

## Hydrological modeling in the agrotechnological district (DAT) of Jacupiranga: climate trends and hydrological drought

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### Abstract

Climate change has significantly altered hydrological regimes in many regions, affecting water availability and intensifying extreme events such as hydrological droughts. This study assessed climate trends and drought occurrences in the Jacupiranga Agrotechnological District watershed (São Paulo, Brazil) using hydrometeorological time series (1961–2019) and hydrological modeling with the Soil and Water Assessment Tool (SWAT). Statistical analyses revealed significant increases in minimum (+2.15°C) and maximum (+2.45°C) temperatures, along with persistent hydrological droughts following the 2013–2015 water crisis, indicating shifts in the regional hydrological regime. The SWAT model accurately captured seasonal streamflow patterns, though it overestimated peak streamflow. Further model calibration will refine the analysis of climate change and land-use impacts on hydrological variables. The findings underscore the importance of public policies and water conservation practices to enhance regional water resilience and guide sustainable resource management.

**Keywords:** Temperature trends; SWAT model; Drought events.

### 1. Introduction

Changes in meteorological variable patterns, such as temperature, precipitation, and relative humidity, have caused significant impacts on climate at both global and regional scales (Tirupathi et al., 2018). These changes are associated with an increase in

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the frequency and intensity of extreme events, such as droughts and floods, which affect the hydrological cycle and compromise key sectors, such as agriculture, water supply, and natural resource management (Tirupathi et al., 2018; Teutschbein et al., 2023).

Among the different types of drought, meteorological drought has been widely studied due to its rapid onset and easy identification. However, hydrological drought — resulting from prolonged deficits in river flows and water storage levels — has more lasting and severe impacts, particularly on urban water supply, agricultural yield, and the maintenance of aquatic ecosystems (Teutschbein et al., 2023). Therefore, understanding the dynamics of hydrological drought, especially in watersheds, is crucial for the planning and sustainable management of water resources.

Comprehensive assessment of these changes requires integrated approaches combining statistical analysis of historical hydro-meteorological data with advanced hydrological modeling. Non-parametric methods (Kendall, 1975) are particularly valuable for detecting trends and abrupt changes in time series, providing crucial insights into climate variability and change signals.

The SWAT (Soil and Water Assessment Tool) model has emerged as a powerful complement to these statistical analyses, enabling spatially distributed simulation of hydrological processes under varying climate and land use scenarios (Neitsch et al., 2011). Its capability to model watershed-scale water balance and sediment transport makes it particularly effective for assessing anthropogenic impacts on water resources.

In this context, this study aims to analyze climate change signals and hydrological drought occurrences in the Jacupiranga Agrotechnological District watershed (São Paulo, Brazil) through SWAT modeling. The research seeks to: 1) quantify climate impacts on watershed streamflow; 2) identify hydrological drought patterns; and 3) provide technical support for adaptive water resource management under climate vulnerability scenarios.

## **2. Methods**

### ***Trend analysis***

This research project encompasses the Agrotechnological Districts (DAT) of both Jacupiranga and Alto Alegre in São Paulo state. The present study focuses specifically on the Jacupiranga DAT watershed, with the Alto Alegre DAT watershed to be analyzed in subsequent phases of the research. To assess the quality of meteorological data (precipitation and maximum and minimum temperature), robust statistical tests were

applied to the daily data from 1961 to 2019, obtained from Xavier et al. (2022). Initially, the Pettitt test was used to detect abrupt changes, followed by the Mann-Kendall (MK) test to identify trends in the time series of precipitation and temperature, aggregated on annual and monthly scales. Non-stationary parametric distributions were used as trend tests to detect changes in the probabilistic structure of the time series. After selecting the appropriate distributions, six non-stationary models based on Generalized Additive Models for Location Scale and Shape (GAMLSS) were applied, which allow describing different patterns of change in the series. The GAMLSS models considered in this study are (Prela-Pantano et al., 2025): Model 1: The mean ( $\mu$ ) and dispersion ( $\delta$ ) of the distribution do not change over time (Stationary); Model 2: Only  $\mu$  varies linearly over time; Model 3: Only  $\delta$  varies linearly over time; Model 4: Both  $\mu$  and  $\delta$  vary linearly over time; Model 5: Only  $\mu$  varies over time as a quadratic polynomial function; Model 6:  $\mu$  varies over time as a quadratic polynomial function and  $\delta$  varies linearly over time.

### ***Hydrological drought***

The Standardized Streamflow Index (SSI) was calculated using the Generalized Extreme Value (GEV) distribution (Svensson et al., 2017). The index was computed for the following accumulation periods: 1, 3, 6, 9, and 12-months. Monthly average streamflow data ( $\text{m}^3/\text{s}$ ), required for the SSI calculation, were obtained from DAEE (Departamento de Águas e Energia Elétrica, 2025) for the period from 2012 to 2023. The missing values were filled using the ARIMA method (Martins et al., 2022).

### ***Hydrological modeling: initial approach***

Hydrological modeling was performed in SWAT (Soil and Water Assessment Tool) using: 1) historical climate data (1961-2022) from Xavier et al. (2022); 2) FABDEM digital elevation model (30m resolution) for watershed topographic characterization; 3) land use maps from three distinct periods (1962 - based on official São Paulo state mapping; 2002 - derived from Landsat imagery; 2022 - obtained from Sentinel-2 imagery); and 4) detailed pedological maps with physicochemical properties and agricultural data. The model is currently undergoing calibration/validation by comparing simulated streamflows (using the 2022 land use map and complete climate series) with observed gauge station data (1966-1971). This integrated approach, combined with high-quality spatial data - including, historical land use maps, and detailed soil parameterization - will enable robust

analysis of the combined impacts of climate change and land use changes on hydrological processes, providing scientific basis for planning climate adaptation measures in the region.

