-1.0 mm yr^{-2}) in the FAO-56 PM ET_o during 1950-2007 using data from 34 weather stations across the Haihe River Basin. Trends were widespread over the basin. Xie and Zhu (2013) also found a similar decreasing rate for ET_o (-0.69 mm yr^{-2}) over the Tibetan Plateau (75 sites from 1970 to 2009). Irmak et al. (2012) based on data from 1893 to 2008 collected at the Platte River Basin, NE, USA, observed a significant decline ($p < 0.05$) in reference ET. The decline was about the same (approximately -0.36 mm yr^{-1}) for both grass and alfalfa as reference crops. Differently, Vicente-Serrano et al. (2014) reported increasing average ET_o during all months and annually in Spain (46 sites from 1961-2011). The authors found the spatial pattern of ET_o to be intricate and mostly random with an annual magnitude of change of $29.4 \text{ mm decade}^{-1}$. Similarly, Dadaser-Celik et al. (2016) examined trends in the FAO-56 PM ET_o over Turkey (77 sites from 1975-2006) to find positive trends in annual ET_o in 58% of the sites, being statistically significant ($p < 0.05$) in 32% of them. Over the country, an average ET_o trend of 1.20 mm yr^{-2} was found. Similar to Tang et al., (2011), the trends in the ET_o driving parameters were widespread over Turkey for the same period. As an attempt to summarize worldwide trend data on E_p and ET_o as well as the contribution of the driving variables McVicar et al. (2010) observed that trends were -3.19 mm yr^{-2} for E_p (average of 55 studies) and -1.31 mm yr^{-2} for ET_o (average of 26 studies).

Most of the studies on ET_o changes typically perform some sensitivity and attribution analysis to quantify the relative contribution of the primary driving variables., i.e., solar radiation, temperature, atmospheric humidity, and wind speed. According to McVicar et al. (2010), any study that focuses on assessing evaporative demand trends has to consider the role of these variables. In their review, McVicar et al. (2010) reported global trends in E_p and ET_o due mainly to declining rates of wind speed (U_2). Based on 148 studies (more than 30 sites observing data for more than 30 years) the average trend in U_2 was $-0.014 \text{ m s}^{-1} \text{ yr}^{-1}$ (-0.7 m s^{-1} over 50 years). Their survey pointed to the aerodynamic component as the primary driver of the negative rates of evaporation over time. The recent works by Vicente-Serrano et al. (2014) in Spain and Dadaser-Celik et al. (2016) in Turkey confirms that. However, positive trends in ET_o were found in their respective countries.

The Northeast of Brazil is on average the driest among of the five geopolitical regions of the country with evaporative demand at least twice the annual precipitation due to the predominance of a semiarid climate. In that region, the São Francisco river is the main source of water for agriculture, power generation, and urban growth. Due to its importance for the regional development and sustainability, this paper uses meteorological data from observatories in the neighborhood and within the São Francisco River Basin to (i) explore the spatial and temporal trends of ET_o , and associated driving variables, (ii) assess the dynamics of ET_o variation, and (iii) quantify the relative contribution of each of the key climatic variables (temperature, solar radiation, relative humidity, and wind speed) to ET_o change. To the knowledge of the authors, this is the first study on ET trend in the SFRB as a pioneer contribution to the understanding of the relationship between climatic changes and water development strategies in the region.

2 | MATERIAL AND METHODS

2.1 | Meteorological data and quality analysis

Weather data used in this study were collected at 101 weather stations and downloaded from the Conventional Weather Station Database (BDMEP) of the National Institute of Meteorology of Brazil (INMET), which is the WMO office in Brazil. Figure 1 shows the spatial distribution of the weather stations in the São Francisco River Basin (SFRB) as well as in a 200-km buffer zone around the basin. For 64 weather stations (Table 1), 55 years of data or more were available up to a maximum of 59 years, extending from 1961 to 2020. For 37 weather observatories, the data period was smaller than 59 years up to a minimum of 30 years. From the total, 49 observatories are located within the limits of SFRB while 52 are distributed in the buffer zone. These outer stations were necessary for spatial interpolation as well as to assure a better representation of the climate within the basin and its surroundings (Amirataee et al., 2016; Oliver & Webster, 1990).

FIGURE 1 Spatial distribution of weather stations inside and outside the limits of the São Francisco River Basin (SFRB). The 200 km width buffer area is also shown around the basin

TABLE 1 Identification of the weather stations inside and outside the São Francisco River Basin (SFRB) with additional information on location, geographical coordinates, number of years of data (starting from 1961), and climate type

