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Reference evapotranspiration trends in the region of the Urucuia Aquifer System – Brazil

Tendências na evapotranspiração de referência na região do Sistema Aquífero Urucuia - Brasil

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ABSTRACT

The Urucuia Aquifer System (UAS) is an important groundwater source in Brazil, where declining river flows and groundwater table levels were observed in the past years. Changes in actual evapotranspiration due to an increase in atmospheric water demand was among many driving causes that were pointed out to explain lowering observed flows. To assess evaporative demand across the Urucuia Aquifer System, in this study we evaluated possible trends in reference evapotranspiration with the FAO Penman-Monteith method, using the ERA5 atmospheric reanalysis data for the period of 1960-2020 after a comparison with ground-based observed data. Our findings revealed a generally good agreement between ERA5 data and ground-based measurements and significant increasing trends of reference evapotranspiration. This increase seems to be caused by increases in air temperature, surface radiation and wind speed. Within the 1960 to 2020 analyzed period, the last two decades from 2000 onward had the highest evaporative demand across the UAS.

Keywords: Urucuia Aquifer System; Reference evapotranspiration; ERA5.

RESUMO

O Sistema Aquífero Urucuia (SAU) é uma importante fonte de água subterrânea no Brasil, no qual foram observadas reduções nas vazões dos rios e nos níveis subterrâneos nos últimos anos. A mudança na evapotranspiração real devido a um aumento na demanda atmosférica de água foi uma das muitas causas apontadas para explicar a redução observada nas vazões. Para avaliar a demanda evaporativa na região do Sistema Aquífero Urucuia, neste estudo avaliamos possíveis tendências na evapotranspiração de referência com o método FAO Penman-Monteith utilizando os dados de reanálise atmosférica ERA5 para o período de 1960-2020 após uma comparação com dados medidos em estações. Os resultados apontaram uma boa concordância entre os dados ERA5 e as observações em estações meteorológicas, e também indicaram tendências crescentes na evapotranspiração de referência. Este aumento parece ser causado pelo aumento da temperatura do ar, da radiação superficial e da velocidade do vento. No período analisado de 1960 a 2020, as últimas duas décadas, a partir dos anos 2000, apresentaram a maior demanda evaporativa em todo o SAU.

Palavras-chave: Sistema Aquífero Urucuia; Evapotranspiração de referência; ERA5.

INTRODUCTION

The Urucuia Aquifer System (UAS) is a set of unconfined sedimentary aquifers that extends over an area of approximately 125 thousand km^2 in Central and Northeastern Brazil (Barbosa, 2016; Gaspar, 2006; Kiang & Silva, 2015). The UAS forms a plateau with maximum elevations close to 1,000 meters and a slight slope towards the east (Barbosa, 2016; Gaspar, 2006). This plateau is drained by several rivers, most of which are tributaries of the São Francisco river. Climate in the region is characterized by distinct wet and dry seasons, with most precipitation occurring during austral summer, and average yearly precipitation ranging between 800 and 1,200 mm (Vieira, 2021).

The region was originally covered by the Cerrado type of vegetation (Eiten, 1972). However, during the last decades, land use in the region was progressively changed to pasture and agriculture (Lima et al., 2022; Andrade et al., 2021; Serviço Geológico do Brasil, 2019). This change was motivated by characteristics that are favorable to agriculture, such as climate, relief and, more recently, availability of water for irrigation. The UAS region is part of one of the irrigation hot-spots identified by the National Water Agency, and is still undergoing expansion of irrigated areas, primarily cultivating soybean, cotton, corn and coffee (Agência Nacional de Águas e Saneamento Básico, 2020). The main irrigation method is center pivot, with an estimated water consumption for irrigation around 1,000 hm^3/year in the western portion of Bahia state, which comprises around 40% of the of the UAS area (Agência Nacional de Águas e Saneamento Básico, 2021a).

The UAS is one of the most important sources of groundwater in the country and has a major contribution to the maintenance of baseflows in rivers that are part of the hydrographic regions of São Francisco, Tocantins-Araguaia and Parnaíba (Barbosa, 2016; Gaspar, 2006; Gonçalves et al., 2020; Vieira, 2021). Therefore, possible changes in the hydrological behavior of the UAS may affect availability of water for irrigation, domestic use and hydropower generation at points located as far as thousand kilometers downstream, such as the lower parts of the São Francisco and Tocantins rivers.

In fact, in recent years, the region has shown changes in hydrological behavior. The main rivers that drain the UAS are showing decreasing trends of streamflow, as was shown by several authors (Reis, 2016; Gonçalves et al., 2016, 2018, 2020; Silva et al., 2021a; Cunha, 2017; Genz & Maia, 2018; Oliveira et al., 2019; Pousa et al., 2019; Marques et al., 2020; Eger et al., 2021; Lucas et al., 2021; Collischonn et al., 2021; Andrade et al., 2021; Lima et al., 2022; Melo, 2022; Mattiuzi & Collischonn, 2023). The decreasing trends in the discharge of several rivers draining the UAS was accompanied by the decline in groundwater storage (Sun et al., 2016; Cunha, 2017; Genz & Maia, 2018; Oliveira et al., 2019; Khaki & Awange, 2019; Marques et al., 2020; Gonçalves et al., 2020; Fontes, 2020; Lucas et al., 2021; Eger et al., 2021; Ribeiro & Rodriguez, 2021; Mattiuzi & Collischonn, 2023).

The analysis of the trends in river discharge and groundwater storage and the attempts to explain its causes brought the UAS to the center of a debate. Several hypotheses have been raised to explain the causes of the observed reductions in water resources across the UAS: climatic variability or change, land use and land cover (LULC) changes, and changes in consumptive water use.

Climatic variability or change may have affected streamflow and groundwater storage through changes in precipitation and evapotranspiration. Negative trends in precipitation over the Brazilian Cerrado region, including the UAS, have been detected by several authors (Hofmann et al., 2023; Pousa & Costa, 2022; Collischonn et al., 2021; Marques et al., 2020; Pousa et al., 2019; Genz & Maia, 2018). However, while some authors emphasize the role of precipitation, others concluded that the changes in precipitation were not significant or that they were insufficient to explain changes in streamflow (Lima et al., 2022; Ribeiro & Rodriguez, 2021; Lucas et al., 2021; Gonçalves et al, 2020).

Motivated by the fact that significant trends were more easily found in streamflow than in precipitation time series (Lima et al., 2022; Silva et al., 2021a, 2022; Gonçalves et al., 2016), several authors suggested that land use and land cover changes play a major role on the observed decline in the discharge of rivers and groundwater storage in the UAS region (Salmona et al., 2023; Melo et al., 2023; Santos et al., 2022; Melo, 2022). However, the way by which LULC changes would lead to decrease in streamflow is not clearly described in these references. In fact, most of the documented empirical evidence about hydrological impacts of land use changes in the world suggests that the effect of LULC change in the UAS should lead to increasing river discharges, which is exactly the opposite of what occurred (Andreassian, 2004).

The attribution of LULC changes as the main cause of hydrological changes is strongly motivated by the correlation in time between river discharge, or groundwater storage, and land use. Reductions in streamflow and groundwater storage were observed in the decades after the 1990's, while the period since the 1980's was marked by a progressive change in land use and vegetation, from native cerrado to agriculture. Over the period from 2002 to 2021, the percentage natural vegetation (of forest and non-forest formations) decreased from 81% to 66%, while the percentage of farming increased from 17% to 31% (Mattiuzi & Collischonn, 2023).

