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Key Points:

- We developed a novel framework by extracting hydrological drought events from catchments and computing their co-occurrence across all areas
- Brazil can be divided into five regions that share similar drought characteristics, connectedness, and also catchment features like aridity
- Understanding drought connectedness can inform risk pooling strategies and enhance resource allocation efficiency

Supporting Information:

Supporting Information may be found in the online version of this article.

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Spatially Compounding Drought Events in Brazil

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Abstract Spatially compounding drought events affect multiple locations simultaneously, severely affecting food, water, energy, human health, and infrastructure sectors. Despite the cascading impacts and challenges compound droughts impose on society, we still lack an in-depth understanding of spatially connected drought occurrences. Given the complexity and costs of droughts in Brazil, identifying regions prone to co-experiencing droughts is critical for developing effective adaptation measures. Here, we develop a novel framework to assess the spatial co-occurrence of hydrological drought events, which can be adapted for global applications to evaluate spatially compounding drought. This framework involves extracting drought data from individual catchments and calculating the co-occurrence of droughts across all catchments. We apply this method to investigate the spatial connectedness of droughts in 511 Brazilian catchments over 39 years (1983–2022). Additionally, we classify catchments based on drought duration, intensity, deficit, number of events, and spatial connectedness to identify regions with similar drought behavior. Our findings reveal significant variability in drought characteristics and connectedness across Brazil, with the Central-Northeast and Northwest Amazon regions being most affected by multiple and widespread droughts. We identify five distinct regions in Brazil that exhibit common drought behaviors, sharing attributes such as aridity, catchment area, and precipitation seasonality. These regions hold the potential to guide future adaptation plans for managing hydrological compound extremes at both the catchment and regional scales, including the development of risk pool networks. Our results underscore the importance of considering the interactions of spatially compounding hydrological droughts in risk assessments and adaptation strategies.

Plain Language Summary Droughts are a serious problem in Brazil and can greatly impact food, water, energy, human health, and infrastructure. However, we do not yet understand where and how droughts occur in multiple locations at the same time. To address this issue, we propose a novel framework to study the relationship between droughts in 511 catchments across Brazil over 39 years. Our results show that drought severity and connectedness vary in different parts of the country, with the Central-Northeast and Amazon's Northwest being the most affected. We divided the country into five regions with unique drought patterns to help us understand where these connected droughts might happen. This information can guide future plans for managing extreme droughts and risks. Our method can be used in other places too, helping us to understand drought connections globally.

1. Introduction

Hydrological droughts are characterized by periods of water scarcity or reduced water availability within the hydrological system (Van Loon & Laaha, 2015). They can affect large areas and persist from months to years, posing risks to individuals, economies, natural resources, and ecosystems (Bakke et al., 2020; Mishra & Singh, 2011; Wan et al., 2017). The intensification of the hydrological cycle due to climate change is projected to exacerbate future drought conditions in various regions worldwide, that is, Southwestern South America, Western North America, Mediterranean Europe, and Northern Africa (Cook et al., 2020; Satoh et al., 2022). Consequently, it becomes imperative to implement effective climate change governance and adopt mitigation and adaptation strategies for disaster risk management, as underscored by international initiatives such as the Sustainable Development Goals (SDG), the Sendai Framework for Disaster Risk Reduction (2015–2030), and the Paris Agreement on climate change (Peduzzi, 2019).

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To effectively implement disaster risk management, it is highly important to understand the intricate trade-offs, synergies, and interactions associated with multihazard risks in relevant hazards and sectors, while also considering the temporal and spatial aspects of extremes and the implications of their co-occurrence (Raymond et al., 2022; Ward et al., 2022). Traditional approaches to disaster risk management have often focused on individual hazards, overlooking the complex nature of climate extremes, which arise from a combination of spatially and temporally dependent processes (Ward et al., 2022; Zscheischler et al., 2018). In order to gain a deeper understanding of the risks posed by extreme events, it is crucial to take into account compound events, particularly at regional and global scales (Zscheischler et al., 2020). Compound events involve multiple drivers and/or hazards that contribute to societal and environmental risks. Among these, spatially compounding events represent a specific type, in which multiple locations are simultaneously impacted by the same hazard within a specific timeframe (Brunner, 2023; Zscheischler et al., 2018). Such events can trigger cascading effects on vital systems such as food and energy production and the economy, both at regional and global levels, thus emphasizing their significance as an important area of study (Zscheischler et al., 2020). For example, the severe drought in Brazil in 2019 and 2020, which affected multiple regions such as the Amazon and Pantanal, led to significant socio-ecological and economic consequences, such as reduced food production, animal deaths, and disruptions in transport due to low river levels (Marengo et al., 2021).

In recent years, there has been significant progress in understanding spatially compounding drought events on a global scale. Singh et al. (2021) conducted a thorough global investigation into the synchronized occurrence of meteorological droughts resulting from large-scale climate variability. Their findings revealed that during these occurrences of large-scale climate variabilities, the likelihood of experiencing widespread and severe compound droughts increased. Additionally, Mondal et al. (2023) have identified the potential for large-scale simultaneous meteorological droughts across regions known as drought hotspots, including southern Europe, Northeast Brazil, Australia, and the Northwest United States of America (USA). Moreover, Brunner et al. (2021) have observed an increase in the spatial extent of hydrological droughts, suggesting that ongoing global warming may further increase the extent of drought in the USA. Konapala et al. (2022) investigated spatial meteorological drought propagation in North America and indicated that coupled oceanic-atmospheric interactions, the net flux of water, and wind directions primarily control the spatial distribution of the source locations and drought propagation. Notably, existing studies examining spatially compounding droughts have focused predominantly on meteorological droughts, with limited attention given to hydrological droughts.

Despite extensive global research efforts, South America, particularly Brazil, has received limited attention in drought research, even though it covers approximately 50% of the continent and has recently experienced severe drought events (Cunha et al., 2019). Previous studies in Brazil have primarily focused on specific areas and other types of compound events, such as the combination of droughts and heatwaves (Geirinhas et al., 2021; Libonati et al., 2022). Studies specifically addressing hydrological droughts are fewer and often concentrate on specific regions or the transition from meteorological to hydrological droughts (Gonçalves et al., 2023; Junqueira et al., 2022). For instance, several investigations have focused on the semi-arid region, a drought-prone area (da Silva et al., 2024; Van Langen et al., 2021). Exceptions to this regional focus are rare but noteworthy. For example, Cuartas et al. (2022) studied hydrological droughts in basins used for hydropower across the country. Tang et al. (2023) estimates terrestrial water storage changes to characterize hydrological droughts in Brazil. Additionally, Bevacqua et al. (2021) investigated hydrological drought propagation nationwide.

Brazil's significance as one of the world's main breadbaskets highlights its crucial role in global food security (Zeigler & Nakata, 2014). The occurrence of large-scale and spatially connected droughts in Brazil could have far-reaching consequences, leading to synchronized crop yield failures (Gaupp et al., 2019; Mehrabi & Ramankutty, 2019). These events not only affect the agricultural sector, but also spread to other industries heavily reliant on water resources, including the hydroelectricity sector, which supplies approximately 70% of Brazil's energy needs (Gesualdo et al., 2021). Consequently, water scarcity and drought-induced disruptions have the potential to cascade across various sectors, threatening the country's food, energy, and water supply, thus demanding a comprehensive approach to water security and disaster risk management. Despite their potentially severe impacts, spatially compounding hydrological drought events in Brazil and many regions worldwide have not yet received extensive investigation. Therefore, this study aims to comprehensively investigate how hydrological droughts are spatially connected throughout the Brazilian territory and group catchments according to their drought connectedness.