### 3. Results and Discussion

Trend analyses of hydroclimatic variables (1961-2019) reveal significant warming, with annual temperature increases of +2.15°C (minimum) and +2.45°C (maximum) (Table 1). Monthly trends show pronounced warming (+2.0°C for both temperature extremes in January/October) and a modest yet statistically significant precipitation increase (+1.89 mm in January). Non-parametric tests demonstrate distinct patterns: precipitation remained stationary (Model 1), while both minimum (Model 3: linear  $\mu$  increase) and maximum temperatures (Model 2: linear  $\delta$  increase) exhibited significant upward trends. These results provide robust evidence of climate change, indicating fundamental shifts in the watershed's energy balance that may intensify evapotranspiration rates and alter hydrological regimes, with critical implications for water resources management.

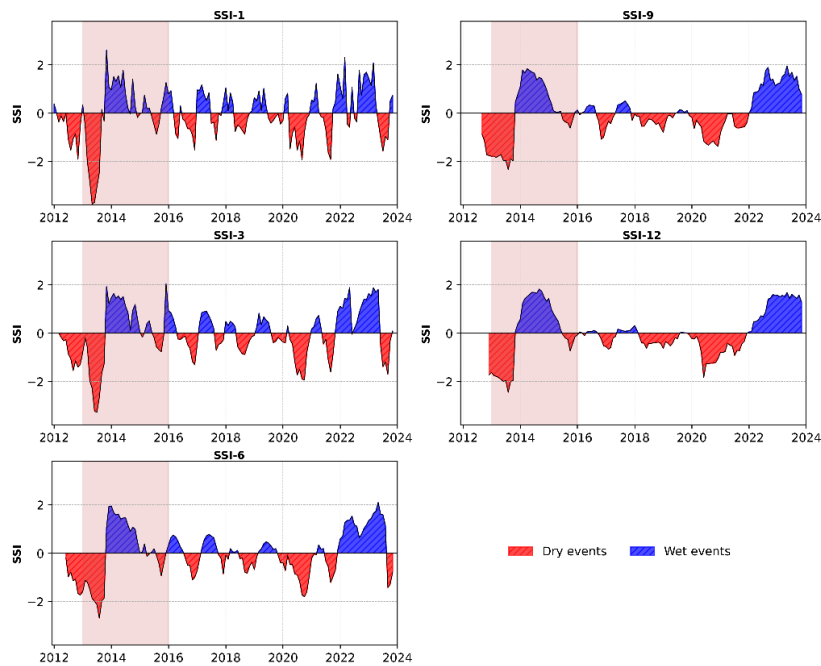
**Table 1.** Trend Analysis of Annual Precipitation and Maximum and Minimum Temperatures (1961–2019).

Variable	MK	MK p-value	Pettitt p-value
Precipitation	0.1	0.924	>0.999
Tmin	2.15	0.031	>0.999
Tmax	2.45	0.014	>0.999

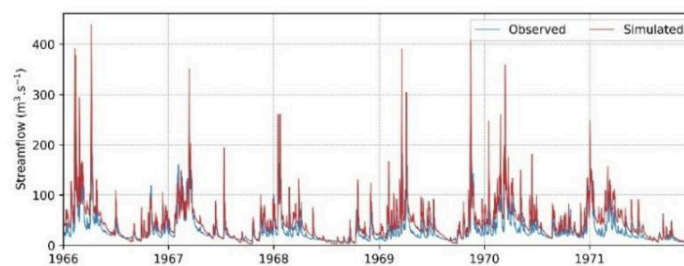
Statistically significant results are highlighted in red.

Regarding hydrological droughts, since the 2013–2015 water crisis, streamflow deficits have persisted across all time scales (Figure 1), especially at longer scales (SSI-6, SSI-9, SSI-12). Recent wet events at shorter scales (SSI-1 to SSI-6, 2022–2023) were insufficient to offset long-term deficits. Combined with observed warming trends, these findings indicate significant changes in the regional hydrological regime. Figure 2 shows preliminary results of the hydrological modeling for 1966–1971. The SWAT-simulated streamflow reproduced the seasonal flow pattern reasonably well, though it overestimated peak discharges. This underscores the need for more precise adjustment of parameters related to basin hydrodynamics. Thus, rigorous calibration and validation are essential to improve simulation accuracy and support reliable assessments of land use

impacts on basin hydrology. Once calibrated, the model will be a key tool for analyzing anthropogenic effects and guiding adaptation strategies under climate change in this watershed.



**Figure 1.** SSI estimate with GEV distribution for 1-, 3-, 6-, 9- and 12- months. Highlight for the drought of 2013-2015.



**Figure 2.** Observed streamflow (blue) and SWAT-simulated streamflow (red) for the period 1966–1971 in Jacupiranga.

#### 4. Conclusion

Trend analyses from 1961 to 2019 reveal significant increases in minimum (2.15°C) and maximum (2.45°C) temperatures, indicating clear evidence of climate change with potential impacts on regional hydrological dynamics. The continued occurrence of hydrological droughts since the 2013–2015 water crisis suggests a delayed recovery of the basin's water system. These results, together with preliminary hydrological modeling, underscore the importance of strengthening public policies and adopting effective water conservation measures to enhance the resilience of water resources under changing climate conditions.

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