Increases in consumptive water use, mainly for crop irrigation, have been suggested as a driver of river discharge reduction and of total water storage reduction along the last decades (Lima et al., 2022; Lucas et al., 2021; Gonçalves et al., 2016, 2020; Marques et al., 2020; Santos et al., 2020). According to data from the National Water Agency irrigation survey (Agência Nacional de Águas e Saneamento Básico, 2021b), irrigated area in the western Bahia region was approximately 170 thousand hectares in 2019, and projections show this area could more than double until the year 2040, possibly reaching up to 390 thousand hectares. The irrigation hot spot located on western Bahia includes six municipalities and comprises around 40% of the Urucuia Aquifer system area. Current water demands for irrigation on these municipalities are around 32 m^3/s, and projections show an increase up to 75 m^3/s in 2040 (Agência Nacional de Águas e Saneamento Básico, 2021b).

The way in which streamflow reacts to changes in precipitation, vegetation cover or water use for crop irrigation depends largely on how evapotranspiration is affected. This is especially true in regions where average annual precipitation and evapotranspiration have very similar magnitudes, as is the case in the UAS region. In long dry periods, there is considerable uncertainty regarding the sign of the evapotranspiration response (Zhao et al., 2022). On the one hand, it is assumed that real evapotranspiration tends to decrease, due to the lower availability of water in the soil. On the other hand, actual evapotranspiration may increase, as a result of an increase in potential evapotranspiration, which typically occurs in drier periods (Collischonn & Tucci, 2014).

Therefore, several authors analyzed trends in evapotranspiration in the UAS region, or over the whole São Francisco river basin. Their results, however, are somewhat contradictory, with some authors showing a trend of increasing actual evapotranspiration in the UAS (Lucas et al., 2021; Andrade et al., 2021) and others showing minor positive trends of no statistical significance (Gonçalves et al., 2020), or no trends (Ribeiro & Rodriguez, 2021). These contradictory results about the trends in actual evapotranspiration in the UAS region may be related to the variety of the applied methods, the geographical extension of the analysis, and the time period. Increasing trends in actual evapotranspiration could result from increasing trends in potential evapotranspiration, which can be represented by reference evapotranspiration. Therefore, it is interesting to investigate if there are trends in reference evapotranspiration in the UAS region.

The analysis of trends in reference evapotranspiration has been done before in the same region by other authors, but using different datasets and more sparse data, for shorter period of times, and within areas that didn't include or weren't representative of the entire Urucuia Aquifer System region. Melo (2022) and Andrade et al. (2021) used potential evapotranspiration data from Xavier et al. (2016), which was interpolated from weather stations across Brazil, to assess trends and relationship with other variables in the São Francisco River Basin from 1985 to 2019, and in four basins on the UAS from 2000 to 2013, respectively. Lima et al. (2022) used temperature data from the Climate Research Unit database to estimate potential evapotranspiration using the Hargreaves–Samani across ten sub-basins in the São Francisco River Basin from 1985 to 2015. Guimaraes et al. (2019) used daily meteorological data from the NASA POWER system from 1983 to 2018 to estimated potential evapotranspiration across western Bahia region. Silva (2017) used data from meteorological stations from 1961 to 2015 to estimate potential evapotranspiration across the São Francisco River Basin using the FAO Penman Monteith method, but only one station is located within the UAS limits.

As we can see, the analysis of reference evapotranspiration has been done before but using different datasets, which were interpolated or had more sparse coverage, for shorter period of times, and within areas that didn't include or weren't representative of the Urucuia Aquifer System region. In the present work, to address the knowledge gaps identified in previous studies, we assessed trends of reference evapotranspiration and related variables across the entire region of the Urucuia Aquifer System, for a longer period - covering the years from 1960 to 2020, and using an atmospheric reanalysis dataset assessed against ground-based observations.

Scope and aims of the paper

We analyzed possible trends in reference evapotranspiration across the Urucuia Aquifer System region with the FAO Penman-Monteith method (Allen et al., 1998). For this, we used the ERA5 atmospheric reanalysis data, after an evaluation of the performance of this reanalysis dataset compared to the observed data of meteorological variables in automatic meteorological stations.

Reference evapotranspiration is an important component of the hydrologic cycle, essential for water balance studies, hydrologic models, agricultural water assessments, and irrigation (Vanella et al., 2022; Vicente-Serrano et al., 2022; Singer et al., 2021; Mayes et al., 2020; Novick et al., 2016), among other applications. Given the impact of both natural and human-induced occurrences on the environment (Wagener et al., 2010; Milly et al., 2008), it's important to investigate the behavior of reference evapotranspiration, especially at regional and local scales (Fowler et al., 2022; Montanari et al., 2013).

The quantification of changes in reference evapotranspiration on a regional scale is limited by data availability since hydrometeorological ground-based stations have sparse networks and are more locally representative. Ground-based observations may be affected by errors in sensors due to instrument fault or lack of maintenance, and by malfunctioning, resulting in time-series gaps (Vanella et al., 2022). These shortcomings may be overcome by the use of gridded reanalysis datasets, which allow applications over extensive regions (Pelosi et al., 2020).

ERA5 is the fifth generation of ECMWF (European Centre for Medium-Range Weather Forecasts) atmospheric reanalysis of the global climate covering the period from January 1940 to present. ERA5 is produced by the Copernicus Climate Change Service (C3S) at ECMWF (Hersbach et al., 2023). The choice of ERA5 as the source of data for the evaporation calculation is justified because ERA5 is used to estimate actual evapotranspiration within gEESebal (Laipelt et al., 2021), and in a following paper we will investigate trends in actual evapotranspiration estimated using geeSEBAL. ERA5 is recognized as a high-quality product, having been used in many applications such as climate assessments and indicators (Hersbach et al., 2020), drought monitoring systems (Vicente-Serrano et al., 2022) and other studies, including in Bahia (Matsunaga et al., 2023). ERA5 has hourly data of climatic variables in a 0.25° x 0.25° horizontal resolution with global covering, and has been widely used in many studies.

ERA5 data was used to estimate reference evapotranspiration and to compare against other reanalysis products and ground-based measurements across Iran (Nouri & Homaee, 2022) and in different climates and topography in Italy (Vanella et al., 2022; Pelosi et al., 2020). Reference evapotranspiration estimated with ERA5 was also used in the development of a global drought monitoring system based on the Standardized Precipitation Evapotranspiration Index (Vicente-Serrano et al., 2022), in a soil water balance model to study global crop irrigation requirements (Rolle et al., 2021), and for drought estimates using climate projections (Aadhar & Mishra, 2020). These studies had applications from local, regional and global scales. Overall, these studies found good performance of ERA5 data; Vanella et al. (2022) also highlighted the possibility of using reanalysis data where stations ground-based measurements are scarce.

MATERIALS AND METHODS

Study area

The Urucuia Aquifer System (UAS) is situated in central Brazil and covers approximately 125 thousand km^2 across six states (Serviço Geológico do Brasil, 2014) (Figure 1). The UAS is an unconfined aquifer system in the Urucuia geological group, which is located on the morphological plateau of the São Francisco hydrogeological province (Gaspar & Campos, 2007; Gaspar, 2006). Elevations on the plateau range from 240m to 1,049m, with higher altitudes in the western parts (1,000 to 900m) and lower altitudes in the eastern parts (700 to 600m), indicating a moderate dip in the plateau towards the east (Barbosa, 2016; Gaspar, 2006).