Specifically, our analysis addresses the following questions: (a) "How susceptible is Brazil to droughts on a local scale?," (b) "Which climatic factors and physiographic attributes influence this local drought susceptibility?," (c) "How are droughts connected in space?," and (d) "Which catchments are similar in terms of their local and regional drought hazard?." In order to answer these questions, we propose a novel framework to assess the spatial co-occurrence of hydrological drought events in 511 Brazilian catchments over a 39-year period (1983–2022). This framework allows us to present the first comprehensive country-wide assessment of spatially compounding hydrological droughts in Brazil. Based on our findings, we propose a division of the country into five catchment groups. By undertaking this investigation, we facilitate informed decision-making regarding water resources and disaster risk management.

2. Material and Methods

2.1. Study Region and Data Set

The co-occurrence of hydrological drought was investigated in 511 catchments in Brazil using a large-sample data set of Catchment Attributes for Brazil (CABra) (Almagro et al., 2021a). The CABra data set provides daily climate and streamflow variables for a 30-year period (1980–2010) and includes catchments with time series of up to 10% of missing data. Moreover, it provides catchment attributes related to topography, climate, streamflow, groundwater, soil, geology, land use and land cover, and hydrologic disturbance classes. In this study, we updated the original daily streamflow time series of the CABra data set for a 39-year period (1980–2019). The distribution of the catchments within the country across biomes and the 12 Brazilian hydrographic regions is visualized in Figure 1. We also add catchment aridity index scales by area as a reference for the reader (Figure 1c).

Assessing spatially compounding hydrological drought events consists of three main steps (Figure 2) described in the following subsections: (a) extracting drought events in individual catchments; (b) determining drought co-occurrence across all catchments; and (c) grouping of catchments according to their co-occurrence of drought.

2.2. Drought Event Identification

The drought events were extracted in individual catchments using a variable threshold level method (VTLM) and the 15th flow percentile with a 30-day moving window (Figure 2a). VTLM identifies streamflow anomalies instead of low flows and is suitable for regions with seasonal streamflow regimes (Brunner et al., 2021; Heudorfer & Stahl, 2016; Van Loon, 2015). The daily streamflow time series was smoothed over a 30-day moving window prior to event identification to avoid identification of dependent events (Brunner et al., 2021) and the drought threshold was set at the 15th flow percentile. This percentile was computed for each day of the year based on the rolling time series of flows 15 days before through 15 days after the day of interest. To illustrate, for a specific day, such as 16 January 1980, we averaged the streamflow data from 1 to 30 January 1980. Similarly, for 31 January 1980, we averaged the streamflow data from January 16th to February 14th, 1980, and so forth until 15 December 2020. It's important to note a missing 30-day moving average streamflow data from 1 to 14 January 1980, and from 16 to 31 December 2020, were considered not relevant due to the comprehensive analysis covering a 40-year period. As for the minimum duration, we consider 30 days, in order to limit our event selection to significant events and facilitate our result comparison with other indices, such as the Standardized Runoff Index (SRI) utilized by the Brazilian Drought Monitor (Monitor de Secas do Brasil—MSB), which operates on monthly time scales (de Brito et al., 2021).

For each catchment, we determined the number of drought events, and for each identified event, we computed different drought characteristics, namely duration (days), deficit (mm.event^{-1}), and intensity (mm). The duration was determined as the number of consecutive days during which the smoothed streamflow time series was below the threshold. The drought deficit, that is, drought volume, is the area between the drought threshold and the smoothed time series, calculated as the sum of deviations from the threshold times the number of days during the entire drought event. Intensity is defined here as the absolute value of the minimum flow during the drought event.

To investigate the relationship between catchment attributes and the mean drought characteristics, we computed Spearman's correlation coefficient, which is non-parametric rank correlation test. Spearman's test measures monotonic trends between variables, making it robust in cases where linear relationships are not present. This test has been extensively employed in hydrology, particularly in studies involving drought indices (Tijdeman et al., 2018;

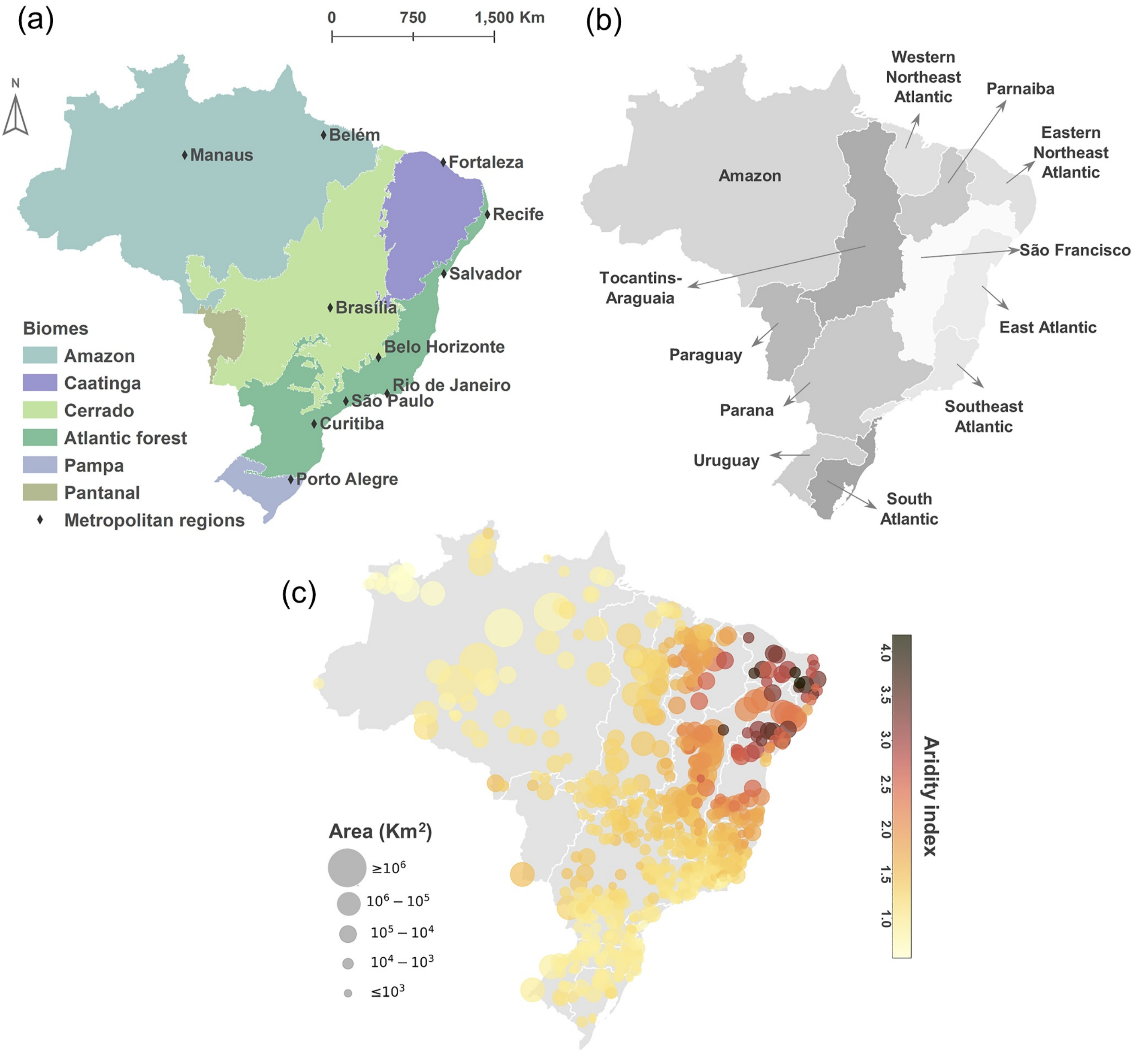

Figure 1. (a) Brazilian biomes and the main metropolitan regions, (b) 12 hydrographic regions, and (c) CABra's catchments, colored according to their aridity index and scaled by area.

