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Hydrological responses to land use changes and precipitation variability in Southern Brazil

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ABSTRACT

Study region: Meridional plateau, Uruguay River Basin, Southern Brazil
Study focus: This study investigates the relative impacts of rainfall and LULC changes on streamflow variations over the Meridional plateau in the region comprising the Uruguay River basin in Southern Brazil. We used MapBiomas annual LULC data set and the CAMELS-BR data set by aggregating daily observations from gauging stations (rainfall and streamflow) to annual indices from 1985 to 2018. We employed time series and trend analysis across three identified clusters with 78 gauging stations through an unsupervised machine learning algorithm.
New hydrological insights for the regions: We found an extensive and statistically significant agricultural expansion for soybean croplands following a transition from other temporary crops (i.e., maize, wheat, oats, etc.), which was accompanied by statistically significant runoff coefficient decrease (i.e., 34 %), while the results for rainfall and flow were statistically insignificant. Furthermore, we observed a 27 % rise in water demand linked to the expansion of soybean croplands, a phenomenon corroborated by existing research. The growth in the number and capacity of dams further may reinforce these findings across the analyzed periods. The identified remarkable decrease in runoff coefficient may, therefore, be primarily attributed to LULC changes. Our findings might provide insights for improved water resource management for future land use planning to develop more resilient catchments against changing environmental and climatic conditions.

1. Introduction

Spatiotemporal changes in land use and land cover (LULC) and climate modify the streamflow regimes by altering surface and subsurface runoff, groundwater cycle, evapotranspiration, and consequently water supply (Vicente-Serrano et al., 2019; Ketchum

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et al., 2023). Climate variations, whether they are seasonal, annual, or exceptional, have been observed to have indirect effects on streamflow (Chagas and Chaffe, 2018; Tan and Gan, 2015), groundwater replenishment, and surface water retention, which in turn affects flood hazard and water resources. Alongside LULC changes like deforestation, irrigation, and agricultural growth—all of which are considered of as direct flow regulators—dam construction modifies the landscape's natural capacity to control water causing to decreased or increased runoff (Haddeland et al., 2006; Liu et al., 2015; Boutt and Iroume, 2018; Best, 2019; Ketchum et al., 2023).

. Previous studies revealed that increased irrigation and dam development were accountable for decline in streamflow (Filoso et al., 2017; Tan and Gan, 2015; Vicente-Serrano et al., 2017). Accordingly, it has been proposed that changes in land use and land cover were responsible for a significant amount of reported decreases in streamflow in China (Zhang et al., 2008) and East Africa (Guzha et al., 2018) and increases in sediment delivery in Uruguay (Foucher et al., 2023). However, Levy et al. (2018) showed that LULC changes (i.e., primarily deforestation) had increased the streamflow over the last half-century while climate had remained stationary in the arc of deforestation in Brazil. Meanwhile, it has been demonstrated that the effects of shifting rainfall regimes are rather complicated (Tan and Gan, 2015). Recent streamflow trends have been mostly ascribed to climate change in the USA (Ficklin et al., 2018; Frans et al., 2013). However, it has been observed that these changes do not directly alter the streamflow regimes throughout Southern Brazil (Chagas and Chaffe, 2018).

Despite a wealth of studies on the influences of variations in LULC and climate on watershed hydrology, a consensus on hydrological responses has not been reached (Chagas and Chaffe, 2018; Guzha et al., 2018). Therefore, there is currently no definitive answer regarding the relative influence of climate and LULC on watershed discharge dynamics, due to the high complexity associated with diverse discharge behaviors observed across various landscapes, such as mountainous natural areas compared to lowland agricultural catchments. Consequently, further research is required in areas where i) significant land degradation is occurring and ii) where the impacts of floods are high (Stein et al., 2024)

Southern America, and particularly Brazil, have experienced intensive (Dias et al., 2016) -almost twofold expansion in row crop area (Zalles et al., 2019)- but temporally varying LULC changes (i.e., expansion rate) since 2000, which may have altered hydrological cycles. The temporal variations in LULC expansion are attributed to the impacts of the global economic and food crisis on the production and export of commodity crops (e.g., coffee and soybean) (Winkler et al., 2021). Southern Brazil is identified as a significant hotspot in the evolution of LULC due to soybean cropland expansion since 2000 (Song et al., 2021), compared to a decline in soybean cropland expansion inside the Amazon and Cerrado Biomes following the implementation of Brazil's Amazon Soy Moratorium after 2006 (Heilmayr et al., 2020). Therefore, this region deserves detailed studies because of its proneness to intensive environmental changes.

Previous studies have examined the effects of rainfall variability and different LULCs on the streamflow regime in Southern Brazil (Tucci and Clarke, 1998; Tucci et al., 2003; Collischonn et al., 2001; Bartiko et al., 2017). For example, on the one hand, hydrological modeling (a period from 1977 to 2000) indicated that the transition from forested regions to agricultural areas resulted in an increase in monthly flow within the Ibicui River basin (Pena Vieira Leal et al., 2023). Furthermore, Collischonn et al. (2001) demonstrated that the variability in runoff from 1960 to 2000 cannot be exclusively attributed to changes in LULC or alterations in the rainfall regime over the Paraguay River basin. On the other hand, Foucher et al. (2023) demonstrated the expansion of soybean cropland caused rapid land degradation through accelerated sediment fluxes. Therefore, research on the effects of LULC temporal evolution on streamflow dynamics during ongoing discussions about climate variabilities continues to be much needed to improve our understanding of the intricate interactions between hydrological cycles and human activities. Additionally, after analyzing more than 610,000 papers worldwide, Stein et al. (2024) also noted a specific need for hydro-related research, establishing that South Brazil is a less studied yet significantly impacted region.