Station ID	Location	State	Lat (deg)	Lon (deg)	Alt (m)	In operation since	Climate
Stations located within the basin boundaries							
Upper section of the basin							
83582	BambuÍ	MG	-20.04	-46.00	661.27	08/26/1926	Cwb
83587	Belo Horizonte	MG	-19.94	-43.93	915.00	03/03/1910	Aw
83533	Bom Despacho	MG	-19.68	-45.36	695.00	01/01/1981	Cwa
83536	Curvelo	MG	-18.76	-44.45	672.00	09/03/1912	Aw
83635	Divinópolis	MG	-20.17	-44.87	788.35	10/11/1995	Cwa
83581	Florestal	MG	-19.88	-44.42	753.00	04/09/1960	Cwa
83632	Ibirité	MG	-20.02	-44.05	814.54	04/06/1959	Aw
83637	Oliveira	MG	-20.68	-44.82	966.50	01/01/1961	Cwa
83483	Pirapora	MG	-17.35	-44.93	505.24	12/23/1912	Aw
83570	Pompeu	MG	-19.23	-45.00	690.91	11/01/1972	Aw
83586	Sete Lagoas	MG	-19.47	-44.26	732.00	05/03/1926	Aw
Middle section of the basin							
83384	Arinos	MG	-15.91	-46.05	519.00	05/04/1976	Aw
83179	Barra	BA	-11.08	-43.17	401.58	03/03/1925	Aw
83236	Barreiras	BA	-12.16	-45.00	439.29	01/01/1924	Aw
83288	Bom Jesus da Lapa	BA	-13.27	-43.42	439.96	01/11/1941	Aw
83408	Caririnha	BA	-14.28	-43.76	450.18	01/12/1927	Aw
83286	Correntina	BA	-13.34	-44.63	549.47	11/08/1975	Aw
83338	Espinosa	MG	-14.92	-42.86	569.64	01/03/1974	Aw
83334	Formoso	MG	-14.93	-46.26	840.00	03/04/1976	Aw
83395	Janaúba	MG	-15.80	-43.29	516.00	15/03/1975	Aw
83386	Januária	MG	-15.48	-44.38	473.71	19/06/1912	Aw
83481	João Pinheiro	MG	-17.70	-46.17	760.36	09/12/1925	Aw
83452	Juramento	MG	-16.77	-43.66	648.00	14/11/1986	Aw
83389	Mocambinho	MG	-15.08	-44.03	452.00	01/11/1975	Aw
83388	Monte Azul	MG	-15.08	-42.75	603.63	01/03/1974	Aw
83437	Montes Claros	MG	-16.68	-43.83	646.29	01/01/1912	Aw
83479	Paracatu	MG	-17.23	-46.88	712.00	13/05/1918	Aw
83076	Santa Rita de Cassia	BA	-11.03	-44.52	450.30	13/12/1911	Aw
83428	Unaí	MG	-16.38	-46.56	460.00	07/04/1976	Aw
Lower middle section of the basin							
1111	Bebedouro	PE	-9.15	-40.37	365.30	01/01/1975	Bsh
82886	Cabrobó	PE	-8.52	-39.33	341.46	17/10/1927	Bsh
82887	Floresta	PE	-8.61	-38.57	309.73	01/01/1961	Bsh
83182	Irecê	BA	-11.33	-41.87	747.16	01/12/1970	Bsh
1111	Mandacaru	PE	-9.40	-40.43	356.20	01/01/1975	Bsh
83184	Morro do Chapéu	BA	-11.22	-41.22	1003.27	13/01/1913	Aw
82753	Ouricuri	PE	-7.90	-40.05	459.28	16/09/1975	Bsh
82983	Petrolina	PE	-9.37	-40.47	370.46	01/01/1941	Bsh

82979	Remanso	BA	-9.63	-42.10	400.51	01/10/1927	Bsh
Lower section of the basin							
82989	Água Branca	AL	-9.28	-37.90	605.34	05/05/1928	Bsh
82890	Arcoverde	PE	-8.42	-37.09	680.70	01/02/1973	Aw
82990	Pão de Açúcar	AL	-9.76	-37.44	19.10	14/03/1927	Bsh
82986	Paulo Afonso	BA	-9.37	-38.22	252.69	01/02/1951	Bsh
83097	Propriá	SE	-10.21	-36.87	19.92	10/05/1925	Bsh
Stations located at the buffer zone							
82970	Alto Parnaíba	MA	-9.10	-45.93	285.05	21/08/1976	Aw
83096	Aracaju	SE	-10.95	-37.05	4.72	01/03/1910	Aw
83442	Araçuaí	MG	-16.83	-42.05	289.00	06/09/1918	Aw
83579	Araxá	MG	-19.61	-46.93	1023.61	07/09/1916	Cwb
83689	Barbacena	MG	-21.26	-43.77	1126.00	09/06/1914	Cwa
82784	Barbalha	CE	-7.32	-39.33	409.03	01/01/1948	Bsh
82975	Bom Jesus do Piauí	PI	-9.10	-44.12	331.74	19/04/1971	Aw
83377	Brasília	DF	-15.78	-47.93	1159.54	12/09/1961	Aw
83339	Caetité	BA	-14.08	-42.49	882.47	01/01/1907	Aw
82795	Campina Grande	PB	-7.24	-35.88	547.56	01/01/1911	Aw
82777	Campos Sales	CE	-7.00	-40.39	583.50	01/06/1960	Bsh
82976	Caracol	PI	-9.31	-43.33	522.77	03/10/1975	Aw
83526	Catalão	GO	-18.19	-47.95	840.47	01/01/1913	Cwb
83192	Cipó	BA	-11.08	-38.51	145.31	01/01/1935	Bsh
83589	Conceição do Mato Dentro	MG	-19.02	-43.44	652.00	30/06/1925	Aw
83037	Coronel Pacheco	MG	-21.59	-43.26	435.00	01/01/1955	Cwa
82693	Cruzeta	RN	-6.46	-36.58	226.46	01/01/1930	Aw
83538	Diamantina	MG	-18.26	-43.61	1296.12	13/04/1918	Aw
83379	Formosa	GO	-15.53	-47.33	935.19	01/01/1925	Aw
83630	Franca	SP	-20.58	-47.38	1026.20	01/01/1911	Cwb
82893	Garanhuns	PE	-8.89	-36.52	822.76	01/02/1913	Aw
82686	Iguatu	CE	-6.39	-39.33	217.67	01/01/1911	Bsh
83522	Ipameri	GO	-17.71	-48.16	772.99	10/02/1977	Cwb
83195	Itabaianinha	SE	-11.12	-37.82	208.00	06/08/1923	Bsh
83244	Itaberaba	BA	-12.52	-40.28	249.89	21/08/1931	Aw
83488	Itamarandiba	MG	-17.85	-42.86	1097.00	27/03/1925	Aw
83292	Ituaçu	BA	-13.81	-41.30	531.43	18/02/1973	Bsh
83186	Jacobina	BA	-11.19	-40.47	484.74	01/12/1912	Aw
83591	João Monlevade	MG	-19.83	-43.12	859.84	01/01/1961	Am
83692	Juiz de Fora	MG	-21.77	-43.35	939.96	01/01/1910	Cwa
83687	Lavras	MG	-21.76	-45.00	918.84	18/02/1911	Cwb
83023	Lavras-UFLA	MG	-21.23	-45.00	842.42	18/02/1911	Cwb
83242	Lençóis	BA	-12.59	-41.39	438.74	01/09/1931	Aw
82994	Maceió	AL	-9.67	-35.70	64.50	01/01/1909	Aw