Yang et al., 2019). The selected attributes cover topography, climate, hydrology, groundwater, and hydrological disturbance (Table 1) they were calculated and retrieved from Almagro et al. (2021b).

We performed a sensitivity analysis to investigate how changes in drought characteristics respond to variations in the choice of threshold and the moving window at individual sites. We varied the drought threshold between the 10th, 15th, and 20th percentile and adjusted the moving window for smoothing the time series to 10, 20, and 30 days, following common practices in variable threshold-level approaches for droughts (Van Loon & Van Lanen, 2012) and noted in various studies (Heudorfer & Stahl, 2016; Hisdal et al., 2024; Sutanto & Lanen, 2021). The sensitivity analysis focused on the impact of the drought threshold and moving window on drought characteristics such as the number of events, intensity, deficit, and duration. A lower threshold resulted in fewer events with shorter duration, smaller deficits, and lower intensity values (Figure S1 in Supporting Information S1). Similarly, a shorter moving window was associated with a smaller number of drought events, shorter duration,

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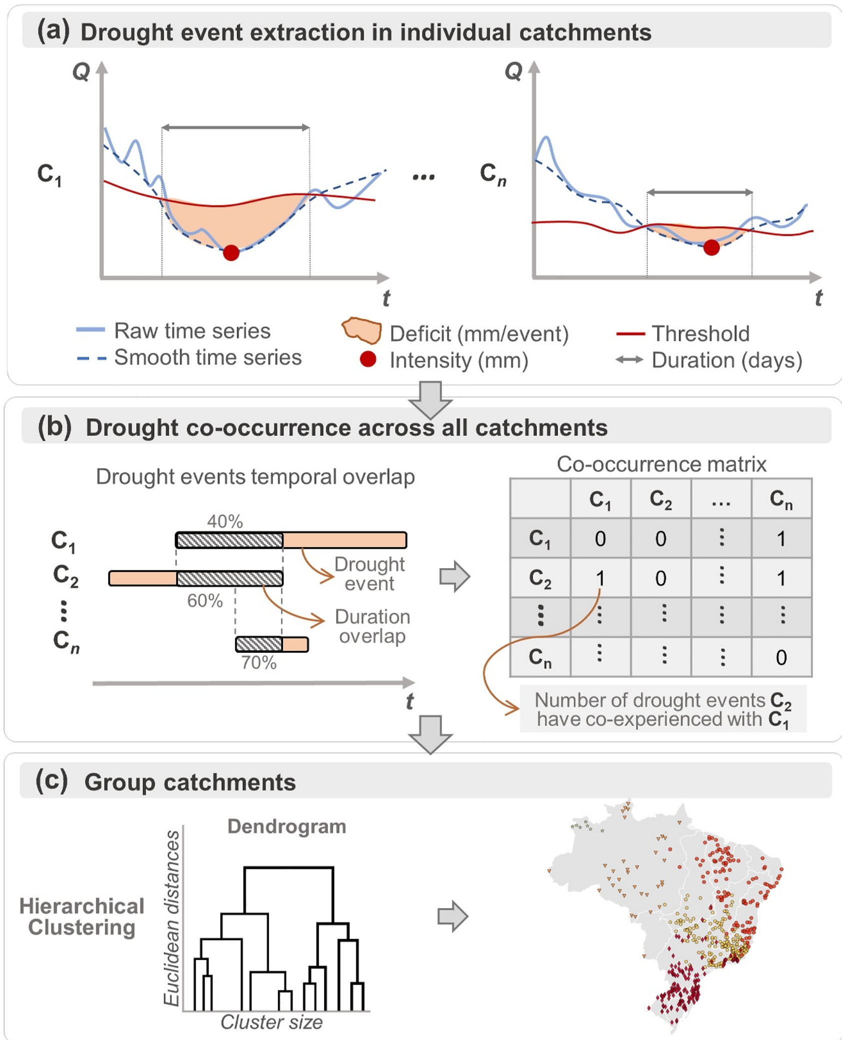

Figure 2. Workflow illustration of the spatially compounding hydrological drought event assessment: (a) extract drought events in individual catchments $(C_1, \ldots, C_n)$ using a variable threshold level method (VTLM); (b) determine drought co-occurrence across all catchments $(C_1, C_2, \ldots, C_n)$; and (c) group catchments according to their drought co-occurrence risk by applying agglomerative hierarchical clustering to different drought characteristics.

and smaller deficit and intensity. While the number of events and the duration of the event was to some degree sensitive to the choice of the threshold, the event deficit and intensity showed minimal variation with changes in the threshold and moving window length. For the subsequent analysis, we selected a drought threshold at the 15th flow percentile and a 30-day smoothing window, which resulted in an average of 20 drought events per catchment over the 39-year period, with a median duration of 66 days. We acknowledge that while we aimed to choose the most representative values for this methodology, the selection of a specific threshold level can be subjective, as highlighted by Fleig et al. (2006), representing a limitation of the method.

2.3. Quantification of Drought Event Co-Occurrence

The spatially compounding drought events were identified based on the connectedness measure introduced by Brunner et al. (2020). This measure quantifies the number of catchments that co-experience a drought event with a specific catchment, enabling the quantification of synchronized drought events and the spatial analysis of catchments and their dependencies. For instance, if a catchment C_n is experiencing a drought and five other catchments are also undergoing drought conditions simultaneously, the connectedness measure would be five, indicating that the catchment C_n is experiencing a drought event concurrently with five other catchments.

Table 1
Selected Catchment Attributes, Retrieved From Almagro et al. (2021b)

Type	Attribute	Description	Unit
Topographic	Catchment area	–	Km^2
	Mean slope	–	%
	Mean elevation	–	m.a.s.l.
Climatic	Precipitation seasonality	The timing of the precipitation and temperature seasonal cycles, with positive values indicating summer precipitation, and negative ones referring to winter precipitation	–
	Aridity index	The ratio between mean-annual potential evapotranspiration and precipitation, that is, the higher the index value, the greater the aridity (Meira Neto et al., 2020)	–
Hydrological	Streamflow elasticity	Indicates the impact of precipitation on streamflow	–
Groundwater	Height above the nearest drainage (HAND)	Normalized drainage version of a digital elevation model, which indirectly indicates the water table depth	m
Hydrological disturbance	Distance to coast	Distance between the gauge (outlet) and the nearest coast	km
	Distance to urban centers	Distance between the gauge and the nearest urban center	km
	Hydrological disturbance index	Estimates the degree of human interactions on water fluxes by taking land use and land cover into account	–

The methodology developed by Brunner et al. (2020) was first introduced to assess the spatial connectedness of floods in the United States, based on complex network analysis. A network is a collection of objects that interact with each other, forming a topology. When this topology is non-trivial, the network is considered complex. Interactions can be binary (node A interacted with node B), weighted (the number of interactions between node A and node B), or temporal (the precise time step when node A interacted with node B) (Kolaczyk & Csárdi, 2014). Complex network theory explores the topological characteristics of interconnected events, and is commonly used to investigate the spatio-temporal characteristics of hydroclimatic extremes, such as monsoonal rainfall (Malik et al., 2012), drought propagation (Konapala & Mishra, 2017), and the spatial and interconnected structure of large-scale droughts (Mondal et al., 2023).