In this context, we used the CAMELS-BR (Chagas et al., 2020) and MapBiomas data sets and employed clustering, time series, and

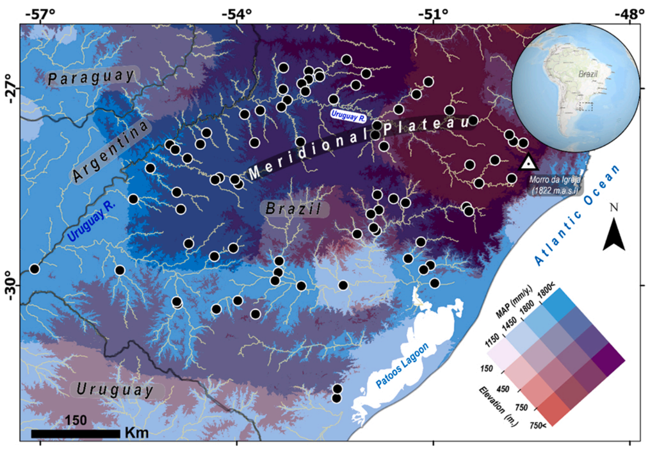


Fig. 1. The spatial distribution of gauging stations across the research areas, along with a bivariate map of mean annual precipitation (MAP; mm/y.) and elevation, illustrates locations where both precipitation and elevation are concurrently elevated (shown by purple) and low (indicated by light gray). * M.a.s.l refers to metres above sea level.

trend analyses to investigate the streamflow variability at 78-gauging stations between 1980 and 2018 across the Meridional Plateau segment of the Uruguay River basin area in Southern Brazil. Considering that research indicates significant alterations in LULC over Southern America (Heilmayr et al., 2020) and corresponding limited variations in precipitation across Southern Brazil (Chagas and Chaffe, 2018), therefore we hypothesize that the effects of land use and land cover changes may exceed the impacts of rainfall fluctuations on hydrological variations (i.e., runoff coefficient) observed regionally in Southern Brazil over the past several decades. Consequently, this study offers the first quantification of LULC evolution over a period longer than three decades (i.e., 1985–2018) in this region to quantify and attribute potential streamflow responses.

2. Study area

This study encompasses mainly the upper segment of the Uruguay Basin, the Atlantic Ocean, and the Patos Lagoon, which are all located in Southern Brazil. It covers an investigated surface area of about 231,000 km^2 in size with 78 catchments (Fig. 1) delineated with outlet of gauging stations that we obtained from the CAMELS-Br data set (Chagas et al., 2020). The mountain ranges delineate the northern border of the study area with the Morro da Igreja peak at 1822 m above sea level. According to the Köppen climate classification, the climate type prevailing in Southern Brazil is humid subtropical (i.e., Cfa), where precipitation varies from ~1500 mm to 2000 mm from south to north, respectively. The South American Monsoon System has an impact on precipitation variability in this region (Carvalho et al., 2016), and it is characterized by a rainfall regime that is evenly distributed across the entire year (Chagas and Chaffe, 2018). The main soil groups found in the region are Ferralsols and Nitisols with deep and weathered properties (Didoné et al., 2021; Londero et al., 2021; Poggio et al., 2021). The region experienced massive deforestation caused by widespread cow-raising (IBGE, Brazilian Institute of Geography and Statistics, 1998, 2006; Chagas and Chaffe, 2018) and it has subsequently diminished post-1970 (Leite et al., 2012). The vast agricultural landscape is the most common LULC feature with the densely forested area in the north to northeast of the study area (Supplementary figure 1). Agricultural practices have evolved through time having traditional tillage between 1980 and 1990, a transition to no-tillage with terraces in the period of 1990–2000, and actual no-tillage without terraces (Didoné et al., 2017; Merten et al., 2015).

3. Data and methods

This study uses streamflow and rainfall data and investigates the impact of LULC changes and rainfall variability on streamflow as summarized in Fig. 2. The subsequent sub-sections describe how these associations have been analyzed and how the research question has been handled.

3.1. Streamflow, rainfall data sets, and indices

Here, we take advantage of the Camels-BR data set over Brazil (Chagas et al., 2020), which consists of daily hydrometeorological (i.e. discharge and rainfall depth) time series and landscape attributes during the period from 1980 to 2018. We used streamflow and rainfall and various landscape attributes (Fig. 3b), which potentially impact streamflow variation in the catchment within CamelsBR data set. The streamflow data used in Camels-BR are obtained by the Brazilian National Water Agency (ANA, 2019), which estimates daily streamflow with rating curves by using daily two averaged measurements: in the morning and in the afternoon. The rainfall data has been compiled per catchment by taking the average value per day from CHIRPS v2.0 (Funk et al., 2015), CPC (NOAA, 2019), and MSWEP v2.2 (Beck et al., 2019) in this data set. The study area, Southern Brazil, is equipped with more than 100 gauging stations. We

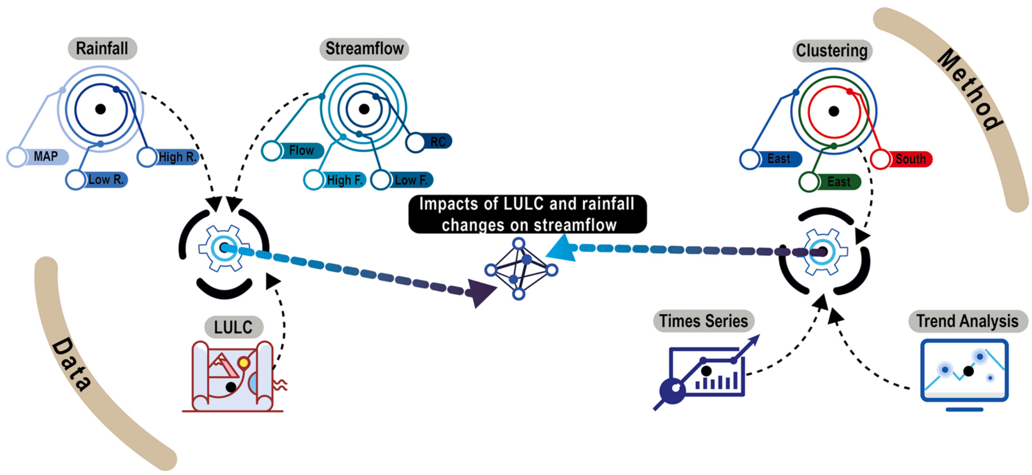


Fig. 2. The flowchart of the study illustrates how we integrated data and employed methods to reveal the impacts of LULC and rainfall changes over the last three decades on streamflow.