83090	Monte Santo	BA	-10.46	-39.33	464.60	15/05/1913	Bsh
82792	Monteiro	PB	-7.88	-37.08	603.66	14/01/1940	Aw
83033	Palmas	TO	-10.19	-48.33	280.00	08/10/1993	Aw
82992	Palmeira dos Índios	AL	-9.48	-36.70	274.90	01/01/1928	Bsh
83531	Patos de Minas	MG	-18.53	-46.44	940.28	23/10/1947	Cwb
82882	Paulistana	PI	-8.13	-41.14	374.22	22/09/1975	Bsh
83228	Peixe	TO	-12.01	-48.35	242.49	01/05/1975	Aw
82780	Picos	PI	-7.04	-41.49	207.93	01/11/1923	Bsh
82996	Porto de Pedras	AL	-9.19	-35.44	50.02	14/03/1927	Am
83332	Posse	GO	-14.10	-46.38	825.64	04/08/1975	Aw
83373	Roncador	DF	-15.93	-47.88	1100.57	28/05/1979	Aw
83441	Salinas	MG	-16.17	-42.33	471.32	05/03/1925	Aw
82689	São Gonçalo	PB	-6.75	-38.22	233.06	08/10/1938	Aw
83688	São João Del Rei	MG	-21.33	-44.28	991.00	01/01/1961	Cwa
83088	Senhor do Bonfim	BA	-10.46	-40.18	558.24	01/01/1940	Aw
83190	Serrinha	BA	-11.63	-38.96	359.63	01/02/1904	Aw
82797	Surubim	PE	-7.83	-35.74	418.32	01/10/1929	Aw
82879	São João do Piauí	PI	-8.35	-42.26	235.33	30/09/1975	Bsh
83235	Taguatinga	TO	-12.40	-46.42	603.59	22/12/1915	Aw
82683	Tauá	CE	-6.00	-40.42	398.77	01/02/1962	Bsh
82789	Triunfo	PE	-7.82	-38.12	1105.00	01/06/1953	Aw
83594	Usiminas	MG	-19.49	-42.53	298.60	01/01/1961	Am
82870	Vale do Gurgueia	PI	-8.42	-43.74	265.00	01/08/1978	Aw
83642	Viçosa	MG	-20.76	-42.86	689.73	01/10/1919	Cfa

Daily reference crop ET was calculated using maximum and minimum air temperature, mean relative humidity, mean wind speed, and daily bright sunshine hours as input variables. Reliable estimates of ET_0 depends on the quality of weather data (Allen, 2008), which becomes an even more critical issue when datasets come from conventional weather stations that are man operated. Therefore, besides the quality control procedures adopted by the INMET, visual and graphical inspections in the data were performed for the occurrence of unacceptable values given the expected range according to the time of year and location. Whenever possible, missing data was filled as averages of values of the previous and subsequent days. The absence of data for three or more consecutive days led to their elimination from the historical series.

2.2 | Reference crop evapotranspiration

The reference crop ET was estimated on a daily basis with the Penman-Monteith equation standardized in the FAO 56 manual (Allen et al., 1998). The FAO56-PM

approach has been widely tested and is seen to be the best to simulate the amount of water lost by an expanse of healthy clipped grass of 12 cm height and surface resistance of 70 s/m under adequately supply of water. We used the software REF-ET (Allen, 2016) developed at the University of Idaho (available at <http://www.uidaho.edu/cals/kimberly-research-and-extension-center/research/water-resources/ref-et-software>) to calculate ET_o as

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \left(\frac{900}{T_a + 273} \right) U_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34U_2)} \quad (1)$$

where ET_o is the reference crop ET (mm d^{-1}), R_n is net radiation ($\text{MJ m}^{-2} \text{d}^{-1}$), G is the soil heat flux ($\text{MJ m}^{-2} \text{d}^{-1}$), with $G = 0$ in a 24-h period, Δ is the slope of the saturation vapor pressure curve ($\text{kPa } ^\circ\text{C}^{-1}$), U_2 is the wind speed at 2 m height (m s^{-1}), T_a is the mean air temperature ($^\circ\text{C}$), e_s is the saturation vapor pressure of air (kPa), e_a is the actual vapor pressure of air (kPa), and γ is the psychrometric constant ($\text{kPa } ^\circ\text{C}^{-1}$).