In this study, we further developed the methodology by Brunner et al. (2020) to analyze the co-occurrence of droughts, building our framework based on complex network analysis. Significant modifications were made to the original procedure due to the longer duration of droughts compared to floods. The primary modification was the definition of connections: we define a pair of catchments as connected when they co-experience at least one drought event with a minimum of 50% temporal overlap. By introducing the 50% overlap measure, we prevent catchments with short or very long drought durations from having excessive or poor co-occurrences.

The procedure is illustrated in Figure 2b using an example of three catchments. The drought event in C_2 has a temporal duration overlap of 60% with C_1, so C_2 is considered to co-experience a drought with C_1. However, the opposite is not true, since the drought event in C_1 has only 40% of temporal duration overlap with the drought event in C_2, which does not satisfy the connectedness condition. The same behavior happens with C_n, which is considered to co-experience drought with both C_1 and C_2, with a temporal overlap of 70%. However, the droughts in C_1 and C_2 are unconnected with C_n, since their temporal overlap is much smaller than the threshold of 50%.

The co-occurrence results are then summarized in a matrix that quantifies, for each pair of catchments, how many drought events they have co-experienced. This matrix allows us to quantify the connectedness of individual catchments, indicating the number of times a catchment co-experiences a drought event with others.

2.4. Grouping Catchments

In order to identify groups of catchments that are similar in terms of drought occurrence and are likely to co-experience drought, we applied an agglomerative hierarchical clustering algorithm (Figure 2c). The similarity matrix used for hierarchical clustering was computed considering different drought characteristics, that is, deficit, intensity, duration, number of events, and spatial connectedness. Using the algorithm, every catchment is first assigned to its own cluster, and at each iteration, the two most similar clusters are joined until there is a single cluster. The similarities between clusters are measured at each iteration using Ward's criterion (Rao & Srinivas, 2006). We determined the appropriate number of clusters by combining clustering trees with the dendrogram and the silhouette width, settling on five clusters due to their stability and silhouette score (Figure S2 in Supporting Information S1). Furthermore, we examined the characteristics of the catchment (Table 1), such as streamflow elasticity, the aridity index, mean elevation, mean slope, distance from the coast, the hydrological disturbance index, the catchment area, and precipitation seasonality, within the different drought clusters.

3. Results

3.1. Spatial and Temporal Drought Patterns

Our findings show that drought characteristics vary substantially across Brazil (Figure 3). Compared to the north-central part of Brazil, the number of drought events is substantially higher in the Northwest of the Amazon, the South and Southeast of Brazil, and the coastal areas (Figure 3a). Although these regions face a higher number of events, they also experience droughts with shorter durations (Figure 3b). Especially in the Amazon Northwest and the Southeast of the country, droughts are highly intense and have large deficits (the highest records in the country) (Figures 3c and 3d). It is worth noting that the high-intensity droughts found in the catchments in the Southeast near the Metropolitan Region of São Paulo pose a high risk to this densely populated region. In contrast, long-lasting events were found in the semi-arid Brazilian region, as expected, since it is a drought-prone area.

The Spearman's correlation between the different drought characteristics and the 11 selected catchment attributes (Table 1) is summarized in Figure 4. We find significant correlations between catchment aridity and all drought characteristics. The aridity index is positively correlated with drought duration ($p = 0.31$) and negatively with deficit ($p = -0.70$), intensity ($p = -0.57$), and the number of events ($p = -041$), highlighting that more arid regions have longer-lasting events with lower deficit and intensity. These arid catchments are located along Northeastern Brazil and are known for their frequent droughts (Brito et al., 2018). We also observed a significant positive correlation between the catchment area and drought duration ($p = 0.30$) and a negative correlation between the catchment area and drought deficit ($p = -0.37$), showing that larger basins have longer-lasting droughts with lower deficits. The second most correlated attribute with drought intensity is streamflow elasticity ($p = -0.37$), which has a negative correlation, indicating that catchments with a higher sensitivity of streamflow to precipitation show less intense droughts. These catchments can be found in Brazil's Northeastern region. We also find a negative correlation between precipitation seasonality and the number of drought events ($p = -0.35$), indicating that places, where the precipitation season occurs in summer (precipitation seasonality values close to +1), have fewer drought events.

3.2. Drought Connectedness

We find that also drought connectedness varies substantially across the country. It is represented by the number of synchronized drought events between a pair of catchments, as indicated by the gray lines in Figure 5 and by the mean number of events per year during which a catchment is connected with other catchments as indicated by the color of the nodes. Connectedness is high (connectedness $\geq$18) along the Central-Northeast and Amazon's Northwest. In addition, the Central-Northeast region, which includes the large basins of the São Francisco and South Atlantic, as well as the Parnaiba and Tocantins-Araguaia rivers, has the highest number of connected events per year. This suggests that this region is the most susceptible to the occurrence of multiple and widespread droughts in the country. Despite the fact that the Amazon's Northwest has a high level of drought connectedness, the mean number of connected occurrences per year is low ($\leq$30). This is because the catchments in the region are connected to one another, but the probability of co-occurrence with drought events in other regions of the country is low. As a result of this disconnection, the number of connected events per year is comparably low. A similar connection pattern is observed in the country's Southern catchments. They are mostly linked to each other, but appear to be independent of drought events in other parts of the country.

3.3. Drought Similarity Regions

The country was divided into five regions (clusters) based on similar drought characteristics and catchment spatial connectedness (Figure 6). In the first cluster (C1), catchments in Central Brazil exhibit high connectedness, low deficit and intensity, and significant variability in the number of drought events and their duration. The second cluster (C2) comprises the majority of catchments in Northeastern Brazil, characterized by a large variability in