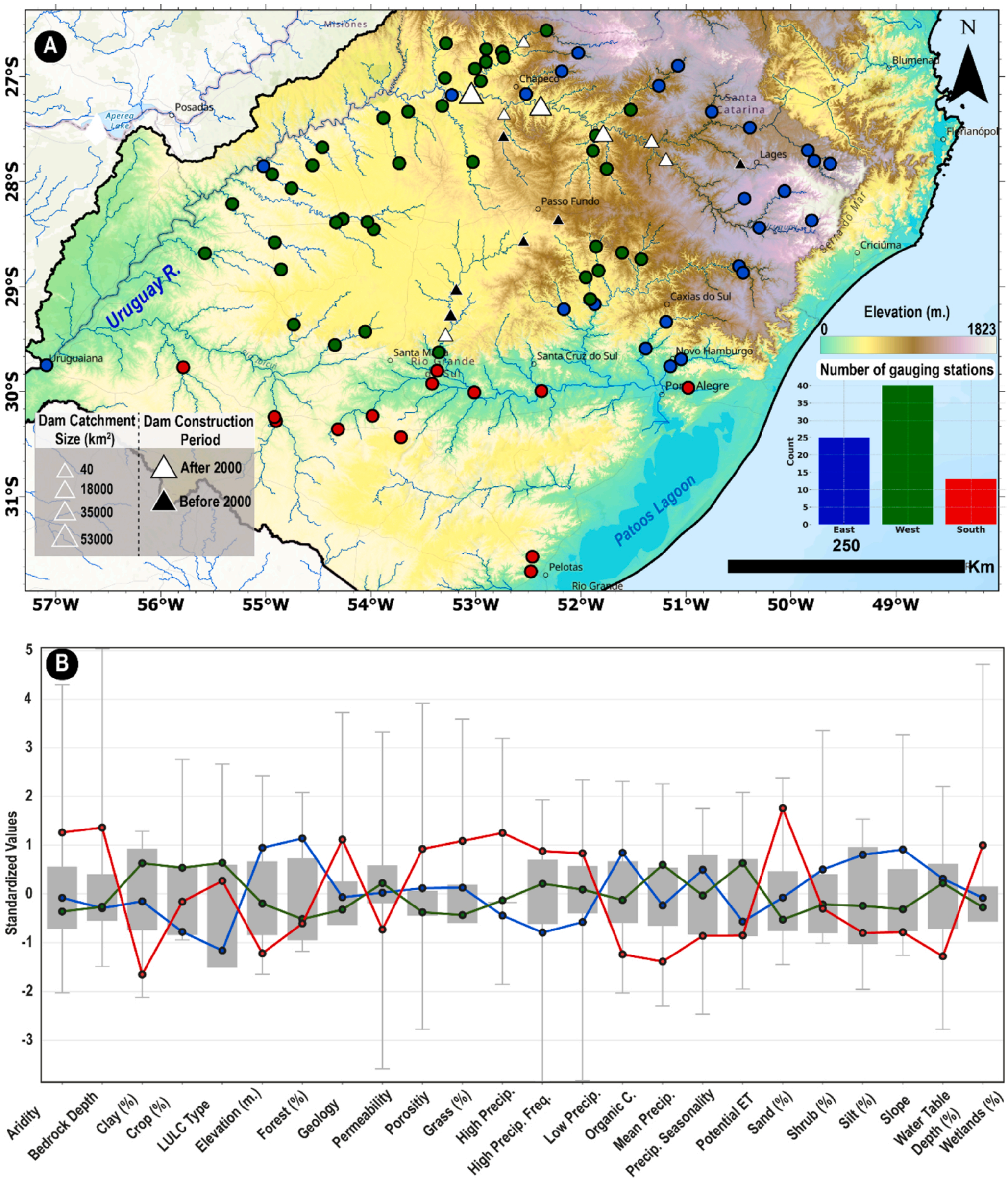


Fig. 3. The obtained clusters within the study area together with a) their spatial distribution and the spatiotemporal distribution of dams represented by triangles, b) the environmental parameters, which are used in clustering analysis taken from the Camels-BR data set. The box plots illustrate the variation of each environmental parameter, while the lines display the median values for each cluster corresponding to each environmental parameter.

Table 1
The streamflow and rainfall indices used for this study.

Indices	Abbreviation	Explanation	Unit
High Flow	*Hf*	The number of annual instances where streamflow exceeded the 90th long-term percentile criterion.	event per year
Low Flow	*Lf*	Magnitude of yearly minimum 7-day moving-window average discharge	mm/day
Runoff Coefficient	*RC*	A dimensionless coefficient that relates runoff to precipitation received.	-
High Rainfall	*Hr*	The number of annual instances where rainfall exceeded the 90th long-term percentile criterion	events per year
Low Rainfall	*Lr*	A period of dry weather where the amount of rainfall is less than 1 mm	days

arbitrarily set a maximum threshold of 1000 days missing value for analysis, or roughly 7 % of all days throughout the 38 years, to select gauging stations ensuring data quality and consistency, resulting in a set of 78 gauging stations analyzed in this study.

In order to align with the annual LULC change, we aggregated daily to annual time steps of streamflow (mm/y) and rainfall (mm/y) data, we derived hydrological and rainfall indices. We picked three streamflow and two rainfall indices apart from flow and rainfall that quantify the spatiotemporal evolution of the rainfall and streamflow regimes in order to capture both different behaviors of rainfall and streamflow: high flow (*Hf*), low flow (*Lf*), and runoff coefficient (*RC*), and similarly high rainfall (*Hr*) and low rainfall (*Lr*) have been chosen for streamflow and rainfall, respectively (Table 1).

These indicators, which allow us to comprehend hydrologic changes over time, have been portrayed as the hydrometeorological fingerprints of catchments (Chagas and Chaffe, 2018) and used also for understanding runoff modelling studies (Landemaine et al., 2023). To calculate the RC for a rainfall event, the total volume of runoff (separated from baseflow using a digital filter) and total precipitation in the catchment were combined using the following equation:

$$RC = \frac{Vr}{Vp} \quad (1)$$

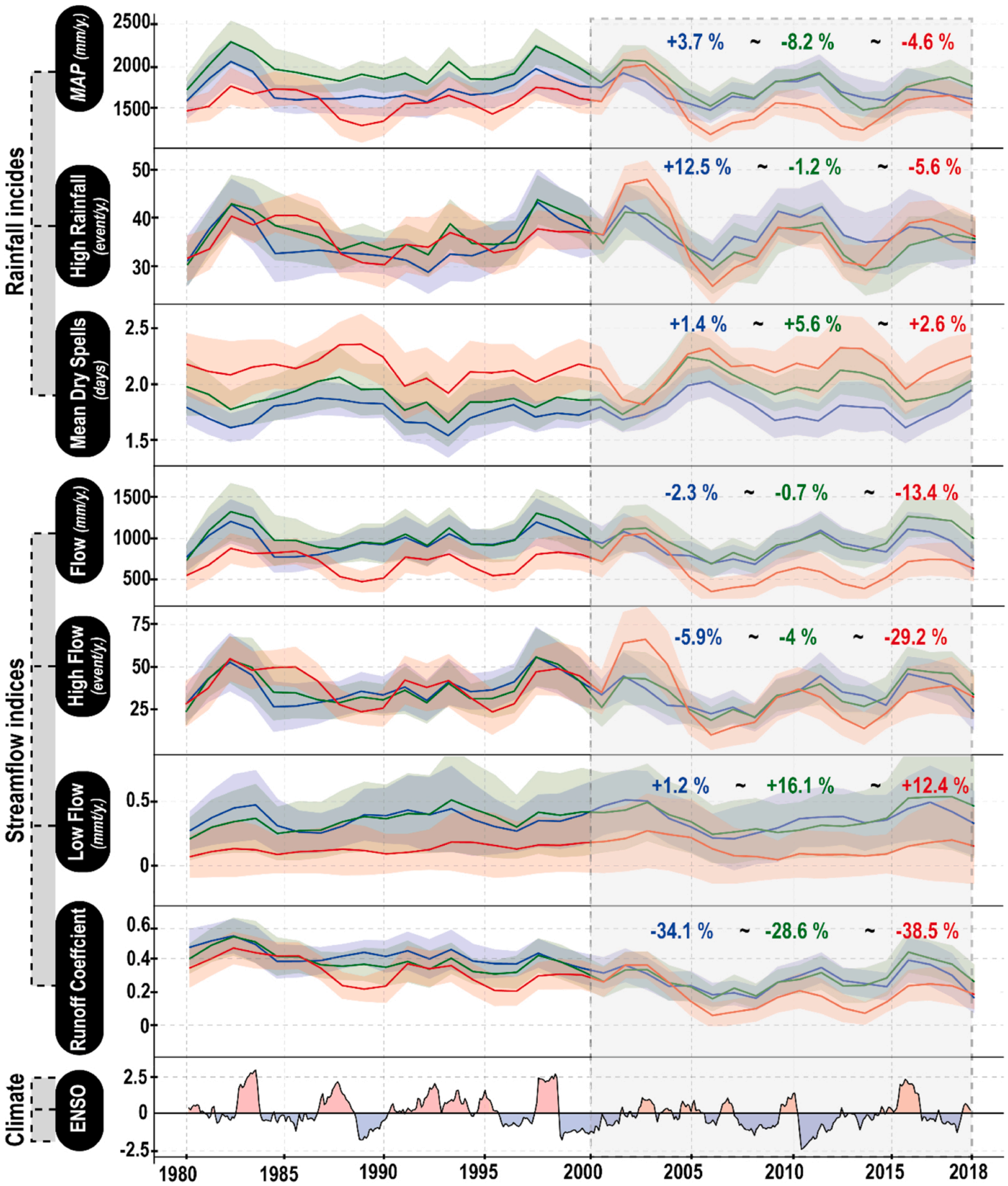


Fig. 4. Time series of the rainfall and streamflow indices compared in two periods: pre.

Where RC is the runoff coefficient; V_r is the runoff volume; and V_p is the precipitation volume. The recursive digital filter, also known as the Eckhardt filter method, requires a filter parameter and $BFI_{\max}$ values (long-term ratio of baseflow to total streamflow) (Combalicer et al., 2008). The general form of digital filtering is:

$$b_k = \frac{(1 - BFI_{\max}) * \alpha * b_{k-1} + (1 - \alpha) * BFI_{\max} * Q_k}{(1 - \alpha * BFI_{\max})}$$

In this equation, $b_k$represents baseflow at time step k, b_{k-1}represents baseflow at time step *k-1*, Q_k represents total streamflow at time step k, $BFI_{\max}$ is the baseflow index (the ratio of baseflow to total flow), and α is the filter parameter. We have chosen $BFI_{\max} = 0.98$ and $\alpha = 0.7$ by following a sensitivity analyses by Helfer et al. (2025) conducted in Southern Brazil Employing recursive digital filter is appropriate for national-scale datasets like CAMELS-BR because it allows for automated and consistent baseflow separation across a variety of catchments without requiring calibration particular to each catchment.

3.2. Land use and land cover (LULC)

We use MapBiomas Collection-9 (at 30 m pixel resolution), which comprises the annual LULC classes from 1985 to 2023 in Brazil (Souza et al., 2020). As part of a concept of gradually modifying land cover map collections, the MapBiomas project (https://mapbiomas.org) was established to develop a system capable of producing annual land cover maps based on Landsat satellite imagery collection (Baeza et al., 2022). Therefore, we quantified the spatiotemporal changes using annual LULC raster data in 30 m pixel resolution to understand the 38-year evolution of LULC over the study area. The evaluation of LULC changes has been conducted within the catchments derived from the CAMELS-BR dataset (Chagas et al., 2020). Consequently, LULC, rainfall, and streamflow data are aggregated to the catchment and annual scale, allowing for a uniform assessment of all data. Changes in LULC have been determined through pixel-by-pixel analysis to calculate annual percentage variations and were then used to analyze variations in streamflow (Fig. 4).

3.3. Clustering

Cluster analysis provides an effective tool for classifying and identifying shared characteristics between items (Jain, 2010). In this study, we employed the K-means unsupervised clustering approach (MacQueen, 1967; Ball and Hall, 1965; Lloyd, 1982), which is a commonly used method of identification of different clusters on given data sets in Earth science applications (e.g., Avcıoğlu et al., 2022; Moreno-de las Heras and Gallart, 2016; Türkeş and Tatli, 2011). We applied this algorithm to acquire vast and unique regions of Southern Brazil for streamflow by considering the physical attributes (Fig. 3b). These attributes compiled by Chagas et al. (2020) can mainly be assessed in 4 groups; Climate/Hydroclimate (aridity, high precipitation., high precipitation Frequency, Low precipitation., mean precipitation, precipitation Seasonality, potential evapotranspiration), Topography/Geomorphology (Elevation (m), Slope, Water Table Depth (m)), Soil/Geology (Bedrock Density, Clay (%), Sand (%), Silt (%), Permeability, Porosity, Organic Carbon, Geology), Land Use / Land Cover (LULC Type, Crop (%), Forest (%), Grass (%), Shrub (%), Wetlands (%)). The primary reason is their utilization, as they generally affect hydrological dynamics both directly and indirectly, thereby enhancing our ability to create homogeneous and distinctive clusters from a hydrological standpoint. For instance, aridity may affect the infiltration capacity of the surface, while LULC classes can influence hydrological processes by regulating infiltration, evapotranspiration, and surface runoff across various classes. This algorithm generates the given number of clusters following main steps: (i) a random assignment of centroids within data space, (ii) k clusters are formed by assigning the closest mean to each observation, and (iii) the iterative improvements of the centroid of clusters established and repeats first two phases of the algorithm until positions of the cluster centers and the arrangement of the cluster groups stabilize.