2.3 | Temporal trend analysis

The nonparametric Mann-Kendall test (Mann, 1945; Kendall, 1975) was used to investigate the trend of ET_o related variables across the SFRB. This test has been extensively used to detect trends in atmospheric and hydrologic time series (Salmi et al., 2002; Zheng et al., 2009; Moratiel et al., 2011; Gocic and Trajkovic, 2013). The test indicates the degree to which a trend is consistently increasing (positive) or decreasing (negative) over time. The objective is to test the null hypothesis (H_0) of no trend against the alternative hypothesis (H_1) of the existence of an increasing or decreasing monotonic trend.

Gilbert (1987) gives the steps for the application of the Mann-Kendall test for the case where the number of data is higher than ten ($n \geq 10$), which is the case for the selected SFRB weather stations (Table 1). That procedure starts with the calculation of the Mann-Kendall statistic S as follows:

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^n \text{sgn}(x_j - x_k) \quad (2)$$

where n is the number of data and $\text{sgn}(x_j - x_k)$ is an indicator function with $j > k$, and

$$sgn(x_j - x_k) = \begin{cases} +1 & x_j - x_k > 0 \\ 0 & x_j - x_k = 0 \\ -1 & x_j - x_k < 0 \end{cases} \quad (3)$$

When $n \geq 10$, the statistic S is approximately normally distributed, and the next step is to calculate the variance of S by the following equation, which takes into account that ties (equal values) may exist in the time series:

$$Var(S) = \frac{[n(n-1)(2n+5) - \sum_{p=1}^q t_p(t_p-1)(2t_p+5)]}{18} \quad (4)$$

where q is the number of tied groups and t_p is the number of data in the p^{th} group.

In the sequence, the Z-statistic test (normal approximation) is calculated from values of S and $Var(S)$ as follows:

$$Z = \begin{cases} \frac{S-1}{\sqrt{Var(S)}} & S > 0 \\ 0 & S = 0 \\ \frac{S+1}{\sqrt{Var(S)}} & S < 0 \end{cases} \quad (5)$$

The presence of a statistically significant trend is evaluated using the Z value. A positive value of Z indicates an upward trend and a negative value a downward trend. The existence of an upward or downward monotonic trend was tested at $\alpha = 0.05$ and $\alpha = 0.01$ level of significance (a two-tailed test), such that, H_0 was rejected when the absolute value of Z was larger than $Z_{1-\alpha/2}$, this values being obtained from cumulative distribution tables.

According to Gilbert (1987), the magnitude of a trend or true slope (change per unit time) may be estimated with linear regression methods or determined with the technique developed by Sen (Sen, 1968). Restrictions on the use of the first approach exist if there are gross errors or outliers in the data, which is not a problem for the latter method, with the advantage that the slope can be computed when data are missing (Gilbert, 1987).

The Sen's nonparametric method is used when the trend can be assumed linear as follows:

$$f(t) = Qt + B \quad (6)$$

where Q is the slope and B is a constant. The value of Q (the Sen's estimator of the slope) is obtained by firstly calculating the slopes of all data pairs:

$$Q_i = \frac{x_j - x_k}{j - k} \quad (7)$$

where $j > k$. If there is only one datum per time period, one gets as many as $N = n(n-1)/2$ slope estimates Q_i and the Sen's estimator of the slope is the median of these N values.

In this paper, trend analysis was performed on an annual basis over the study period (maximum of 55 years, according to Table 1). Then, for a single weather station, the trend was based on mean annual values (one value/station/year), and the trend representative of the entire basin was obtained from spatial means (one value/all stations/year). The same procedure was applied to total annual ET_o data. More detailed trend analysis has been performed for shorter time steps as well (monthly and seasonal) (Xie and Zhu, 2013; Donohue et al., 2010; Gocic and Trajkovic, 2014).

As suggested by Tabari & Talee (2013), the relative change of a variable over time was obtained as:

$$RC = \frac{n\beta}{|\bar{\alpha}|} 100 \quad (8)$$

where RC is the relative change (%), n is the time series size, β is the magnitude of the time series trend, and $\bar{\alpha}$ is the mean value of the data series.

2.4 | Attribution of changes in ET_o

Equation 1 can be rewritten as the sum of two terms (ET_{oE} as the energetic and ET_{oA} as the aerodynamic term):

$$ET_o = ET_{oE} + ET_{oA} = \frac{0.408\Delta(R_n - G)}{\Delta + \gamma(1 + 0.34U_2)} + \frac{\gamma\left(\frac{900}{T_a + 273}\right)U_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34U_2)} \quad (9)$$

Each term can have different impacts on ET_o estimation. Roderik et al. (2007) and Donohue et al. (2010) used a differential form of Equation 9 to show that time changes in ET_o can be attributed to change in ET_{oE} and ET_{oA} . Therefore:

$$\frac{dET_o}{dt} = \frac{dET_{oE}}{dt} + \frac{dET_{oA}}{dt} \quad (10)$$

In the energetic term, input variables are R_n , T_a , and U_2 . With Δ as a function of T_a (Allen et al., 1998) the ET_{oE} term is composed of the sum of three derivatives as follows:

$$\frac{dET_{oE}}{dt} = \frac{\partial ET_{oE}}{\partial \Delta} \frac{d\Delta}{dT_a} \frac{dT_a}{dt} + \frac{\partial ET_{oE}}{\partial R_n} \frac{dR_n}{dt} + \frac{\partial ET_{oE}}{\partial U_2} \frac{dU_2}{dt} \quad (11)$$