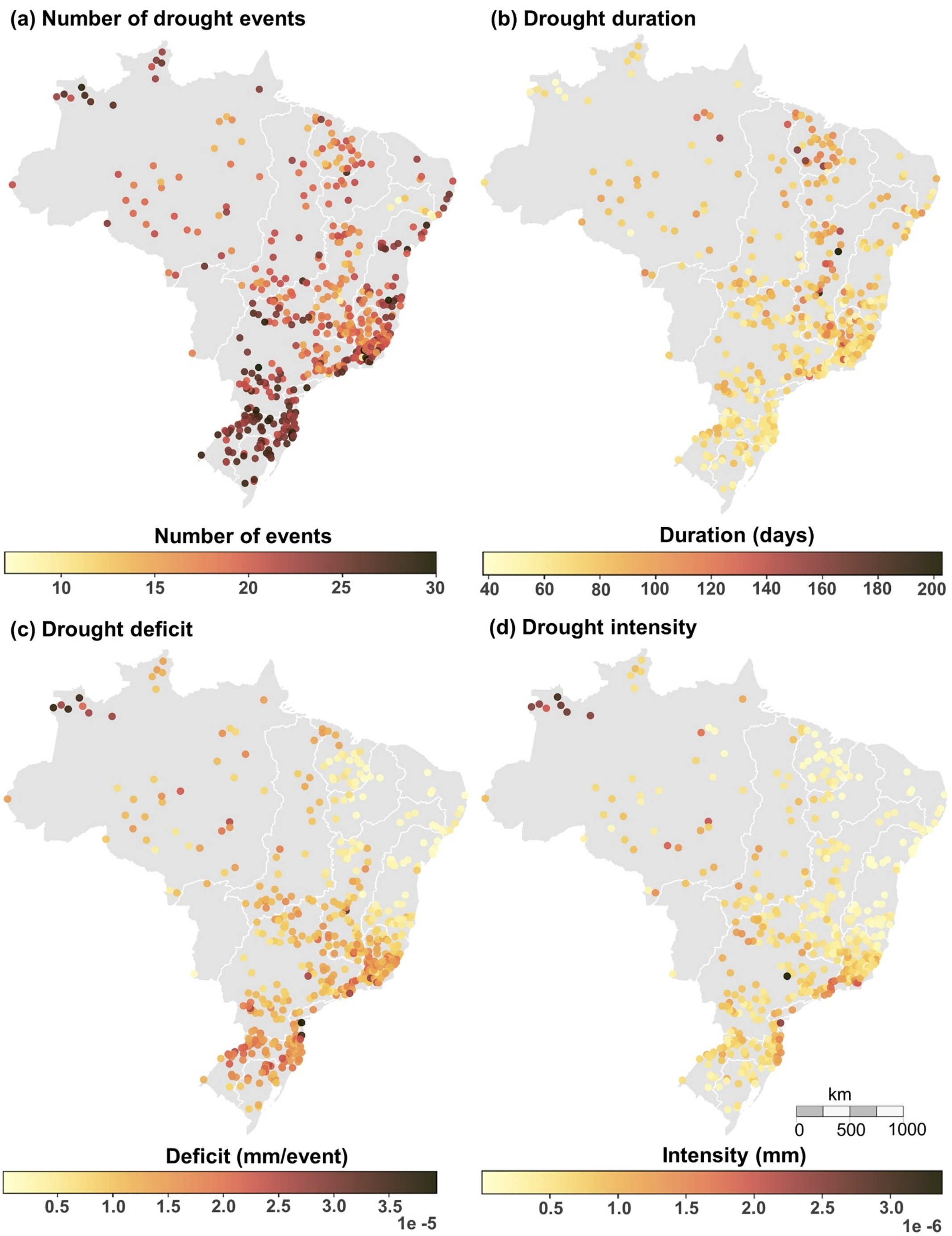

Figure 3. Spatial distribution of drought characteristics: (a) number of drought events, (b) drought duration in days, (c) drought deficit in mm per event, (d) drought intensity in mm.

drought duration, number of events, and connectedness. However, compared to the rest of the country, the intensity and deficit of droughts are small. The catchments in the country's Southeast and South build the third cluster (C3 ♦). It shows medium connectedness and deficit, as well as moderate duration and intensity, but a high number of events. The fourth cluster (C4 ▼) includes the majority of the catchments in the Amazon and Pantanal, sharing characteristics like weak connectedness and moderate intensity, along with considerable variability in drought duration. The fifth cluster (C5 ★) is composed of seven catchments in the Northwest Amazon, delineated by low drought connectedness and duration, as well as high drought intensity, deficit, and number of events.

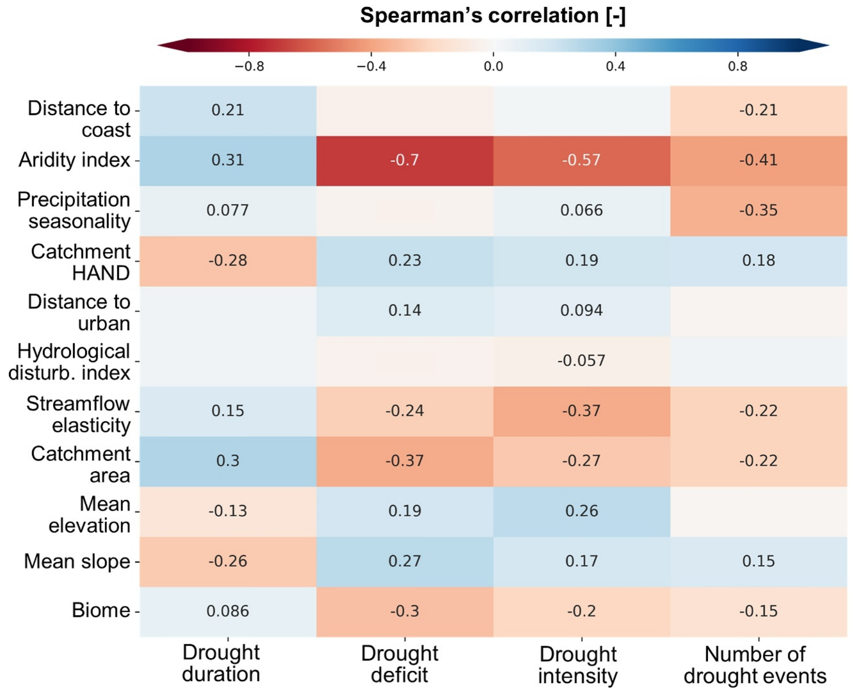

Figure 4. Heatmap of Spearman's correlation between four mean drought characteristics and different catchment attributes. All reported values indicate a significant correlation (p-value ≤ 0.05). Positive and negative correlations are indicated by red and blue colors, respectively.

We further explore the catchments' physiographic and hydro-climatic attributes across the drought clusters (Figure 7). Catchments located in the C1, C3, and C5 regions have a low aridity index, substantial variability in slope and elevation, and are characterized by small catchment areas and high precipitation seasonality. These two regions differ in their hydrological disturbance, with C1 catchments showing medium disturbance and C3 including catchments with a wide variety of disturbances, that is, catchments without any disturbance but also catchments with the highest values of hydrological disturbance among all catchments. Catchments in C2 are located mostly in the semi-arid region of the country, marked by significant aridity (Figure 7b), and show a high streamflow elasticity and seasonality of precipitation. C4 and C5 are both characterized by low elevations and weak hydrological disturbances but differ in terms of precipitation seasonality, with C5 having very low seasonality. C5 also stands out for including very small and very large catchments, including the largest in the country (Figure 7g).

4. Discussion

4.1. Drought Connectedness and Similarity Regions

We here combined an assessment of local hydrological drought characteristics with an assessment of the spatially compounding nature of hydrological drought. Our regional hazard assessment revealed that the Amazon Northwest experiences intense droughts with relatively short event duration (Figure 3). This finding aligns with previous studies reported in the literature. For instance, Chaudhari et al. (2019) observed severe meteorological droughts in most of the Amazon River basin in 1995. However, the severity of the corresponding hydrological drought was relatively minor due to the region's strong sub-surface storage regulation. This event illustrates the important role of groundwater-surface water exchange in mitigating dry conditions and leading to comparably short drought durations even in cases of extended dry seasons (Espinoza et al., 2016; Marengo & Espinoza, 2016). In contrast to the Northwest region, the Central North region of the Amazon experiences a smaller number of drought events, characterized by lower deficit and intensity but longer duration. Considering that the larger catchments are predominantly situated in the Amazon's Central North region, this spatial variation can be explained by the correlation between catchment area and drought duration (positive correlation) as well as with the drought deficit (negative correlation) (Figure 4).

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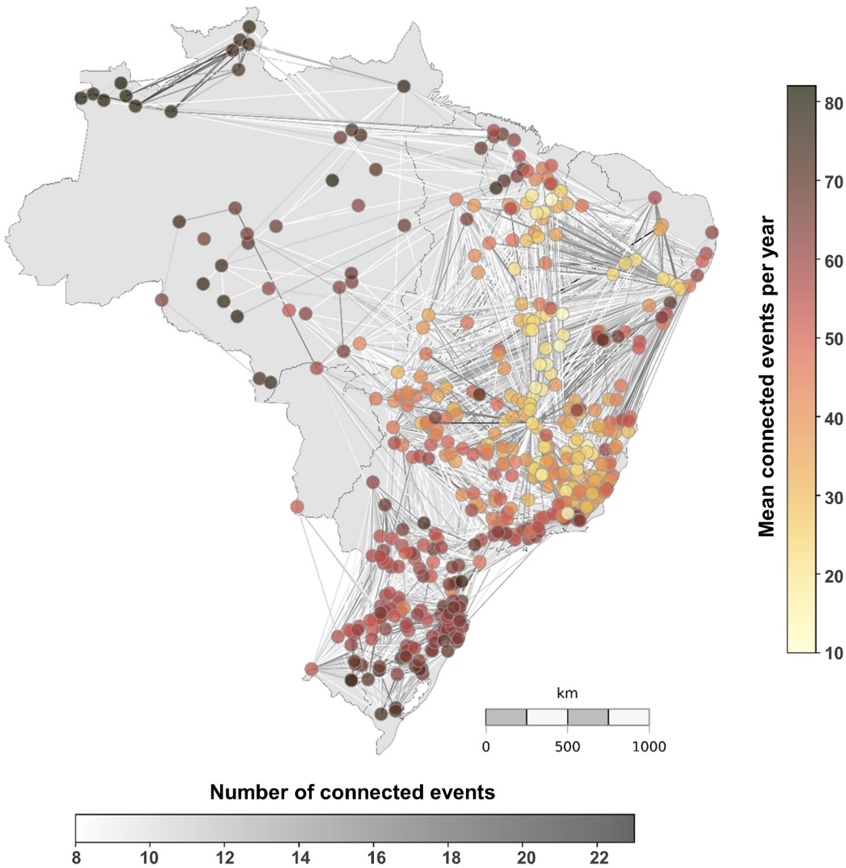