3.4. Trend analysis

Trend analysis has been used to quantify annual changes in streamflow, precipitation, and LULC. We used the Mann-Kendall (MK) analysis, which is a non-parametric (Kendall, 1975; Mann, 1945) and a commonly used statistical test in hydrological science applications (Akbas, 2024; Levy et al., 2018). We applied the modification to MK proposed by Hamed and Ramachandra Rao (1998) to address serial autocorrelation issues regarding seasonal time series. This method is based on the main hypothesis test; H_0: null hypothesis (no trend) and H_1: alternative hypothesis. The p-value represents the significance level (α), which we have set at 5 % (0.05). If $p \le \alpha$: Rejects the null hypothesis (H_0) and accepts the alternative hypothesis (H_1) indicating a statistically significant trend. We applied MK trend analysis on the parameters - mean annual rainfall (mm/y), flow (mm/y), RC (unitless), and annual soybean cropland changes (km^2/y) to quantify the changes in annual scale. Further confidence intervals have been calculated using the Sen's slope estimator associated with magnitude of the changes over three clusters for 78 catchments within the 95 % confidence limit. Using a normal approximation, this procedure determines the lower and upper rank positions by taking pairwise slopes for each time step, which in our case is one year, calculating the median trend estimate, and defining the 95 % confidence interval from the slope distribution.

4. Results and discussion

4.1. Clustering analysis

We defined three main clusters; East, West, and South that divide the region into three zones helping to understand variations in the streamflow behavior by inputting parameters related to climate, hydrology, geology, and LULC (Fig. 3). These clusters provide insights into comprehending different changes in streamflow over time by considering their physiographical attributes.

Cluster 'East' is delineated by the eastern and northeastern boundaries of our study area with the 26 gauging stations, which include the southern part of the Atlantic Forest. The headwaters of the Uruguay River basin are also located in this region. Therefore, Cluster East exhibits a spatial distribution where elevation ($\bar{x} = 990$ m), slope ($\bar{x} = 70$ m/km), and forest density ($\bar{x} = 62$ %) are higher than in other regions. Moreover, since it is characterized by a relatively rougher topography, the cropland cover proportion is lower than in other regions. This region shows a lower frequency of high streamflow over the studied period compared to other regions where rainfall is 1741 mm/y, unlike the mountainous environment, which creates microclimatic settings, relatively higher humidity, and orographic effects.

Cluster West comprises 40 gauging stations and represents the geomorphologically transitional region where the mean elevation is 527 m between Cluster East and South where the topography is rougher and flatter, respectively. However, its characteristics—such as aridity, bedrock depth, geology, permeability, porosity, high precipitation, etc.—are more similar to those of Cluster East than those of Cluster South. Furthermore, this region depicts a landscape with the highest cropland cover proportion (18 %) and MAP values of 1870 mm/y over the entire study area. Additionally, the soil texture is primarily made up of finer particles, with the largest percentage of clay (52 %) and the lowest percentage of sand (22 %).

Cluster South with 12 gauging stations is the smallest region that is delineated by the southern boundary of the study area with Uruguay. Compared to the other regions, Cluster South is characterized by the flattest ($\bar{x} = 27$ m/km), the lowest elevation ($\bar{x} = 188$ m), less rainfall ($\bar{x} = 1562$ mm/y), and the sandiest soil texture ($\bar{x} = 39$ %). Even though this region is the driest in comparison to others, it was surprising to find that the high precipitation amount and high precipitation frequency are identified as the highest across the entire research area. The findings also demonstrated that this area has the highest bedrock depth. Furthermore, the results show that while the permeability is the lowest, porosity is the highest in this region.

4.2. Spatiotemporal variations in rainfall and streamflow indices

The spatiotemporal changes in rainfall indices have been observed for a period of more than three decades. Mean annual precipitation shows a slightly decreasing pattern in Clusters West and South while an increasing pattern was observed in Cluster East over time. This finding raises an unsettled issue: although some research found that precipitation had generally increased (Penalba and Robledo, 2010; Doyle and Barros, 2011; Naumann et al., 2012), other studies found that precipitation in the study area had remained constant during the last 40 years (Dethier et al., 2022; Feron et al., 2024). After the year 2000 and compared to the years between 1980 and 1999, there were changes in the overall pattern not only in rainfall but also in the other indices that we examined, which were either decreasing or increasing. Therefore, we have also considered the regional variations in the Multivariate ENSO Index Version 2 (MEI.v2) (Zhang et al., 2019) and it shows a more frequent and longer La Niña than El Niño phase (Fig. 4). It has been noted that La Niña makes Southern Brazil experience a drier season and reduces crop production (USDA Foreign Agricultural Service, 2023); accordingly, this could be one of the reasons why rainfall declined after 2000 (Fig. 4). This finding is further supported by a decrease of 5.6 % and 1.2 % in high rainfall frequency and increased mean dry spell values of 2.6 % and 5.6 % in Cluster South and West, respectively. Contrary to these two regions, Cluster East experienced an increase of 12.5 % in high rainfall, and the mean dry spells have stayed essentially stationary.

and after-2000. The percentage values represent the median changes in percentages after-2000 for different clusters within the grey-shaded area. The lines indicate the mean values over time with different colors representing East, West, and South clusters for blue, green, and red, respectively. The shaded area also shows the standard deviation (±1σ) around the mean reflecting the variability in rainfall and streamflow indices across the study area and time. Flow (mm/) refers to the mean annual streamflow and MAP (mm/y) indicates the mean annual precipitation. ENSO is the Multivariate El Niño Southern Oscillation index (MEI V2). See Table 1 for definitions of streamflow and rainfall indices given in the figure.

The indices of streamflow (e.g., high and low flow and RC) have shifted notably while flow (mm/y) remained relatively stationary in Clusters East and West. Differently, the Cluster South showed a 13 % decrease in streamflow after 2000 while the rainfall only decreased by 4.6 % during the same period. Contrary to previous studies (Teixeira and Satyamurty, 2011; Cavalcanti et al., 2015; Tedeschi et al., 2016), we found a remarkable decrease in the temporal pattern of high streamflow. The most noticeable shifts in high flow have mostly taken place in Cluster South (-29.2 %), where the region exhibits alluvial plains and floodplains as main landscape features. However, this reduction does not directly imply that the area has been less affected by flood events during this period since catastrophic disasters took place such as the 2011 flood (Ávila et al., 2016) and the most recent one, the April-May 2024 flood events (Célia dos Santos Alvalá et al. 2024) in Southern Brazil. This association is frequently explained by the distribution of these occurrences, in which the magnitude increases linearly while the frequency decreases as an inverse power function with increasing magnitude (Malamud and Turcotte, 2006). Overall, the fluctuations in the high-flow pattern over time called also flood flow, are attributed to the El Niño–Southern Oscillation (ENSO) (Seager et al., 2010; Chagas and Chaffe, 2018) with which we obtained consistent association in our study areas (Fig. 4). However, Detzel et al. (2016) attributed to the increase in high flow to LULC change over the 30 years in the Iguazu Basin in southern Brazil. The result also showed that the widespread increase in low-flow indices, particularly in Clusters West (16.1 %) and South (12.4 %) occurred during the period after 2000 compared to pre-2000. This result is consistent with that of research conducted in the same geographic area (Chagas and Chaffe, 2018; Detzel et al., 2016), even if their temporal evolution period primarily examined the years from 1970 to 2010. Furthermore, several studies (Guimberteau et al., 2013; Petry et al., 2025; Scheuerer et al., 2025) highlighted that changing climate are expected to increase already existing hydrological trends, reinforcing the case for improved monitoring and adaptive planning strategies over southern America. For example, Petry et al. (2025) showed that recent projections through CMIP6 models under scenarios SSP2–4.5 and SSP5–8.5 also suggest an increasing pattern extreme precipitation and flooding across southern Brazil.