According to the Köppen-Geiger climatological classification (Beck et al., 2018) the UAS is situated within the Aw – tropical savanna climate type, characterized by average temperatures above 18°C, distinct wet and dry seasons, with most precipitation occurring during summertime. Dry season occurs from April to September, and wet season from October to March; average annual precipitation varies between 800 mm to 1,200 mm from east to west due to orographic control (Vieira, 2021). The Urucuia Aquifer System is regionally important for surface water resources, since it is responsible for maintaining baseflow of rivers that are part of three major hydrographic regions in Brazil: São Francisco, Parnaíba and Tocantins-Araguaia. Additionally, the UAS supplies water for urban demands, hydropower, and agriculture (Gaspar, 2006).

The natural characteristics of the region where the UAS is situated have been conducive to the development of irrigated agriculture, which started in the 1980s (Silva et al., 2021a; Pimentel, 2011). Today, the UAS is acknowledged as one of the most important irrigation hubs in Brazil (Agência Nacional de Águas e Saneamento Básico, 2020). Over the period from 1985 to 2020, there have been changes in land cover within the UAS: the area covered by Savanna decreased from 48% to 40%, Grasslands reduced from 41% to 30%, while Farming related land cover increased from 3% to 24% (MAPBIOMAS, 2022).

Ground-based meteorological data

We used ground-based meteorological data from Brazil's National Meteorology Institute Dataset (*INMET – Instituto Nacional de Meteorologia*) from 11 automatic stations located in and nearby the region of the Urucuia Aquifer System; data availability ranged from 2007 to 2020 (Instituto Nacional de Meteorologia, 2022); Figure 1 shows stations locations.

Each station dataset has hourly measurements of Solar Radiation (R_s – kJ/m^2), Air Temperature (T_{air} - °C) and Wind Speed measured at 10m height (W_{10m} - m/s). To avoid gap filling uncertainties, we selected only years with more than 99.5% of complete data and then submitted to preliminary analysis. After data collection and pre-processing, data availability ranged from 1 up to 9 years; Table 1 summarizes ground-based meteorological station data.

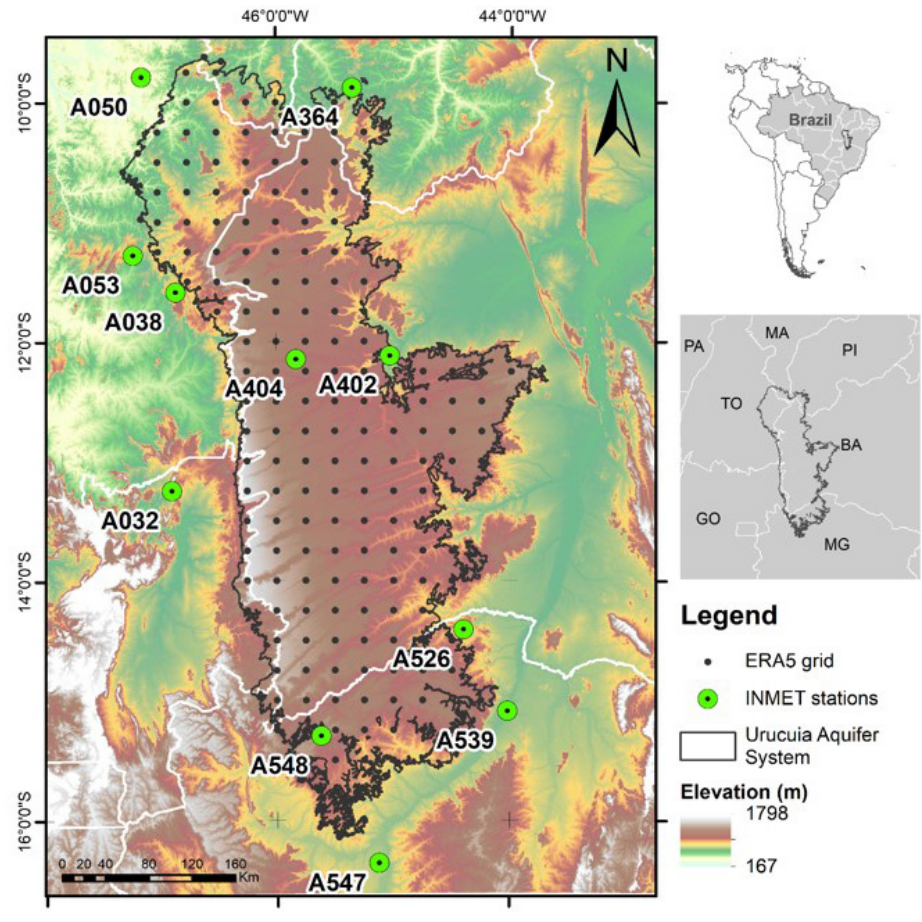

Figure 1. Location of the study area and spatial distribution of ERA5 grid points and INMET stations.

Table 1. Locations and data availability of the ground-based automatic meteorological stations.

ID	Station	Long	Lat	Alt (m)	Years available	N° of years
A032	Monte Alegre De Goiás	-46.89	-13.25	552	2014, 2016	2
A038	Dianópolis	-46.85	-11.59	728	2014, 2017	2
A050	Rio Sono	-47.13	-9.79	291	2020	1
A053	Almas	-47.21	-11.28	503	2018, 2019	2
A364	Gilbués	-45.35	-9.88	425	2011, 2014	4
A402	Barreiras	-45.03	-12.12	474	2007, 200, 2011, 2014, 2015, 2016, 2018, 2020	8
A404	Luiz Eduardo Magalhães	-45.83	-12.15	761	2007, 2010, 2011, 2014, 2016, 2017, 2018, 2019	8
A526	Montalvânia	-44.4	-14.41	519	2008, 2009, 2010, 2011, 2013, 2018, 2019, 2020	8
A539	Mocambinho	-44.02	-15.09	454	2008, 2009, 2010, 2011, 2012, 2016, 2017, 2018, 2020	9
A547	São Romão	-45.12	-16.36	490	2008, 2009, 2011, 2012, 2014, 2017, 2018, 2019	8
A548	Chapada Gaúcha	-45.62	-15.3	873	2008, 2009, 2012, 2015, 2020	5

Reanalysis data

We obtained gridded reanalysis data from ECMWF (*European Centre for Medium-Range Weather Forecasts*) ERA5 in *NetCDF* file format through Climate Change Service Copernicus platform (Hersbach et al., 2023) for the Urucuia Aquifer System region, with 0.25° spatial resolution.

ERA5 is the fifth generation ECMWF reanalysis for the global climate and weather and provides hourly estimates for a large number of atmospheric, ocean-wave and land-surface quantities with a latency of 5 days. ERA5 reanalysis dataset contained hourly data from 1940 to 2020 for the following variables: 2m dewpoint temperature (T_{dew} - °C), 2m temperature (T_{air} - °C), 10m u-component of wind ($Wind_{10m-u}$ – m/s), 10m v-component of wind ($Wind_{10m-v}$ – m/s), and surface solar radiation downwards (R_s – J/m^2). We extracted data from all the 179 ERA5 points within the Urucuia Aquifer as shown in Figure 1.

Data processing and daily reference evapotranspiration estimative

We aggregated ERA5 reanalysis data and ground-based observations at daily time step for analysis and reference evapotranspiration (ET_0) estimation. Daily minimum and maximum air temperature (T_{air}) and dewpoint (T_{dew}) temperature were obtained from hourly data, and T_{air} was estimated by the average of daily maximum and minimum temperature. Solar radiation daily values were aggregated in 24h basis.