Applying the right-hand side partial derivatives of Equation 11 to the ET_{oE} component of Equation 9 results in the following expressions:

$$\frac{\partial ET_{oE}}{\partial \Delta} \frac{d\Delta}{dT_a} \frac{dT_a}{dt} = \frac{0.408\gamma R_n (1 + 0.34U_2)}{[\Delta + \gamma(1 + 0.34U_2)]^2} \frac{d\Delta}{dT_a} \frac{dT_a}{dt} \quad (12)$$

$$\frac{\partial ET_{oE}}{\partial R_n} \frac{dR_n}{dt} = \frac{0.408\Delta}{\Delta + \gamma(1 + 0.34U_2)} \frac{dR_n}{dt} \quad (13)$$

$$\frac{\partial ET_{oE}}{\partial U_2} \frac{dU_2}{dt} = - \frac{0.13872\Delta\gamma R_n}{[\Delta + \gamma(1 + 0.34U_2)]^2} \frac{dU_2}{dt} \quad (14)$$

In the aerodynamic term, input variables T_a , U_2 , e_s , and e_a . Like Δ , e_s is also a function of T_a only (Allen et al., 1998) and ET_a can be expressed as the sum of four derivatives as indicated:

$$\frac{dET_{oA}}{dt} = \frac{\partial ET_{oA}}{\partial \Delta} \frac{d\Delta}{dT_a} \frac{dT_a}{dt} + \frac{\partial ET_{oA}}{\partial e_s} \frac{de_s}{dT_a} \frac{dT_a}{dt} + \frac{\partial ET_{oA}}{\partial e_a} \frac{de_a}{dt} + \frac{\partial ET_{oA}}{\partial U_2} \frac{dU_2}{dt} \quad (15)$$

The following equations result when the partial derivatives on the right-hand side of Equation 15 are applied to the ET_a component of Equation 9:

$$\frac{\partial ET_{oA}}{\partial \Delta} \frac{d\Delta}{dT_a} \frac{dT_a}{dt} = - \frac{\gamma \left(\frac{900}{T_a + 273} \right) U_2 (e_s - e_a)}{[\Delta + \gamma(1 + 0.34U_2)]^2} \frac{d\Delta}{dT_a} \frac{dT_a}{dt} \quad (16)$$

$$\frac{\partial ET_{oA}}{\partial e_s} \frac{de_s}{dT_a} \frac{dT_a}{dt} = \frac{\gamma U_2 \left(\frac{900}{T_a + 273} \right)}{\Delta + \gamma(1 + 0.34U_2)} \frac{de_s}{dT_a} \frac{dT_a}{dt} \quad (17)$$

$$\frac{\partial ET_{oA}}{\partial e_a} \frac{de_a}{dt} = - \frac{\gamma U_2 \left(\frac{900}{T_a + 273} \right)}{\Delta + \gamma(1 + 0.34U_2)} \frac{de_a}{dt} \quad (18)$$

$$\frac{\partial ET_{oA}}{\partial U_2} \frac{dU_2}{dt} = \frac{\gamma(\Delta + \gamma) \left[\left(\frac{900}{T_a + 273} \right) (e_s - e_a) \right]}{[\Delta + \gamma(1 + 0.34U_2)]^2} \frac{dU_2}{dt} \quad (19)$$

The summation of Equations 12, 16, and 17 quantitatively represents the changes in ET_o (dET_o/dt) due to changes in T_a (dT_a/dt) under the assumptions that: (a) it is negligible the effect of dT_a/dt on dR_n/dt as the longwave component of R_n is a function of air temperature and (b) Δ and e_s are a function of T_a only (Roderick et al., 2007; Donohue et al., 2010; Tang et al., 2011; Xie and Zhu, 2013). The impact of dU_2/dt on dET_o/dt is given by summing Equations 14 and 19 since U_2 is a variable in both terms of the FAO56-PM equation. Such procedures resulted in four equations, each one representing the effects of the four primary driving variables of ET_o , as listed below:

$$\frac{\partial ET_o}{\partial T_a} \frac{dT_a}{dt} = \frac{\partial ET_{oE}}{\partial \Delta} \frac{d\Delta}{dt} \frac{dT_a}{dt} + \frac{\partial ET_{oA}}{\partial \Delta} \frac{d\Delta}{dt} \frac{dT_a}{dt} + \frac{\partial ET_{oA}}{\partial e_s} \frac{de_s}{dt} \frac{dT_a}{dt} \quad (20)$$

$$\frac{\partial ET_o}{\partial R_n} \frac{dR_n}{dt} = \frac{\partial ET_{oE}}{\partial \Delta} \frac{dR_n}{dt} \quad (21)$$

$$\frac{\partial ET_o}{\partial e_a} \frac{de_a}{dt} = \frac{\partial ET_{oA}}{\partial e_a} \frac{de_a}{dt} \quad (22)$$

$$\frac{\partial ET_o}{\partial U_2} \frac{dU_2}{dt} = \frac{\partial ET_{oE}}{\partial U_2} \frac{dU_2}{dt} + \frac{\partial ET_{oA}}{\partial U_2} \frac{dU_2}{dt} \quad (23)$$

3 | RESULTS AND DISCUSSION

3.1 | Temporal trend of ET_o and driving variables

Trends in reference ET and meteorological variables have been investigated in many parts of the world to assess impacts of the ongoing process of global warming on atmospheric demand for water vapor.