Figure 5. Brazil's drought co-occurrence network. The lines represent drought connectedness between catchments, with at least eight events in common. The catchment nodes are colored according to the mean number of connected events a catchment experiences per year, calculated by considering an average of the number of times a catchment co-experiences a drought event with other catchments over a 39-year period. The darker the color, the greater the number of connections.

In terms of the number of drought events, the Amazon's Northwest, as well as the South, Southeast, and coastal areas of the country exhibit significantly more drought events compared to Brazil's North-Central region (Figure 3a). These findings are consistent with Tang et al. (2023)'s systematic investigation of hydrological drought in Brazil, which found a high frequency of events in the northeastern and southeastern parts of the country. Additionally, the frequency of drought events is negatively correlated with precipitation seasonality (Figure 4). In Brazilian catchments, a higher degree of precipitation seasonality (values close to one) appears to favor baseflow while discouraging quickflow (Ballarin et al., 2022). This phenomenon could explain why catchments characterized by summer-dominant rainfall (with precipitation seasonality close to one, and therefore favored by baseflow), such as those found in the Midwest and southeastern Brazil, exhibit fewer drought events.

The North-Central region of Brazil, specifically the hydrographic regions of São Francisco, Tocantins-Araguaia, Western Northeast Atlantic, and Parnaiba—known as the semi-arid region—undergo long-lasting droughts (Figure 3). This semi-arid region is naturally dry and has a history of water scarcity, motivating a complex network of over 17 thousand reservoirs (Nascimento & Ribeiro Neto, 2017), which not only alters local flow regimes but also impacts hydrological extremes. The reservoir network in the region could explain the negative correlation between the aridity index and drought intensity and deficit (Figure 4) since previous studies have demonstrated that reservoir regulation has a local-scale influence on drought characteristics, reducing their severity in terms of magnitude and volume while increasing their duration (Brunner, 2021).

Generally, drought intensity is negatively correlated with streamflow elasticity—highlighting the sensitivity of the streamflow to precipitation (Figure 4). This suggests that catchments with higher streamflow sensitivity to precipitation tend to have less intense droughts, as observed in the Northeast region (Figure 3d). The hydrological

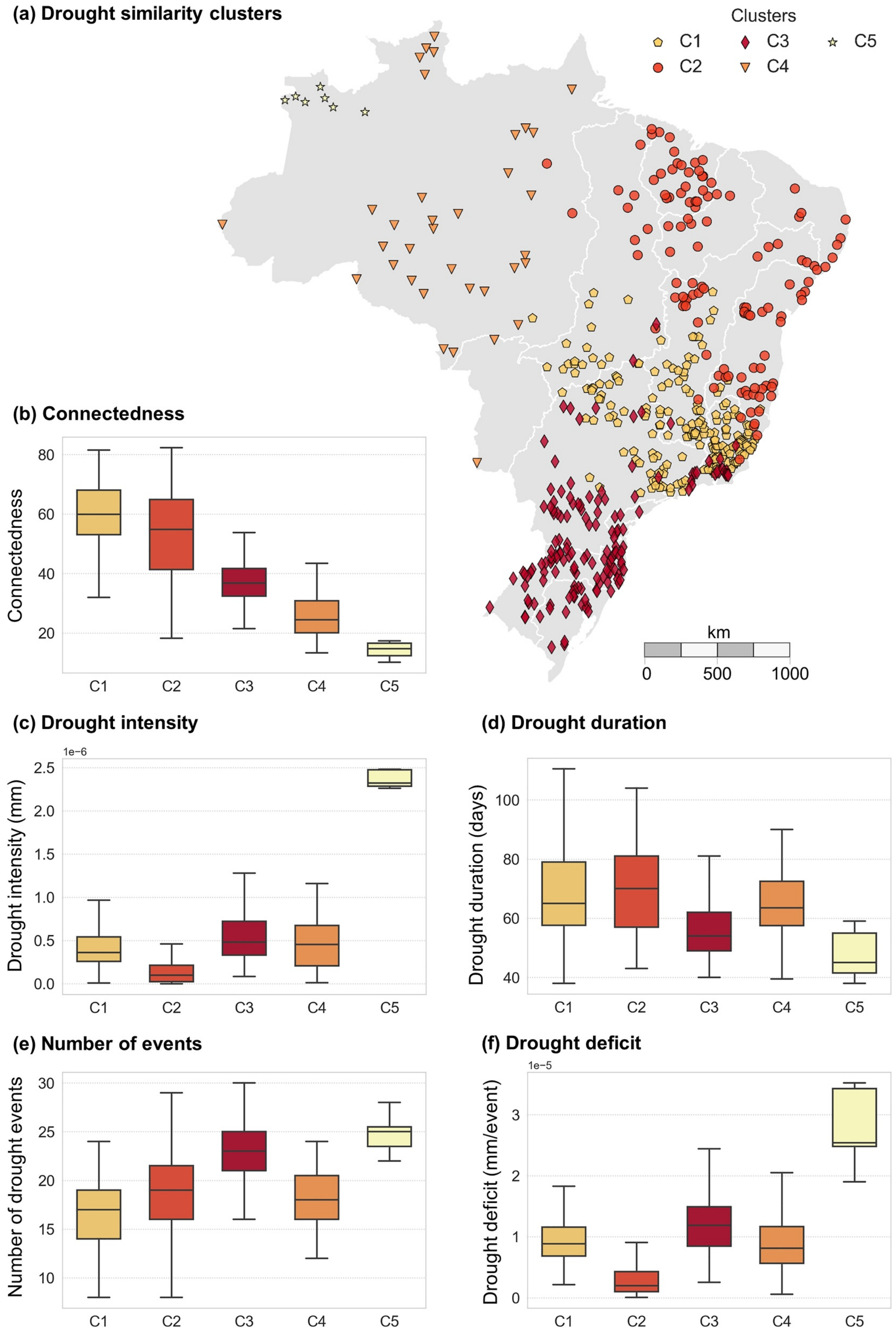

Figure 6. Drought similarity clusters and their characteristics. (a) Drought similarity clusters, (b) connectedness, (c) drought intensity (mm), (d) drought duration (days), (e) number of events, and (f) drought deficit (mm/event). The drought characteristics (b–f) were used to compute the similarity matrix which was used for hierarchical clustering.