Daily wind speed at 2m was calculated using horizontal and vertical components at 10m ($Wind_{10m-u}$ and $Wind_{10m-v}$) adjusted to 2m with the wind profile relationship (Equation 1) as suggested in Allen et al. (1998), where u_2 is the wind speed at 2m above ground surface (m/s), u_z is the measured wind speed at z m above ground surface (m/s), and z is the height of measurement above ground surface, in this case, 10m.

$$u_2 = u_z \frac{4.87}{\ln(67.8z - 5.42)} \tag{1}$$

Daily relative humidity (RH) was calculated as the ratio between actual (e_a) and saturation ($e_0(T)$) vapor pressure, as suggested in Allen et al. (1998), according to Equations 2 to 4.

$$RH = 100 * \frac{e_a}{e_0(T)} \tag{2}$$

$$e_a = 0.6108 * \exp\left(\frac{17.27 * T_{\text{dew}}}{T_{\text{dew}} + 237.3}\right) \tag{3}$$

$$e_0(T) = 0.6108 * \exp\left(\frac{17.27 * T_{\text{air}}}{T_{\text{air}} + 237.3}\right) \tag{4}$$

The Penman-Monteith method as defined in the FAO-56 paper (Allen et al., 1998) was used to calculate daily ET_0 according to Equation 5, where ET_0 is the daily reference evapotranspiration (mm/day), R_n is the surface net radiation (MJ/m^{2}d), G is the soil heat flux density (MJ/m^{2}d), T is the mean daily T_{air} (°C), Δ is the slope of saturation vapor pressure curve at T_{air} (kPa/°C), γ is the psychrometric constant (kPa/°C), e_s is the saturation vapor pressure at T_{air} (kPa), e_a is the average daily actual vapor pressure (kPa), and u_2 is the wind speed at 2m height (m/s). The soil heat flux density was considered to be zero as recommended by Allen et al. (1998).

$$ET_0 = \frac{0.408 * \Delta * (R_n - G) + \gamma * \frac{900}{T + 273} * u_2 * (e_s - e_a)}{\Delta + \gamma * (1 + 0.34 * u_2)} \tag{5}$$

Statistical indicators and trend analysis

We compared results between ERA5 reanalysis data and ground-based observations using the slope of the regression line forced by the origin, Coefficient of Determination (R^2), Root Mean Square Error (RMSE – Equation 6) and Mean Absolute Error (MAE – Equation 7).

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} (S_i - O_i)^2}{n}} \tag{6}$$

$$MAE = \frac{1}{n} \sum_{i=1}^{n} |S_i - O_i| \tag{7}$$

Where S_i is the value from ERA5 dataset, O_i is the observed value from ground-based stations measurements, and n is the number of observations.

Finally, we evaluated trends in the ERA5 dataset for meteorological variables and reference evapotranspiration estimative on the period comprising 1960-2020 using Mann-Kendall test, which was originally developed by Mann (1945) as a non-parametric test for trends and was later modified by Kendall (1975). The Mann-Kendall test does not require assumptions about the underlying probability distribution function of the data (Wang et al., 2011) and is less sensitive to outliers (Hamed, 2008) We used the *python* library *pyMannKendall* (Hussain & Mahmud, 2019) with significance level set to 0.05.

RESULTS AND DISCUSSIONS

We first present the comparison between ground-based and reanalysis data for the variables air temperature, solar radiation and wind speed, and for the estimated relative humidity and reference evapotranspiration. Then we present the investigation of spatial distribution and time series analysis of the five previous variables using only reanalysis dataset for the period of 1960-2020 across de Urucuia Aquifer System region and trend analysis with Mann-Kendall test.

Ground-base and reanalysis data comparison

Table 2 presents the evaluation results obtained by comparing ERA5 reanalysis and ground-based measurements for Air Temperature (T_{air}), Surface Radiation (R_s), Wind Speed at 2m height (W_s), Relative Humidity (RH) and estimated Reference Evapotranspiration (ET_0) for all INMET stations combined, at daily, monthly and yearly time scales; Figure 2 shows scatterplots for all stations in daily, monthly and yearly time scale with the adjusted trend line (dotted red) and the x = y line (black).

Air temperature RMSE ranged from 1.44 °C to 0.96 °C and MAE ranged from 1.14°C to 0.80°C from daily to yearly scale; R^2 had better adjustment in monthly scale, with 0.78; the slope (a) of the adjusted regression lines between variables going through the origin was 1.03 in all time scales, indicating a good adjustment and an overestimation from ERA5 data in relation to ground-based measurements. Average daily temperature presented the best agreement between reanalysis and ground-based measurements; air temperature is an important variable since it controls the atmospheric capacity of holding water, and influences on atmospheric demand for moisture and evapotranspiration (Trenberth et al., 2014). Vanella et al. (2022) studied ground-based and ERA5 data comparisons in seven irrigation districts distributed under different climates and topography Italy and also observed that average air temperature had the most accurate results

Surface radiation R^2 also had better adjustment in monthly scale, with 0.72, and the slope (a) values ranged from 0.96 (daily) to 0.98 (monthly and yearly). Daily results are more scattered in lower values; Trenberth et al. (2014) reported that there are concerns about reconstruction of solar radiation data, since it is very dependent on clouds, which can explain the observed better agreement on higher solar radiation values. Slopes results indicated a slight underestimation of reanalysis surface radiation values in comparison to measured data. It's also noted that one year of the station A404 could be an outlier, since it has higher ground-based Rs than others, which is visible on the monthly and specially the yearly chart; this result explains the lower R^2 observed at yearly level.

Wind speed had the lowest agreements among the analyzed variables; R^2 ranged from 0.28 (daily) to 0.16 (yearly); the slope (a) of the adjusted regression lines was 0.95 in all time scales, which reveals an underestimation of reanalysis data. In Figure 2 it is noticeable that some stations (A402, A404) had ground-based values equal to zero while reanalysis values were non-zero, which could suggest ground-based measurement errors; Trenberth et al. (2014) observed that the confidence on wind measurements is low since instrumentation is sensitive to maintenance and site placement issues.

Relative humidity and reference evapotranspiration were estimated with previous variables, and carried possible measurement errors from the other variables series. Relative Humidity R^2 ranged from 0.59 (daily) to 0.23 (yearly), and slope (a) was around 0.92 to 0.93, indicating an underestimation from reanalysis. Vanella et al. (2022) compared ERA5 and ground-base stations in Italy, and

Table 2. Performance of the comparison of daily, monthly and yearly ERA5 dataset variables and INMET ground-based observations; n is the number of observations in the dataset, a is the slope of the adjusted regression lines between variables going through the origin, RMSE and MAE refer to Root Mean Square Error and Mean Absolute Error, respectively.

		n	a	R^2	RMSE	MAE
T_{air} (°C)	daily	20091	1.03	0.71	1.44	1.14
	monthly	660	1.03	0.78	1.13	0.88
	annual	55	1.03	0.62	0.96	0.80
R_s (MJ/m^2)	daily	20091	0.96	0.56	3.47	2.51
	monthly	660	0.98	0.72	47	36
	annual	55	0.98	0.22	382	275
W_s (m/s)	daily	20091	0.95	0.28	0.68	0.56
	monthly	660	0.95	0.23	0.53	0.45
	annual	55	0.95	0.16	0.45	0.38
RH (%)	daily	20091	0.92	0.59	9.90	7.50
	monthly	660	0.93	0.62	8.04	5.89
	annual	55	0.92	0.23	5.51	4.34
ET_0 (mm)	daily	20091	0.99	0.67	0.66	0.50
	monthly	660	1.00	0.80	10	8
	annual	55	1.00	0.37	84	65