As mentioned, ET_o estimates with Penman-type equations like the FAO56-PM approach require measurements of air temperature, solar radiation, relative humidity, and wind speed. Climatic changes are known to affect the dynamics of such variables

(Donohue et al.; 2010), which in turn affect the variation of ET_o over time in a given region. Figure 2 shows the trend for air temperature (mean, maximum, and minimum), wind speed, sunshine hours and net radiation, and actual vapor pressure.

Time trend of ET_o calculated with the FAO56-PM approach is shown across the SFRB in Figure 2. For the study period (55 years), the ET_o trend was positive (increasing with time) in 88 sites and negative (decreasing with time) in 13 sites. The positive trends are widespread in the basin while the negative trends are concentrated in the upper and lower parts of the basin.

Data shown in Table 2 represent the extreme cases (increase and decrease) of climate changes for some weather observatories within the SFRB. It was possible to observe that significant increase ($p < 0.01$) in vapor pressure deficit (VPD), combined with the increase in mean air temperature, contributes to increments in ET_o along the studied period; this can be observed for the Araxá site. The higher the saturation deficit, the lower the relative air humidity, due to increments in air temperature, which leads to high water vapor demand by the atmosphere, significantly contributing to the increase in ET_o at monthly scale (ZHAO et al., 2014; ALLEN et al., 1998).

TABLE 2 Trends in variables related to ET_o calculation with the FAO-PM model for some selected sites in the São Francisco River Basin (SFRB).

Station ID	T_a	U_2	R_n	RH	VPD	ET_o	
	(°C)	(m s ⁻¹)	(MJ m ⁻² d ⁻¹)	(%)	(kPa)	(mm d ⁻¹)	(RC %)
82989	-0.0018 ^{ns}	-0.0083 ^{ns}	-0.0262*	0.383**	-0.0109**	-0.0167*	-12.09
82890	0.0066 ^{ns}	-0.0032 ^{ns}	0.0131*	0.297**	-0.0078**	-0.0123**	-11.21
83579	0.0472**	0.0085 ^{ns}	0.0047*	-0.258**	0.0089**	0.0192**	24.94
83689	0.0206**	-0.0008 ^{ns}	-0.0191**	0.022 ^{ns}	-0.0008**	-0.0038*	-6.54
83179	0.0459**	-0.0161**	0.0134**	-0.27**	0.0148**	0.0083*	5.17
82784	0.0487**	-0.0158**	0.0115*	-0.24**	0.0137**	0.0081*	5.02
83587	0.0314**	-0.0011 ^{ns}	0.012**	-0.199**	0.006**	0.0097**	13.19
83288	0.0541**	-0.0136**	0.0063 ^{ns}	-0.165*	0.0013 ^{ns}	0.0019 ^{ns}	1.61

Note. Based on the Mann-Kendall test: ^{ns} not significant; ** significant at 0.05 probability level; * significant at 0.01 probability level.

In general, when the saturation vapor pressure decreases along with the slope of the saturation vapor pressure curve, a significant increase occurs in the energy term (XIE & ZHU, 2013). The diffusion of the water vapor produced and that is contact with the leaf surface, and the atmosphere is mainly attenuated by the actual water vapor. Hence, when this layer is saturated, there is a significant amount of water molecules leaving the

leaf surface and changing to gaseous state, and this virtually stops evapotranspiration, which explains the effective participation of actual and saturation vapor pressures in the variations of ET_o rates (VAREJÃO-SILVA, 2006).

Net radiation had effective participation in the climatic alterations of ET_o in all stations. Even with large influence of VPD, the absence of significant annual trends ($p < 0.05$) of R_n was sufficient to stabilize ET_o along the years, as observed in the city of Bom Jesus da Lapa. Alterations in solar radiation over time, combined with factors such as high levels of cloudiness, emissions of aerosols and air pollution, have caused abrupt changes in ET_o variation rates, which confirms the impact of solar radiation on ET_o and the existence of climate changes (NORRIS & WILD, 2009; PAPAIOANNOU et al., 2011; LIU & ZHANG, 2013).

Geographic location and climate characteristics are factors that contribute to the change in the relative rate of increase or decrease in ET_o (ZHENG et al., 2009; WANG et al., 2013). This can be observed in Figure 2, in which the stations of Barra and Barbalha are defined by the 'BSH' climate, according to the updated climate classification of Köppen-Geiger, proposed by Kottke et al. (2006). These localities present similar trends of the ET_o key variables (Table 1), respectively showing the increase in water vapor pressure deficit and increase in temperature, consequently reduction in the relative air humidity. These localities are characterized by dry climates represented by Steppes (BS) and by high mean annual temperatures, above 18°C (h) (KÖPPEN-GEIGER, 1961). These results can be explained by the lower amount of water vapor transported by the wind in drier climates compared with more humid climates (TANG et al., 2011; WANG et al., 2013; ALLEN et al., 1998). In contrast, in the relatively humid region in the cities of Água Branca and Arcoverde, relative humidity was more sensitive than air temperature, which caused these reductions in ET_o over time (Table 1).