The most notable changes took place during the period after 2000 compared to pre-2000 in the RC for every cluster identified in the current research. The RC decreased by 34.1 %, 28.6 %, and 38.5 % over the compared period for Clusters East, West, and South, respectively. This finding exhibits a consistency with the decreased mean rainfall and increased low streamflow over the study areas, excluding the Cluster East where rainfall increased by around 4 %. However, it is crucial to emphasize the observed variations in RC magnitude (in percentage), and rainfall shows a substantial difference that might indicate possible additional effects on RC changes. For example, Montgomery, (2007) showed how changes in LULC (i.e., agricultural practice changes) over time have decreased the RC, by improving infiltration and reducing slope flow velocity.

Overall, the time series for streamflow indices showed a similar temporal pattern in Clusters East and West, although the magnitude of changes varied, especially for low flow. Additionally, it is interesting to note that flow does not appear to be much impacted by the reported rise in either MAP or high rainfall in Cluster East, indicating that other underlying variables may be responsible for its fluctuation.

One of the limitations here is that the consideration of rainfall and streamflow indices on an annual scale hindering the short-term variabilities and extreme which might play an important role in hydrological responses. On one hand, although annual scale assessments may constrain the representation of peak flow dynamics, drought frequencies, and intense rainfall periods, long-term trends can be detected by reducing data noise, thereby revealing smoothed hydrological behavior and responses to LULC changes. On the

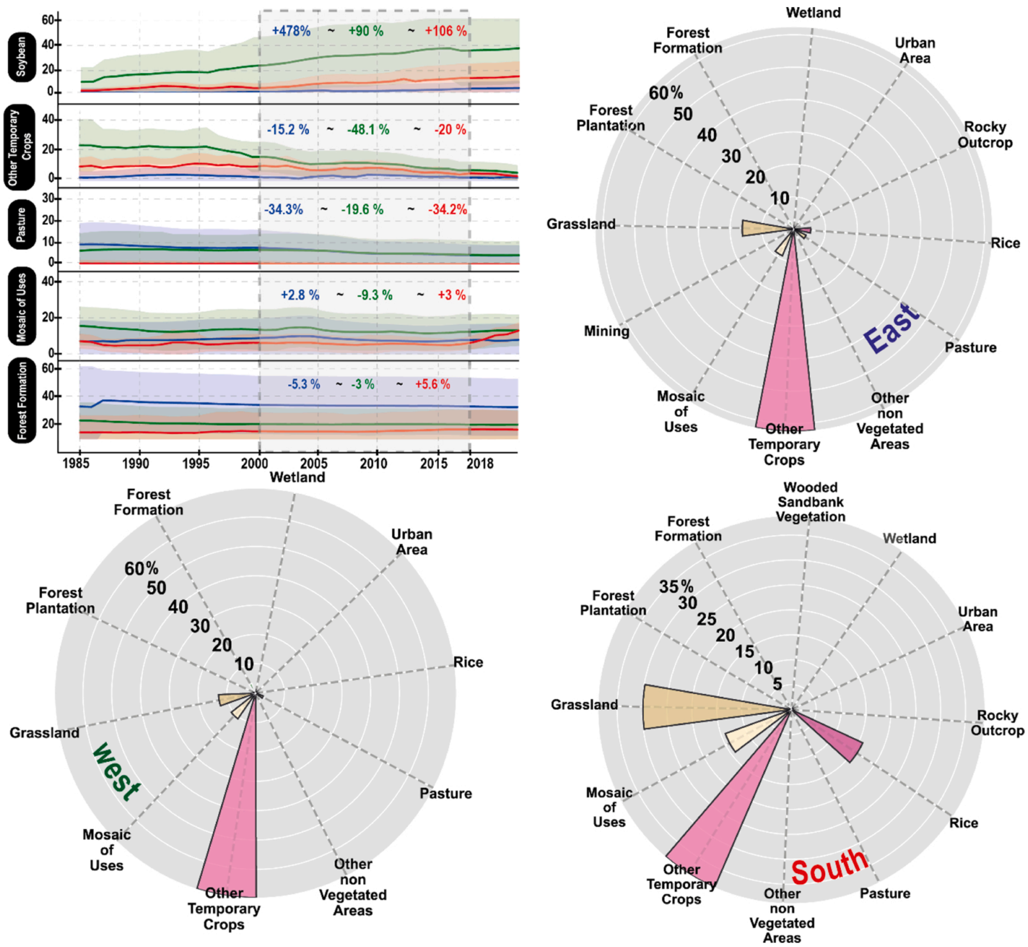


Fig. 5. The time series illustrates the evolution of the main LULC classes over time, and the shaded area represents the median values of the total changes with percentages in the y-axis within each cluster for the years before and after 2000. The radial bar graphs display the proportion of transition to soybean croplands from various LULC classes across clusters during the same comparison periods.

other hand, we had to aggregate rainfall and hydrological indices annually within the scope of this study to better comprehend the relationship whether rainfall or LULC changes are responsible for hydrological changes over study period.