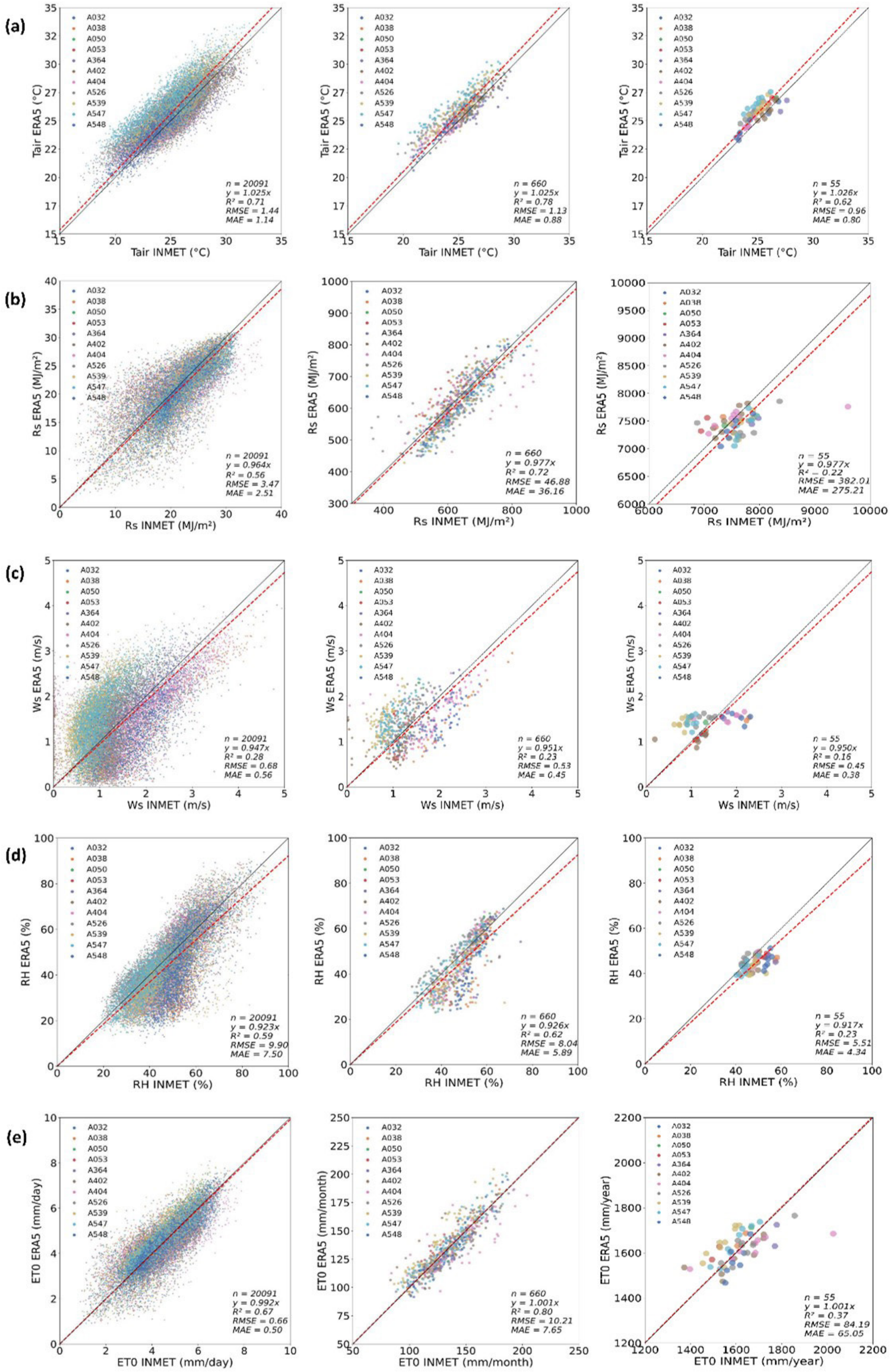

Figure 2. ERA5 versus ground-based data on all stations in daily, monthly and yearly time scales; black line represents x=y, and dotted red line represents linear regression forced by the origin. Sub-plots present results for average air temperature (a), surface radiation (b), wind speed (c), relative humidity (d) and reference evapotranspiration (e).

obtained RMSE values for Relative Humidity ranging from 8.78% to 19.02% at daily scale, our results showed average daily RH RMSE of 9.90%.

Reference evapotranspiration comparison between reanalysis and ground-based data showed good results: the slope (a) of the adjusted regression line ranged from 0.99 (daily) to 1.00 (monthly and yearly), and RMSE varied from 0.67 (daily), 0.80 (monthly) and 0.37 (yearly). In Figure 2 it's possible to see that, at yearly level, again station A404 has a much higher value for ground-based estimation in reference to reanalysis data, as previously seen in the surface radiation plot, and explains lower R^2 at yearly level. Vanella et al. (2022) results for reference evapotranspiration RMSE values ranged from 0.57 mm/day to 0.90 mm/day; we obtained similar results with daily ET_0 RMSE of 0.66 mm/day.

Table 3 and Figure 3 present the summary of residuals of the comparison between ERA5 dataset variables and INMET ground-based observations, for daily, monthly and yearly intervals. For all time scales mean residuals of T_{air} (°C) and W_s (m/s) were above zero, while R_s (MJ/m²) and RH (%) were below zero, indicating that ERA5 data was higher for temperature and wind, and lower for surface radiation and relative humidity in comparison with ground measured data. ET_0 (mm) mean residual was zero for daily values, 0.5 mm/month in monthly scale and 6.5 mm/year in annual scale, which represent higher values for reference evapotranspiration estimated with ERA5 than with INMET data.

Analyzing the residuals from ERA5 dataset in relations to ground-based measurements in INMET stations through the interquartile range at daily scale shows that, in 50% of the time, T_{air} ranged from -0.2 to +1.5 °C; R_s ranged from -2.3 to +1.2 MJ/m²; W_s ranged from -0.4 to +0.6 m/s; RH ranged from -9.1 to +2.5% and finally ET_0 ranged from -0.4 to +0.4 mm/day.

Spatial distribution and trend analysis of ERA5 reanalysis data and estimated ET_0 (1960-2020)

In the first section we analyzed ERA5 reanalysis data against ground-based automatic meteorological stations and results showed good agreement. Since ERA5 data is available for a longer period, in this section we used 179 grid points of 60-year period of reanalysis dataset, from 1960 to 2020, to estimate annual reference evapotranspiration across the UAS region and evaluate trends.

Figure 4 shows the spatial distribution of the 60-year annual average of the five analyzed variables from ERA5 reanalysis dataset (1960 to 2020), ArcMap software was used to interpolate the points over the study area using Kriging; Figure 5 presents the time series of all grid points (shaded blue), the annual mean (dark blue line), the mean from the period of 1960 to 2020 (dotted black line) and the slope from Mann-Kendall trend test (red line); Figure 6 presents boxplots with aggregate data by decade (1960-1969, 1970-1979, 1980-1989, 1990-1999, 2000-2009, and 2010-2019); Figure 7 shows the Mann-Kendall trend analysis results for the 179 grid points over the Urucuia Aquifer System region are presented. Table 4 presents 60-year annual average of the five analyzed variables from ERA5 reanalysis dataset (1960 to 2020) and results from the Mann-Kendall trend test.

Reference evapotranspiration average of the 60-year period mean value was 1,562 mm/year; maximum values were generally observed on northern regions of the UAS, while southern regions presented lowest values. Trend test results pointed to a significant increase in the average series, and all 179 grid points also presented an increase trend. Mean ET_0 by decade increased over time: the lowest

Table 3. Residuals (ERA5 – INMET) between comparison of daily, monthly and yearly ERA5 dataset and INMET ground-based observations.