FIGURE 2 Spatial distribution of ET_0 trends in the São Francisco River basin.

An analysis of distribution of the main meteorological variables contemplating the entire basin is represented by Figure 2. The scenario in the entire SFRB is of increase in the values of the climatic variables, with effects on evapotranspiration (85% of the basin with increase) (Figure 3) and on rainfall (52% of the basin with decrease), both determined in the water balance, since they represent the entry and exit of water in the

soil-plant-atmosphere system. For the other variables, more than half of the basin has shown increases in net radiation, water vapor pressure deficit, and air temperature. Wind speed is the only variable with higher percentage with a decrease (55% of the basin area).

FIGURE 3 Distribution of frequency for the trends of meteorological variables in the entire São Francisco River basin

3.2 | Sensitivity analysis and impacts of ET_o input variables

Table 3 presents the partition of the contributions of the same stations cited in Table 1, also representing a range of results for the sensitivity analysis of each term of the FAO56-PM equation. In the stations with reduction in ET_o rates, especially in Água Branca and Arcoverde, there was higher sensitivity of the actual water vapor pressure (e_a) and it led to greater contribution of the aerodynamic term in these stations. For stations with increase in ET_o rates, the energy term starts to have higher contribution, while there is a reduction in the participation of the actual water vapor pressure and a positive contribution of the saturation pressure (e_s) and especially net radiation.

As suggested by McCuen (1974), for regions close to the ocean, water vapor availability serves as a barrier against the increase in evaporation rates and, therefore, variation in the humidity level influences the gradient and variation of evapotranspiration rates. The lower the contribution of e_a , the higher the water vapor pressure deficit and the higher the ET_o . The increment in net radiation (R_n) sensitivity compared with the contribution of the slope of the water vapor pressure curve played a fundamental role in

the alterations of the energy term, by either contributing to reducing ET_o rates in stations where there were decreases of R_n (for instance, Barbacena), or increasing along with air temperature (for instance, Araxá).

TABLE 3 Sensitivity of the terms and their components of the partial derivatives

Station ID	Energy term				Aerodynamic term				
	Δ	R_n	U_2	ET_{oE}	Δ	e_s	e_a	U_2	ET_{oA}
	$\frac{\partial ET_{oE}}{\partial \Delta} \frac{d\Delta}{dt}$	$\frac{\partial ET_{oE}}{\partial R_n} \frac{dR_n}{dt}$	$\frac{\partial ET_{oE}}{\partial U_2} \frac{dU_2}{dt}$	$\frac{dET_{oE}}{dt}$	$\frac{\partial ET_{oA}}{\partial \Delta} \frac{d\Delta}{dt}$	$\frac{\partial ET_{oA}}{\partial e_s} \frac{de_s}{dt}$	$\frac{\partial ET_{oA}}{\partial e_a} \frac{de_a}{dt}$	$\frac{\partial ET_{oA}}{\partial U_2} \frac{dU_2}{dt}$	$\frac{dET_{oA}}{dt}$
	mm year ⁻²								
82989	-0.046	2.084	0.228	2.267	0.033	0.175	-7.596	-1.008	-8.396
82890	0.171	1.141	0.071	1.383	-0.156	1.114	-6.543	-0.445	-6.032
83579	0.866	0.371	-0.254	0.982	-0.521	4.141	1.311	1.674	6.605
83689	0.373	-1.806	0.018	-1.414	-0.132	1.215	-0.899	-0.085	0.097
83179	0.929	1.349	0.422	2.701	-1.032	3.962	1.255	-4.256	-0.071
82784	0.931	1.157	0.386	2.476	-1.032	3.971	0.771	-3.879	-0.169
83587	0.328	-1.184	0.038	-0.818	-0.193	1.076	0.777	-0.266	1.395
83288	0.999	0.659	0.353	2.012	-0.760	2.792	-0.335	-3.311	-1.615

The distribution of the participation of meteorological variables in each term of the Penman-Monteith equation is represented in Figure 4. For the energy term, R_n and Δ derivatives show the most significant contributions and, combined, in general, they have a great impact on ET_o calculation and even provide the basis for various methods of estimation. The aerodynamic term, in theory, is defined according to the general equation of Slatyer-McIlroy (1961), based on surface and aerodynamic resistances and water vapor pressure deficit. Such relationship is confirmed by the major percentage of wind speed within the aerodynamic term followed by actual and saturation pressures.

FIGURE 4 Percentages of participation of meteorological variables in the partial derivatives of the energy and aerodynamic terms for the entire São Francisco River basin.

Table 4 shows the partition of energy and aerodynamic terms and their respective meteorological components for the entire São Francisco River basin. There is a predominance of the energy term over the aerodynamic term, as both converge to increase the evapotranspiration in the entire territory of the basin.

The main meteorological component causing an increase in ET_o variation rates within the aerodynamic term is VPD, since the other components of this term contribute to reducing evapotranspiration. For the energy term, all meteorological components contribute to increasing ET_o . Results indicate an increment in the variation rates of approximately $2.424 \text{ mm year}^{-2}$ in the entire basin. These results, from the climatic point of view, contrast with those reported by Donohue et al. (2010), Tang et al. (2011) and Xie et al. (2013). These authors found reductions in the evaporation rates, with the aerodynamic term as the factor of highest weight.