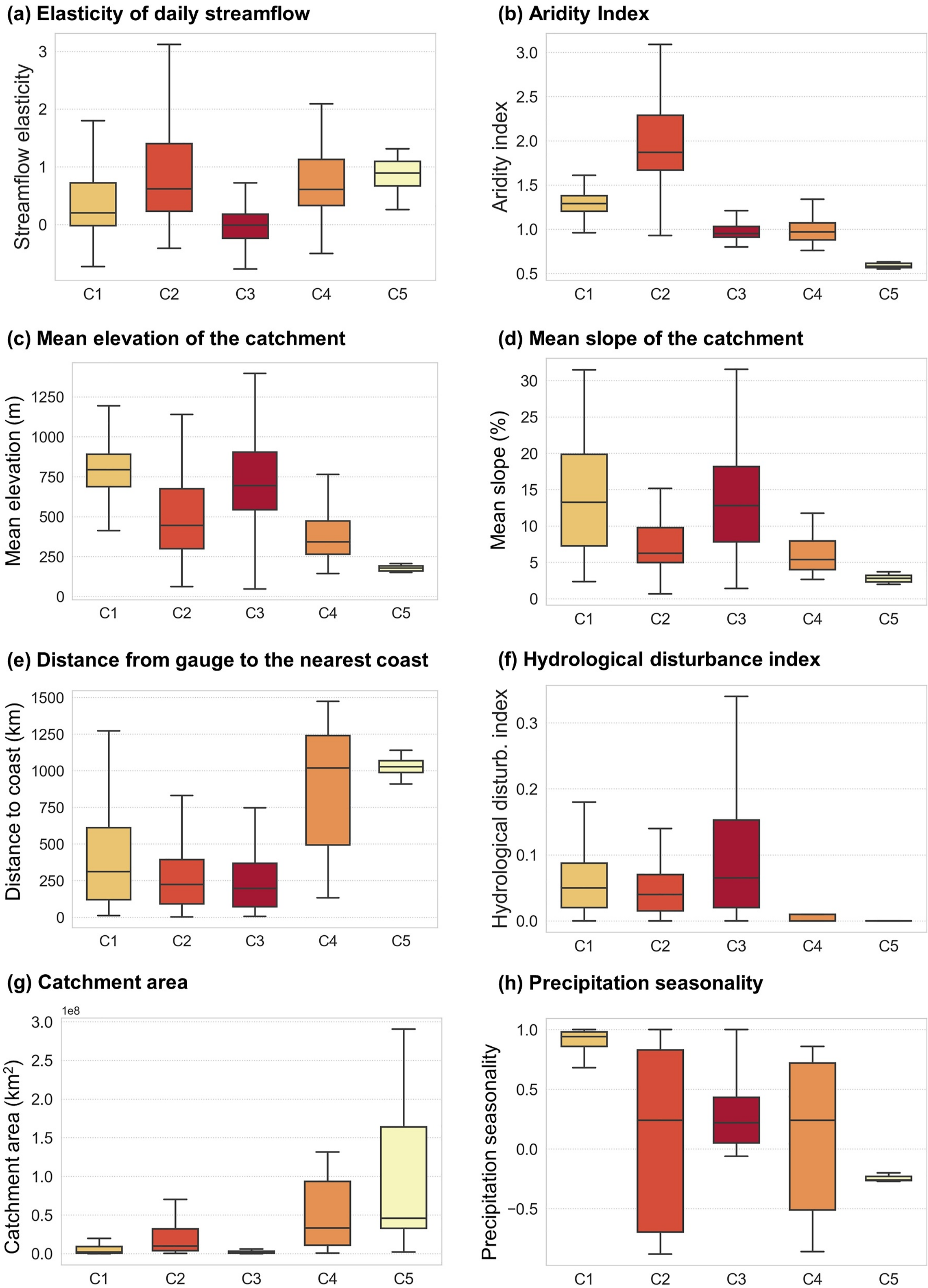

Figure 7. Catchment attribute variability across drought similarity clusters. (a) Streamflow elasticity, (b) aridity index, (c) mean elevation of the catchment (m.a.s.l.), (d) mean slope of the catchment (%), (e) distance from gauge to the nearest coast (km), (f) hydrological disturbance index, and (g) catchment area (km^2), (h) precipitation seasonality. These characteristics were not used for cluster formation.

patterns in the Northeast region are shaped by particular characteristics that affect both surface and subsurface hydrological processes, as emphasized by Montenegro and Ragab (2010). Specifically, the region's unique characteristics, including soil composition, hillslope configuration, and vegetation cover, influence subsurface hydrological processes and contribute to the observed negative correlation between drought intensity and streamflow elasticity (Figure 4). This negative correlation may also result from strong inter-catchment hydrological dependencies in the region, where effective precipitation exceeds surface runoff and contributes to subsurface flow. Consequently, minimal baseflow emerges from deeper groundwater to surface flow in these catchments (Schwamback et al., 2022).

Unlike the catchments in the Northeast of Brazil, the ones located in densely populated areas, particularly in the South and Southeast regions of Brazil within the metropolitan areas of São Paulo, Rio de Janeiro, and Curitiba, exhibit high values of drought deficit and intensity. These findings are consistent with the research conducted by Bevacqua et al. (2021), which identified the most severe and prolonged hydrological droughts in those areas of Brazil that are most impacted by human activities. Other studies also emphasize that the severity of hydrological drought is significantly influenced not only by terrestrial hydrological processes, but also by anthropogenic activities (Van Loon & Laaha, 2015). The Southeast and South regions of the country, which account for approximately 65% of all irrigated areas in Brazil (ANA - Brazilian National Water Agency, 2021), also experience substantial drought deficits. The significant water abstraction for irrigation purposes likely contributes to the pronounced drought deficit observed in these regions.

Shifting the focus from local drought characteristics to drought connectedness in Brazil, the Central-Northeast exhibits significant spatial dependence, highlighting the region's affectedness by spatially compounding droughts (Figure 5). This affectedness becomes particularly evident in the hydrographic regions of São Francisco, Southeast, and Eastern Northeast Atlantic, characterized by the presence of water-intensive crops and significant hydropower production. The rising frequency of drought events coincides with declining trends in both streamflow and baseflow in these regions (de Jong et al., 2018; Lucas et al., 2020). The reduction in baseflow is primarily attributed to groundwater and surface water withdrawals (Lucas et al., 2020). Notably, the Eastern Northeast Atlantic and São Francisco regions stand out as the driest areas in the country, exhibiting a prolonged propagation period from meteorological to hydrological drought (Bevacqua et al., 2021). Moreover, the recovery time from drought in these regions can be more than four times longer compared to other parts of Brazil, such as the South and Northeast Amazon (Bevacqua et al., 2021). When considering catchment attributes and land use patterns in conjunction with these characteristics, the high level of drought connectedness observed in these regions can be better understood.

Meteorological factors influence the spatial variation of drought connectedness across Brazil. The South Atlantic convergence zone (SACZ) emerges as the most probable driver of spatial interdependence in the Central-West and Southeast regions of Brazil, as the failure of SACZ can contribute to a joint deficient rainy season in these areas (Pezzi et al., 2023; Zhang et al., 2017). The SACZ plays a critical role in transporting moisture from the southern Amazon region to the Southeast, traversing the Central-West and Southeast regions of Brazil. The absence of SACZ development during the Austral summer has the potential to trigger widespread droughts. A notable example of the consequences of SACZ suppression, coupled with the resulting decrease in rainfall, was evident in Brazil during the 2013/14 period, which led to water shortages throughout the country (Rodrigues et al., 2019). A similar pattern of connectedness is observed in the North and Northeast regions of Brazil, where the Inter Tropical Convergence Zone (ITCZ) influences the rainfall patterns (Cunha et al., 2018). The effects of ITCZ have been linked to the occurrence of droughts in the Central-eastern Amazon and northeastern Brazil (Y. Liu et al., 2022). Furthermore, connectedness in the Amazon and Northeast regions may also be affected by the El Niño-Southern Oscillation (ENSO) teleconnections, as El Niño can shift the ITCZ northward, causing anomalous warming in those areas (Y. Liu et al., 2022).