4.3. LULC changes

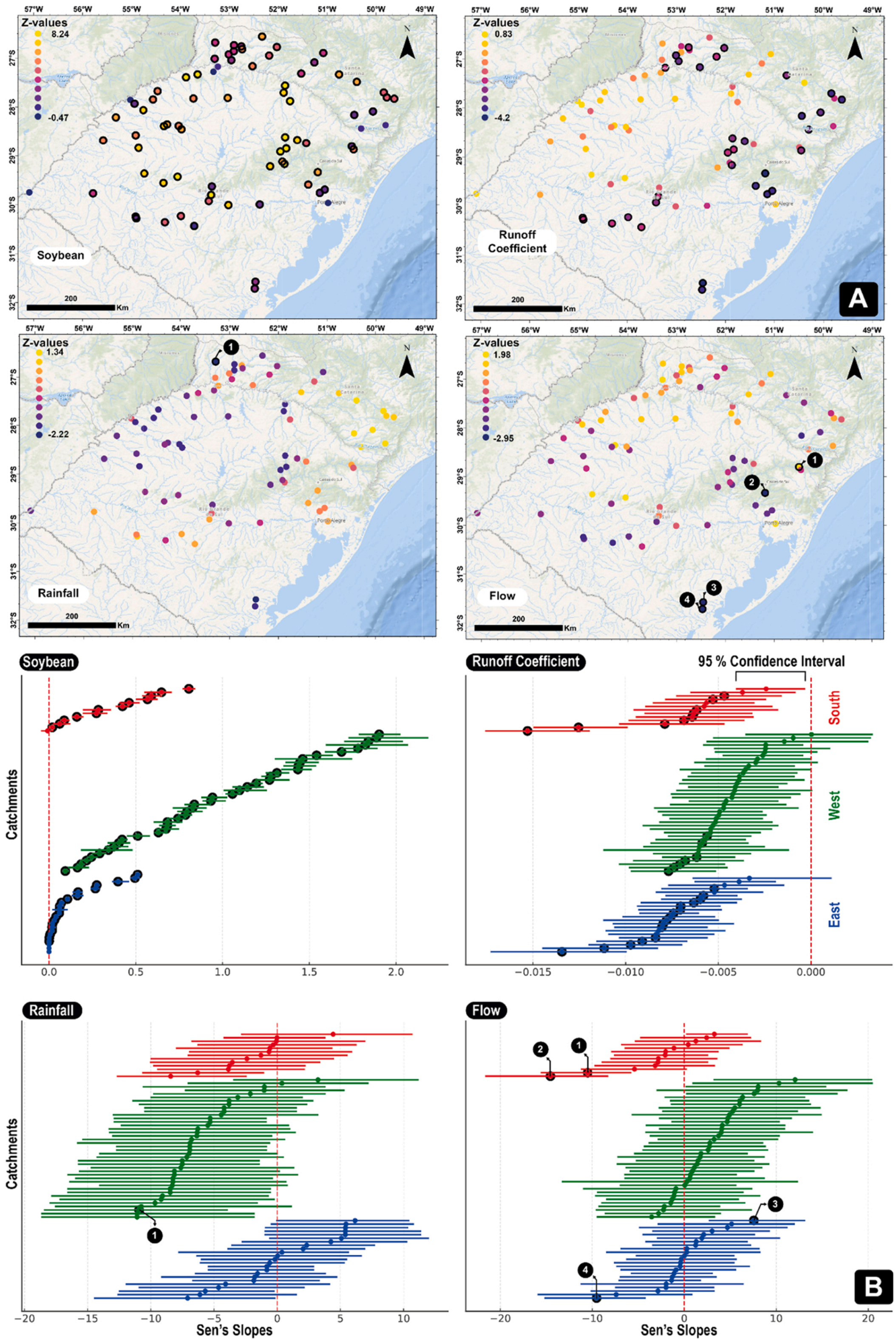
We found considerable changes in LULC between 1985 and 2018 in the study area (Supplementary figure 1). Most of the alterations within the 36 documented LULC classes (Supplementary figure 1) have taken place in regions classified as soybean, pasture, other temporary crops, forest formation, and a mosaic of uses (Fig. 5). The most striking changes occurred in the soybean cropland areas where we have found extensive changes during the period after 2000 compared to the period before 2000 such as 418 %, 90 %, and 106 % increases over clusters East, West, and South, respectively. Despite Brazil's Amazon Soy Moratorium (ASM) after 2006, which, to some extent, reduced the growth rate of the soybean croplands across Brazil (Heilmayr et al., 2020), we demonstrated the ongoing occurrence of soybean cropland expansion in Southern Brazil over time. For example, other temporary crops have mostly been replaced with soybean croplands, particularly in Clusters East and West (Fig. 5). For Cluster South, the predominant shifts in LULC classifications occurred with other temporary crops (40 %) and grassland (30 %), followed by rice (15 %) and mosaics of uses (15 %) unlike other clusters. These results also demonstrate that in contrast to areas like central Brazil (Heilmayr et al., 2020; Song et al., 2021), Southern Brazil has been less affected by deforestation over the last three decades. Instead, other LULC classes were replaced by soybean croplands (Fig. 5).

4.4. Implications on impacts of changes in LULC and rainfall on streamflow dynamics

Here, we explain and discuss the trend analysis results of rainfall, flow, runoff coefficient, and soybean for the entire period (i.e., from 1985 to 2018) since the most significant changes have occurred within the assessed indices and LULC classes. Fig. 6 illustrates the results of the trend analysis, revealing that although the outcomes differed across clusters, most of the gauging stations yielded statistically insignificant results for streamflow and rainfall. It is crucial to acknowledge that, although we recorded mean variations of 3 % in rainfall and 5.4 % in streamflow across the study area, the detected insignificant changes may suggest that the observed fluctuations are not indicative of a consistent long-term trend, as the Mann-Kendall test aims to reveal, but rather the result of isolated or transient oscillations. These findings are also consistent with a study by Chagas and Chaffe, (2018) showing statistically insignificant changes in rainfall and streamflow values even if their time frame spanned from 1975 to 2010.

Contrary to rainfall and flow, we found statistically significant decreasing trends in RC over the 32 stations, i.e. nearly half of the study areas. The findings indicated that 69 % (9 stations out of 13) of the stations in Cluster South exhibited a declining trend, reaching a maximum change magnitude of 0.015 y^{-1} represented by Sen's Slope (Fig. 6b). This result is supported by our findings that the RC and streamflow values in the study area decreased by approximately 38 % and 13 %, respectively, in comparison to the periods before and following the year 2000. Cluster East also showed a considerable decline in 64 % (16 stations out of 25) of the total areas for RC reaching up to 0.015 y^{-1}. Contrary to Chagas et al. (2020), who implied that forested basins would respond less to LULC changes, we found significant changes in Cluster East, which is the most forested region within the same research area (Fig. 3b). Even though Cluster West covers the largest area compared to other clusters, it resulted in the lowest number of stations (7 out of 40) with statistically significant changes in RC with 17.5 % of the total stations. Thus, it might be the consequence of the occurrence of large catchments in Cluster West masking the changes spatiotemporally where we are not able to identify variations.