The contribution of wind in the aerodynamic term followed the same trend found by these authors, i.e., negative contribution to evapotranspiration variations along the entire historical series. In percentage terms, in 81% of the basin territory, the energy term prevails over the aerodynamic term.

TABLE 4 Partition of sensitivity as a function of the energy and aerodynamic terms of the FAO-56 Penman-Monteith equation.

dET_o/dt (Change in ET_o)							
dET_{oE}/dt (Change in ET_{oE})			dET_{oA}/dt (Change in ET_{oA})				
mm year ⁻²			mm year ⁻²				
Sat. vapor pressure slope	Net radiation	Wind speed	Sat. vapor pressure slope	Wind speed	Vapor pressure deficit		
$\frac{\partial ET_{oE}}{\partial \Delta} \frac{d\Delta}{dt}$	$\frac{\partial ET_{oE}}{\partial R_n} \frac{dR_n}{dt}$	$\frac{\partial ET_{oE}}{\partial U_2} \frac{dU_2}{dt}$	$\frac{\partial ET_{oA}}{\partial \Delta} \frac{d\Delta}{dt}$	$\frac{\partial ET_{oA}}{\partial U_2} \frac{dU_2}{dt}$	$\frac{\partial ET_{oA}}{\partial e_s} \frac{de_s}{dt}$	$\frac{\partial ET_{oA}}{\partial e_a} \frac{de_a}{dt}$	
0.638	0.592	0.064	-0.495	-0.500	2.341	-0.215	
						2.126	
	1.294			1.130			
			2.424				

Figure 5 represents the distribution of frequency of the partial derivatives for the entire São Francisco River basin. Confirming what was observed in Table 3, the energy term represents higher weight in the calculation of the evapotranspiration. Net radiation (Figure 5A) in 72% of the São Francisco River basin contributes to increasing evapotranspiration rates. Following this same trend, air temperature (Figure 5B), in 97%

of the area, contributes to the increase in evapotranspiration rates. On the other hand, for the aerodynamic term, the roles are reversed. As shown in Figures 5C and 5D, respectively, in 56% of the localities wind speed acts to reduce evapotranspiration rates, followed by actual water vapor pressure, which also has negative contribution to evapotranspiration calculation, observed in 83% of the localities studied.

FIGURE 5 Distribution of frequency of the partial derivatives of meteorological variables in the São Francisco River basin.

3.3 | Partition of the contribution of input variables in ET_o calculation

Figure 6 presents the spatial distribution of the percent attributions of the input variables in ET_o calculation at monthly and daily scales. In Figure 6A, solar radiation and relative air humidity have the greatest contributions in ET_o calculation at monthly scale.

Due to the great influence of water vapor deficit, the relative air humidity at monthly scale has a higher contribution to ET_o . This is observed mainly in the stations of Água Branca and Arcoverde, where RH increased and water vapor pressure deficit decreased, thus causing reductions in ET_o over time (Table 1). Likewise, in the stations of Araxá and Aracaju, the reduction of humidity along the years allowed significant increase in ET_o .

Daily spatialization of the percent attributions is presented in Figure 6B. Air temperature and solar radiation combined represent more than 70% of the sensitivity caused in ET_o calculation. Different from what happens at monthly scale, relative air humidity no longer plays a major role in the percentages and now gives way to air temperature. In the region of the Middle São Francisco, wind speed enters as a key factor with high percentages (on the order of 30%), even reaching the same relevance of solar radiation, and together have a major percentage of 65% in the stations of Barreiras, Barra and Bom Jesus da Lapa.

FIGURE 6 Percent attribution of monthly (A) and daily (B) impacts of the input variables on ET_0 calculation.

At both monthly and daily scale, relative air humidity has more significant contribution to ET_0 in the stations of Arcoverde and Água Branca. In these stations, these variables have great influence, because they promote reductions in daily and monthly ET_0 rates. At daily scale, solar radiation starts to have greater impact on ET_0 calculation due to the non-variation caused by the mean of the daily values used in the monthly calculation of ET_0 . Thus, a reference day (15th day of each month) was selected as the one representing all days of the month, as proposed by Allen (1998). Because of that, the means smooth R_s and R_n values in monthly periods, which does not occur for the other variables, since there is not an abrupt variation in VPD at daily scale as occurs with solar radiation.

CONCLUSIONS

The scenario in the entire São Francisco River basin is of increase in the values of the climatic variables, particularly evapotranspiration, with increase in 85% of the basin area, and rainfall, with decrease in 52% of the basin area.

The energy term, mainly represented by air temperature and net radiation, surpasses the aerodynamic term in 81% of the basin territory.

Water vapor pressure deficit at monthly scale is the meteorological variable with higher weight on ETo.

At monthly scale, relative air humidity had greater contribution, followed by solar radiation. At daily scale, the roles are reversed; solar radiation starts to have greater impact on ETo calculation.

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Competing Interests

Author Neilon Duarte da Silva and Aureo Silva de Oliveira declare they have no financial interests. The authors have no relevant financial or non-financial interests to disclose.

Author Contributions and participate

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Neilon Duarte da Silva, Aureo Silva de Oliveira. The first draft of the manuscript was written by Aureo Silva de Oliveira and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Data Availability

The datasets generated during and/or analysed during the current study are not publicly available due to as they are source of the National Institute of Meteorology (INMET) but are available from the corresponding author on reasonable request.

Code availability

Not applicable

Ethics approval

Not applicable

Consent for publication

The authors agree with the publication of the article and are responsible for the content

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