		T_{air} (°C)	R_s (MJ/m²)	W_s (m/s)	RH (%)	ET (mm)
Daily	mean	0.7	-0.4	0.1	-3.8	0.0
	std	1.3	3.4	0.7	9.1	0.7
	min	-5.6	-18.8	-3.1	-60.0	-3.5
	25%	-0.2	-2.3	-0.4	-9.1	-0.4
	50%	0.6	-0.5	0.1	-2.8	0.0
	75%	1.5	1.2	0.6	2.5	0.4
	max	5.2	18.7	2.9	28.5	3.8
Monthly	mean	0.7	-13.5	0.1	-3.8	0.5
	std	0.9	44.9	0.5	7.1	10.2
	min	-2.4	-208.1	-1.2	-40.5	-35.7
	25%	0.0	-40.0	-0.3	-7.5	-5.9
	50%	0.6	-17.5	0.1	-2.7	0.0
	75%	1.2	11.1	0.5	1.5	6.2
	max	3.4	190.7	1.7	9.0	34.8
Annual	mean	0.7	-162.4	0.1	-3.8	6.5
	std	0.7	349.0	0.4	4.0	84.7
	min	-1.3	-1837.5	-0.8	-13.2	-341.4
	25%	0.3	-348.4	-0.2	-5.9	-40.7
	50%	0.6	-167.8	0.0	-3.7	8.6
	75%	1.2	41.4	0.5	-1.2	59.5
	max	2.0	593.1	0.9	3.6	162.5

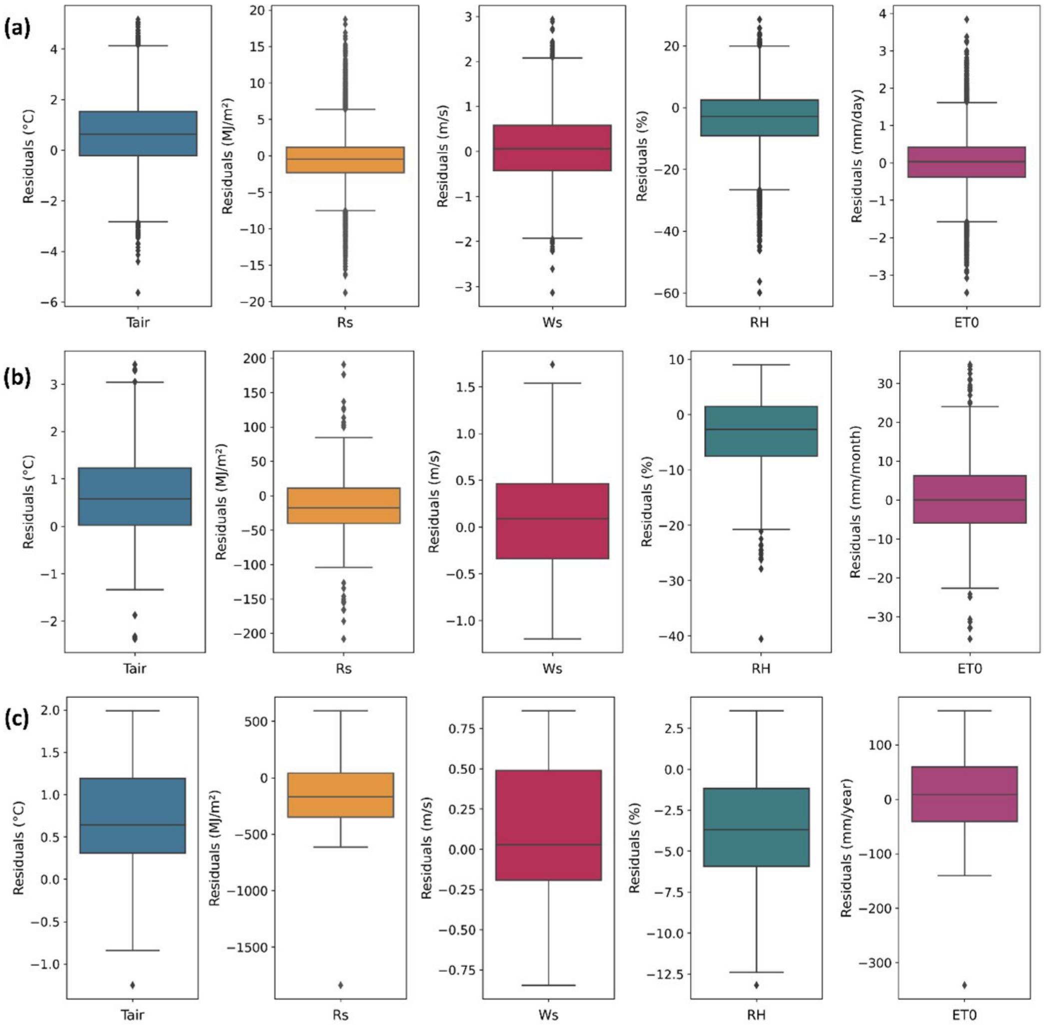

Figure 3. Boxplot of daily (a), monthly (b) and yearly (c) residuals between ground measured and ERA5 data.

Table 4. Mean values of the average 179 grid points of ERA5 dataset in the Urucuia Aquifer System Region from 1960 to 2020 and Mann-Kendall trend tests results.

	Annual Mean (1960-2020)	Trend	Slope
ET_0	1,562 mm/year	increasing	2.385
T_{air}	24.3 °C	increasing	0.025
R_s	7,314 MJ/m²	increasing	3.599
W_s	1.52 m/s	increasing	0.0018
RH	47.7%	decreasing	-0.052

average value was 1,510 mm/year during the 1970-1979 period, and greatest average was 1,641 mm/year during 2010-2019.

Average air temperature of the 60-year period mean was 24.3 °C; maximum values were observed on the north region of the UAS, while south and west regions presented lower temperature values. Trend test results pointed to significant increase in the average series, and all 179 grid points also presented an increase trend on T_{air}. Decade air temperature also increased: lowest mean average air temperature was 23.8°C in the 1960-1969 deacade, while highest average decade temperature was 25.1°C in 2010-2019.

Surface radiation mean was 7,314 MJ/m², maximum values were observed on eastern and northern regions of the UAS, while western and southern regions presented lowest values. According to the trend test results the 1960-2020 annual mean is significantly increasing, but grid trend results showed that on 76 points, which represent 42% of total, the surface radiation is increasing, while on remaining points there was no significant trend; increasing points are located mainly on northwest regions, with a smaller amount at east and south as well. Decade surface radiation reached minimum during 1980-1989 with an average