To understand the changes in RC, we have examined the temporal changes in soybean croplands, given the absence of large variations in rainfall and streamflow, with the most substantial changes occurring in soybean croplands, as illustrated in Fig. 5. The results of the trend analysis further demonstrate that nearly all streamflow stations have experienced a statistically significant expansion of soybean croplands. It is interesting to observe a notable drop in RC (roughly 30 % pre- and after 2000) across the research area where drastic changes occurred with the expansion of soybean croplands. Indeed, it may be anticipated to observe increased surface runoff after replacing the lands with agriculture following the clearance of the forested basin (Mekonnen et al., 2018). However, as stated above and as shown in Fig. 5, most of the soybean croplands replaced other temporary crops. Therefore, we have compared the water demands of other temporary crops (i.e., maize, wheat, oats, rye, rapeseed, and dry beans) and that of soybeans. We observed a 27 % increase in water demands for soybeans relative to the average water demands of other temporary crops (Table 2). This may partly explain why RC decreased by roughly 30 % and why the rainfall variations were insufficient (i.e. magnitude of change) to compensate for RC decline. However, it is crucial to acknowledge that the relationship between drought and surface runoff loss, as indicated in the literature (Allen et al., 2011; Nalbantis and Tsakiris, 2009), may assist in elucidating the drop in RC, considering that we recorded an average 3.2 % increase in mean dry spells (Fig. 4). Therefore, the observed decrease in RC over the last three decades may be intricately linked to the steady expansion of the soybean croplands during the same period. Supporting this finding, on the one hand, literature demonstrated the expansion of croplands leading to increased water usage. For example, the increased water footprint has been shown by Mialyk et al. (2024) for Southern Brazil, which is ~30 % during the period from 1992 to 2019 due to the expansion of soybean croplands. Additionally, the construction of dams has been demonstrated to affect streamflow regimes by altering the variability, size, timing, and frequency of flow (Torabi Haghighi et al., 2014). For example, this effect may further elucidate, in limited extent, expansion of soybean cropland, clarifying the significant decrease in RC observed in the study area, as the number of dams increased from 6 to 14 and the overall catchment area equipped with dams expanded from 23.715 km^2 to 198.338 km^2 after 2000 compared to before 2000 (Fig. 3a). Nonetheless, this impact may be constrained relative to agricultural expansion, as dams are situated solely in the four catchments within our study area. Moreover, within these catchments, there are dams constructed both prior to and subsequent to 2000, which restricts the direct attribution of the dam's influence on alterations in runoff coefficients. Consequently, we



(caption on next page)

Fig. 6. Trend analysis results for rainfall, flow, RC, and soybean cropland areas. A) Spatial distribute of catchments in which Z-values indicate the threshold for statistical significance, with values exceeding + 1.96 or falling below −1.96 considered significant. Black circles surrounding the points indicate statistically significant trend results and some catchments were highlighted in rainfall and flow using black boxed numbers since there were few locations in their panel to improve visibility. B) The plots illustrate confidence intervals (CI) for rainfall, flow, RC, and soybean cropland areas, black circles also show identical catchments which are statistically significant catchments within the different clusters. Black boxed numbers were also used with the same purposes with trend maps improving visibility of the statistically important catchments.

Table 2
Comparison table of water demands for other temporary crops and soybean croplands. The other temporary crops are represented by Maize, Wheat, Oats, Rye, Rapeseed, and Dry Beans.

Crop	Water Demand (m^3/ha)	Source
Maize (Corn)	5000 m^3/ha	FAO (Doorenboos et al., 1977)
Wheat	4500 m^3/ha	FAO (Doorenboos et al., 1977)
Oats	6000 m^3/ha	(Chmielewski, 2007)
Rye	4000 m^3/ha	(Chmielewski, 2007)
Rapeseed (Canola)	6000 m^3/ha	(Chmielewski, 2007)
Dry Beans	3000 m^3/ha	FAO (Doorenboos et al., 1977)
Soybean	6050 m^3/ha	(Mekonnen and Hoekstra, 2010) and (Willaarts, Niemeyer, and Garrido, 2011)

may argue that human disturbances with agricultural expansion may infer the primary driving factor along with local and limited impact of dam construction compared to climatic indices in controlling streamflow patterns over the last three decades.

5. Conclusions

The LULC changes have been a long-standing issue for Brazil leading to severe environmental consequences. In this context, this study focuses on the comprehension of responses of hydrological processes to variations in rainfall and changes in LULC over the last three decades in Southern Brazil. Thereby, firstly, we have demonstrated that hydrological responses are site-specific; even within the same cluster, variances may arise due to differing local characteristics. Consequently, local and case studies are essential, while global analyses may hide the variabilities demonstrated through cluster analysis. Secondly, we have shown that not only deforestation is a major cause but also such spatially extensive changes in cropland types (i.e., the transition from other temporary crops to soybean) may cause significant alterations in surface runoff across Brazil.

Utilizing the annual LULC, rainfall, and streamflow data alongside time series trend analysis, apart from these main conclusions, we have obtained several main findings, which may be summarized as follows:

- The variations during more than three decades when compared to two periods before and after 2000 showed that rainfall remained relatively stable with an average 3 % decrease over the study area. This result is supported by increased mean dry spells and decreased high rainfall periods. The most remarkable runoff coefficient has decreased with a mean of 33.7 % over the study area while streamflow values demonstrate a magnitude (5.4 %) of decrease similar to that of rainfall. Furthermore, time series analysis indicated that spatiotemporal changes have appeared variably at a local scale (within the separate clusters) owing to distinctive environmental attributes, including diverse geomorphological and land use characteristics.
- LULC evolution over the three decades (1985–2018) has been quantified and it reveals a continuous expansion of soybean (~ 226 %) when comparing the situation before and after 2000. The growth of soybean croplands has primarily taken place in areas previously designated for other temporary crops.
- Trend analysis revealed statistically insignificant changes in rainfall and streamflow in line with the previous study by Chagas and Chaffe (2018), while the temporal expansion of soybean croplands was significant across the entire study area. Moreover, the runoff coefficient exhibited statistically significant variations, particularly at gauging stations situated in the East and South, with fewer stations in the West clusters. As a result, our findings indicated that increased water demands (27 %) resulted from the transition from other temporary crops to soybeans, along with limited and localized impact of dam construction could provide insight into the fundamental reasons for the observed decline in runoff coefficient.
- This work emphasizes the necessity for conducting further studies on the complex feedback mechanisms between alterations in crop types and surface runoff at a regional scale, considering climate variability and all crop types to improve watershed management techniques.

CRediT authorship contribution statement

Olivier Cerdan: Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization. **Néverton Scariot:** Writing – review & editing. **Marcos Tassano:** Writing – review & editing. **Olivier Evrard:** Writing – review & editing, Project administration. **Jean Paolo Gomes Minella:** Writing – review & editing. **Thomas Grangeon:** Writing – review & editing, Conceptualization. **Rosalie Vandromme:** Writing – review & editing, Supervision, Project administration, Conceptualization. **Aydoğan Avcıoğlu:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Aydogan Avcioglu reports financial support was provided by Bureau de Recherches Géologiques et Minières. Olivier Cerdan reports a relationship with French National Research Agency that includes:. There is no conflict of interest. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ejrh.2025.102705.

Data availability

Data will be made available on request.

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