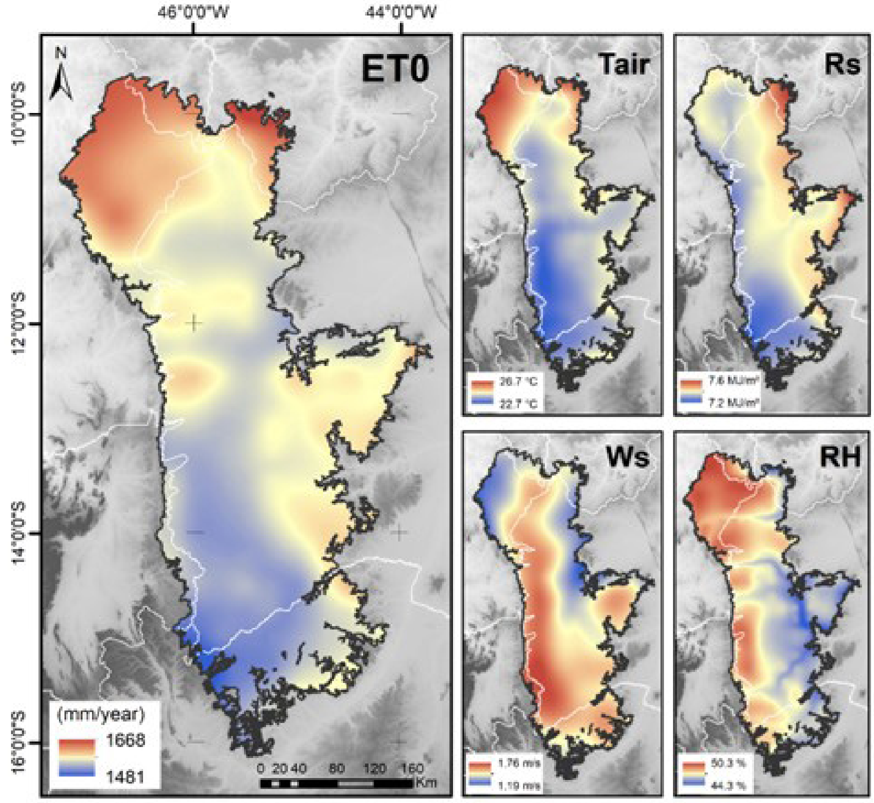

Figure 4. Spatial distribution of 60-year average annual variables from ERA5 reanalysis dataset (1960 to 2020): reference evapotranspiration (ET_0, mm/year), average air temperature (T_{air}, °C), surface radiation (R_s MJ/m²), wind speed at 2m height (W_s, m/s) and relative humidity (RH, %).

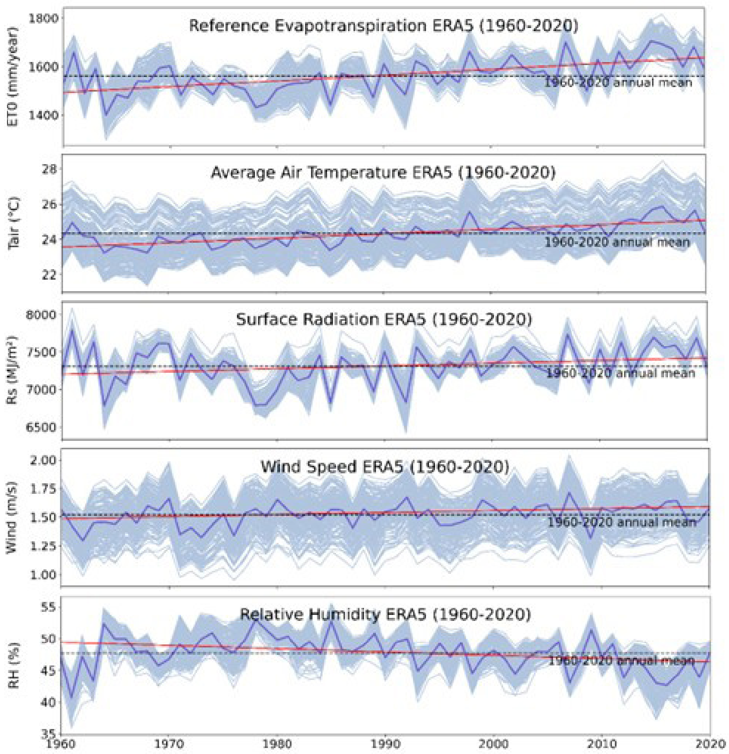

Figure 5. Time series of estimated reference evapotranspiration (mm/year), average air temperature (°C), surface radiation (MJ/m²), wind speed (m/s) and relative humidity (%) from ERA5 reanalysis dataset from 1960 to 2020; blue line is the mean from the 179 points from ERA5 grid, dotted black line is the 60-year period mean, and red line is the Mann-Kendall trend line.

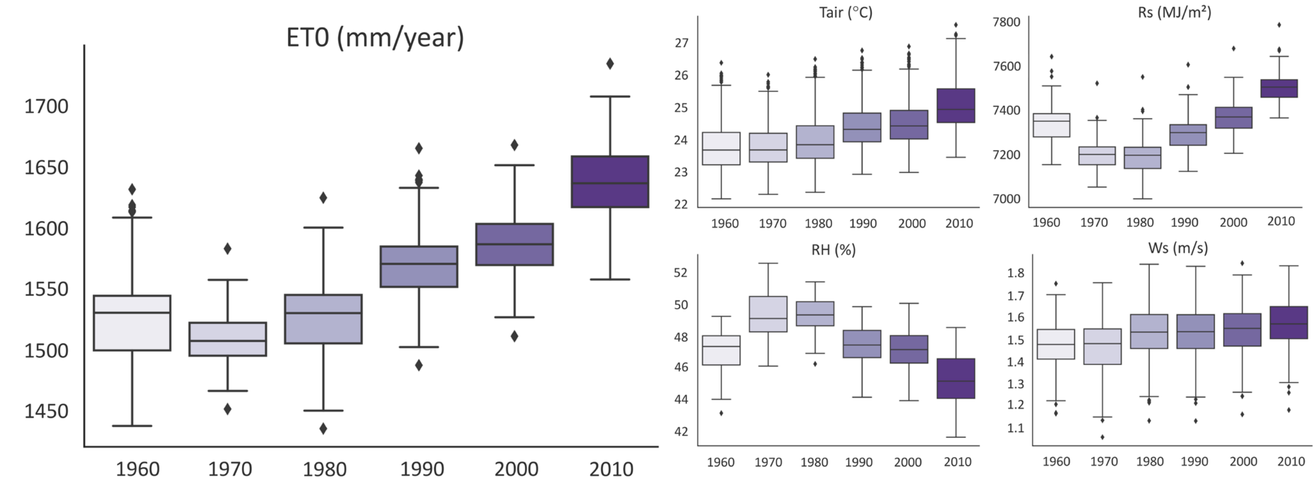

Figure 6. Boxplots of decade data for evapotranspiration (mm/year), average air temperature (°C), surface radiation (MJ/m²), wind speed (m/s) and relative humidity (%) from ERA5 reanalysis dataset from 1960 to 2020 .

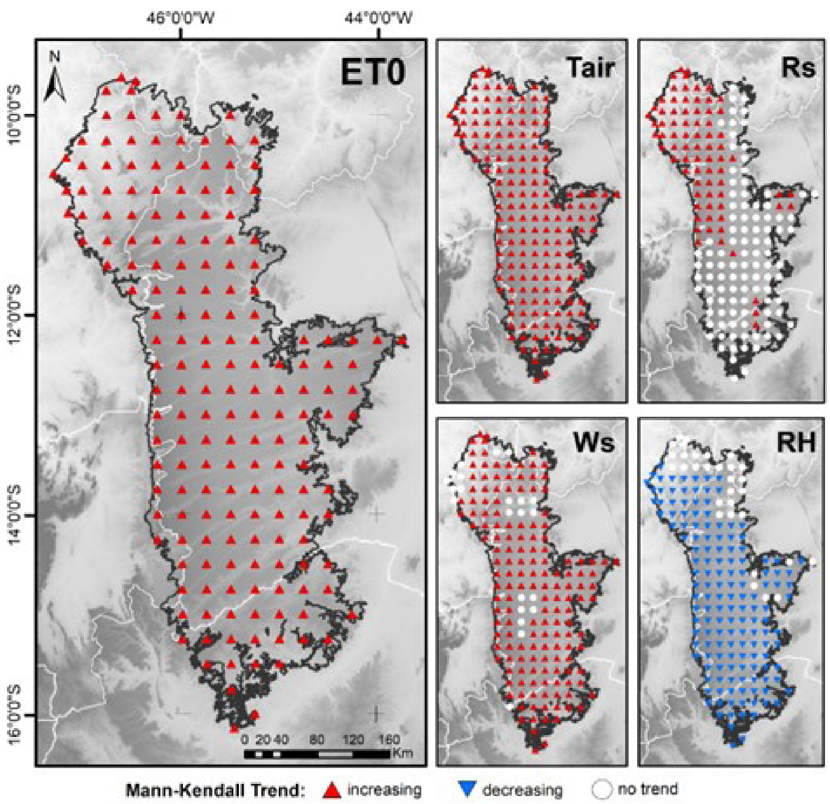

Figure 7. Mann-Kendall trend analysis results of variables from ERA5 reanalysis dataset (1960 to 2020): reference evapotranspiration (ET_0, mm/year), average air temperature (T_{air}, °C), surface radiation (R_s, MJ/m²), wind speed at 2m height (W_s, m/s) and relative humidity (RH, %).

of 7,188 MJ/m², while the highest value was 7,502 MJ/m² and occurred in 2010-2019.

Wind speed mean was 1.52 m/s, with maximum wind observed specially at western and southern portions, but also going northwards, and lowest wind at northwest and northeast boarders. Trend tests results for the 1960-2020 annual mean show wind speed is significantly increasing, grid trend showed that on 157 points (88% of the total) wind speed has an increasing trend, while on the remaining 22 points there was no significant trend. Lower decade average wind speed occurred in 1970-1979 with 1.46 m/s, while highest wind speed was 1.56 m/s in 2010-2019.

Relative humidity average of the 60-year period mean value was 47.7%, with maximum values observed at north and west regions, and lowest values at east. Unlike the other variables, Mann-Kendall test results showed a decreasing trend on relative humidity; grid analysis showed that on 149 points (83% of the total) the trend was decrease and on the other 30 points, which were mostly located on northeast areas, there was no significant trend. Relative humidity was lower during 2010-2019 with an average value of 45.3%, and the highest value was 49.4% during 1970-1979.

Changes in temperature on Brazil have been observed with the significant increase on warm extremes (Regoto et al., 2021; Salvador & Brito, 2018). Regoto et al. (2021) analyzed temperature and precipitation on Brazil during the period of 1961-2018 and found that on northeast Brazil there is a marked sign in precipitation extremes reductions towards a drier climate, with longer droughts periods, especially during summers and autumns. Salvador & Brito (2018) analyzed temperature trends during the period of 1970 to 2012 on the MATOPIBA region, in which the Urucuia Aquifer System is located, and observed that most indexes of air temperature presented strong trend for increase: all series of maximum temperature presented a pattern of positive trend, and most series of minimum annual temperature also presented a strong positive trend behavior; also, extreme temperature climate indexes presented a rise in the frequency of warm days per year. Melo (2022) analyzed reference evapotranspiration and temperature trends between 1985 to 2019 in the São Francisco watershed, which great part of the UAS area is within, and observed a significant increasing trend across the studied region. The authors highlighted that this heating may be associated to large-scale factors like global warming, and local factors, such as anthropic actions. As we can see on Figure 6, the decade from 2010 to 2019, has the highest values for average air temperature, surface radiation and wind speed, and consequently the highest average reference evapotranspiration from the analyzed period; the second highest values were observed in the decade from 2000 to 2009. We can see the median of reference evapotranspiration went from 1,530 mm/year during the 1960-1969 decade to 1,637 mm/year in the 2010-2019 decade, which is an increase of 107 mm/year; for comparison, in sub-basins of the Urucuia region the average year river discharge (for the period of 2002-2022) is 175 mm/year and precipitation is 1,102 mm/year (Mattiuzi & Collischonn, 2023).

Changes in climatic variables could still be a source of impact in the water resources of the Urucuia Aquifer System region. The National Water Agency, in a recent climate change report over Brazilian hydrological regions, observed an increasing trend in reference evapotranspiration until 2100 in the São Francisco River Basin, according to projections from IPCC (Intergovernmental Panel on Climate Change) (Agência Nacional de Águas e Saneamento Básico, 2024). Silva et al. (2021b) studied climate change impacts in the São Francisco River basin alongside increase in consumptive use and reported reducing trends in hydropower generation: the authors highlighted that at the Sobradinho hydroelectric plant, in the São Francisco river, the decrease in projected power generation ranged from −30% to −50% for the period 2021 to 2050 compared to the historical period (1901 to 2000). Pereira et al. (2022) analyzed the effects of climate change on the recharge and the groundwater flow of the Urucuia Aquifer System in the period 2041–2060, and their results showed decrease in recharge rates, from minus 3% up until minus 45%.

As stated before, several studies reported reductions in river flow and lowering water table in the last decades, and have pointed out a variety of possible causes such as decreasing precipitation, increase in water demand and irrigation, changes in land cover, and increase in evapotranspiration (Lima et al., 2022; Melo, 2022; Andrade et al., 2021; Silva et al., 2021a; Lucas et al., 2021; Ribeiro & Rodriguez, 2021; Collischonn et al., 2021; Marques et al., 2020, Fontes, 2020; Gonçalves et al., 2018, 2016, 2020; Oliveira et al., 2019; Pousa et al., 2019; Cunha, 2017). Results from the present study show that, in the last decades, there has been an increase in evaporative demand of the atmosphere, which means an increase in reference evapotranspiration and in meteorological variables such as air temperature, surface radiation and wind speed.

Although the increase in evaporative demand coincides with the period with observed flow reductions, it cannot be determined as the main cause since, as per reviewed studies, the Urucuia Aquifer System region has been going through a lot of changes during that period and before, which means other causes could also be contributing to the changes in water resources dynamics on the area. In a previous study (Mattiuzi & Collischonn, 2023), actual evapotranspiration in the Urucuia Aquifer region was assessed through water balance for the period between 2002 and 2022, and results pointed to a non-significant reduction in actual evapotranspiration. These findings of distinct trends between actual and reference evapotranspiration in the UAS area thought-provoking and will be addressed in following studies.

CONCLUSIONS

In this study, we assessed the potential of using the newly released ECMWF ERA5 climate reanalysis dataset for reference evapotranspiration analysis. The comparison involved the meteorological variables air temperature, surface radiation and wind speed, and estimated variables - relative humidity and reference evapotranspiration - against ground-based measurements collected between 2007 and 2020 in the Urucuia Aquifer System Region.

Our findings reveal a generally good agreement between ERA5 dataset products and the ground-based observations from the 11 meteorologic stations. Air temperature, surface radiation and reference evapotranspiration demonstrated the best results, while wind speed and relative humidity had lower evaluation metric scores.

The annual average reference evapotranspiration over the years 1960 to 2020 was 1,562 mm/year, with maximum values predominantly observed on northern regions of the Urucuia Aquifer System, and lower values in the southern regions. The Mann-Kendall test on the 60-year average series indicated increasing trends on reference evapotranspiration, air temperature, surface radiation and wind speed, while relative humidity trend was decreasing. The period between 2000 to 2019 stood out with higher average decade values for air temperature, surface radiation and wind speed, and the highest average reference evapotranspiration from 1960-2020.

Understanding the temporal variations in reference evapotranspiration and meteorological data is important to comprehend water cycle dynamic, especially in regions like the Urucuia Aquifer System, which has been going through a lot of changes in the last decades. This study revealed an increase in atmospheric evaporative demand, signifying a rise in reference evapotranspiration. However, it is important to note that although this increase aligns with the observed flow reductions and lowering water table levels, it also doesn't necessarily imply an increase in actual evapotranspiration, and it cannot be solely determined as the main cause of changes in the SAU region, as there are other contributing factors, according to previous studies.

Reanalysis datasets are generated through measured data. Continuous investments in ground-based long-term monitoring are imperative to maintain reliable datasets, enabling studies like the present one to contribute to our understanding of hydrological dynamics.

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