To summarize the connectedness and heterogeneity in drought characteristics, the country was divided into five distinct groups sharing similar drought attributes and spatial dependencies (Figure 6). These regions, in addition to the common drought characteristics, also exhibit common physiographic and hydroclimatic attributes, as the propagation of hydrological droughts is driven by catchment attributes and strongly influenced by terrestrial processes and human activities (Bevacqua et al., 2021; Van Loon & Laaha, 2015) (Figure 7). Our analysis revealed a negative relationship between connectedness and the number of drought events within the clusters. Catchments in clusters with relatively low connectedness (C4 and C5) tend to experience a higher average number of drought events compared to catchments in clusters with higher connectedness (C1 and C2). In contrast, we find spatial consistency in the patterns of connectedness and drought duration. Clusters with catchments with longer-lasting droughts (C1 and C2) exhibit higher levels of connectedness, whereas clusters with catchments with more frequent but shorter droughts (C3, C4, and C5) show relatively lower connectedness.

The characteristics of droughts at the local and regional levels may undergo changes in the future. While much of the semi-arid region typically experiences drought conditions with low deficits and intensity, recent research has pointed to a drying trend in these areas over the past few decades (Chagas et al., 2022; Cunha et al., 2018; Marengo et al., 2017; Tomasella et al., 2022). Chagas et al. (2022) have linked this drying trend to reduced rainfall and increased water consumption in Central and Northeastern Brazil's agricultural zones. Our findings in the headwaters of the São Francisco River basin, an area characterized by intensive irrigation, prolonged drought periods, and a substantial water deficit, align with this observation. Furthermore, the analysis by Scanlon et al. (2023) pointed out a strong negative trend in water storage within the San Francisco basin, emphasizing the direct influence of irrigation on water resources and, consequently, on drought conditions. Beyond the São Francisco region, similar trends of decreasing discharge are evident in the hydrographic regions of Tocantins-Araguaia and Western Northeast Atlantic (Miranda et al., 2023). These findings align with our results, which identify these regions as the most susceptible to widespread droughts. This is particularly concerning because of the tendency of these areas to continued drying in the future (Miranda et al., 2023). Additionally, over the past decade, the South and Southeast regions have witnessed rising temperatures and an increase in extreme dry and hot conditions (Geirinhas et al., 2021). These changes may lead to more severe droughts with significant deficits in these areas, further emphasizing the importance of understanding and addressing the spatiotemporal nature of droughts in different regions.

4.2. Implications of the Understanding of Drought Connectedness for Potential Advances in Risk Management

Understanding spatial connections is crucial for assessing the probability of widespread drought, and our findings highlight significant variability in drought connectedness throughout Brazil. This variability must be considered in the design of risk management strategies, including long-term planning and infrastructure development, such as water storage facilities, irrigation systems, and crop diversification strategies (Baum et al., 2018; Leng & Hall, 2019; Lesk et al., 2022). Furthermore, our research has practical implications for water resources allocation. Governments and organizations can improve resource allocation efficiency by recognizing regional drought connections (X. Liu et al., 2021; Olsen et al., 2023; Zeff et al., 2016).

In this study, we identified five regions with similar drought characteristics that provide a framework for establishing a network of risk pool regions. Risk pool regions involve the sharing of unexpected loss risks among multiple entities, offering an effective strategy within a diverse network to mitigate the impacts of widespread shocks (Cronk & Aktipis, 2021). An exemplary illustration is the Caribbean Catastrophe Risk Insurance Facility (CCRIF), which represents the world's first multi-country risk pool comprising 17 Caribbean nations (Haraguchi & Lall, 2019). Through diversification of risks beyond national boundaries, these countries assist each other in addressing short-term cash constraints following natural disasters. We recommend that risk-pooling regions comprise catchments from different drought clusters since they are less likely to concurrently experience drought events compared to catchments within the same cluster. For example, when aiming to mitigate financial risk in multiple catchments located in regions C3 and C1, the risk manager should consider that region C1 demonstrates higher connectedness with fewer drought events, while region C3 shows lower connectedness, but a higher frequency of drought events.

The established drought similarity regions derived in this study also have the potential to support improvements in drought forecasting models and warning systems. This can be achieved by incorporating spatial dependencies between regions into model calibration. For instance, Balti et al. (2023) presents an innovative approach that accurately predicts drought by considering dynamic spatiotemporal correlations among regions. Traditionally, risk assessments tended to neglect spatial dependencies by assuming complete dependence between sites. However, as highlighted by Mondal et al. (2023) the spatial connectivity structure of drought can be used to understand the relationship between model biases in simulating droughts in different regions. Neglecting the spatiotemporal aspects of drought in spatial drought event modeling within drought hazard and

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risk assessment can result in an under or overestimation of risk, as demonstrated by Brunner et al. (2020) in the context of flood risk.

4.3. Limitations and Future Work

Although our study sheds light on regional drought connectedness, it is essential to acknowledge its limitations related to data availability and density. Data availability influenced connectedness estimates to a certain degree as regions with a high density of monitoring stations also exhibited higher drought connectedness. Conversely, it becomes challenging to quantify the connectedness between drought events in regions lacking stations, for example, the Pantanal Biome, where only one catchment is available. The absence of comprehensive data from these regions restricts our ability to fully understand the drought connectedness patterns within their own boundaries and with other regions. Addressing this limitation requires future efforts to expand the data collection infrastructure in areas with limited station coverage.

Most drought indices and methodologies fail to identify droughts in catchments with intermittent flow regimes, and it is challenging to distinguish between drought and natural dry periods. This challenge is recurring when identifying and monitoring hydrological droughts (Kiem et al., 2016; Sarremejane et al., 2022). Our methodology also faces this limitation, particularly when capturing drought events in intermittent and ephemeral rivers. Consequently, our analysis may not accurately reflect the drought dynamics in these specific river systems. To overcome this limitation, we suggest adapting our methodology for these specific river systems in future studies.

Despite these limitations, our findings emphasize the spatial connectedness of droughts, underscoring its relevance in broader hazard research. Investigating other hazards, such as floods, is crucial for a comprehensive understanding of regional connectedness and vulnerability to multiple hazards, including drought-to-flood events. It is essential to understand the compound flood and drought events to mitigate their potential severity, as individual hazard characteristics alone can lead to under- or overestimation of risk (Brunner, 2023; Rezvani et al., 2023).

Future studies should consider potential changes in spatial drought connectedness over time by incorporating different climate change scenarios, which are expected to increase spatial dependence and the likelihood of widespread drought events (Zhao & Dai, 2022). Integrating climate projections into our analysis framework could help to assess how regional connectedness and vulnerability to droughts and other hazards could evolve under different climate change scenarios. This can involve a commonly used approach of a combination of hydrological models with different climate scenarios to generate different future realizations of streamflow (Bosmans et al., 2022; Gesualdo et al., 2019; Teutschbein et al., 2015), which can also be used as input to a connectedness analysis. Such an approach would provide valuable insights for decision-makers, aiding the development of effective adaptation and mitigation strategies to mitigate future climate change impacts. Additionally, we recommend exploring risk pool allocation and assessing extreme event dependencies between risk pool combinations, along with evaluating the effectiveness of risk pooling within the defined groups.

5. Conclusions

We developed a novel approach to study the spatial connectedness of hydrological droughts and combined a local assessment of drought characteristics with an examination of the co-occurrence of droughts across catchments in Brazil. This methodology has broader applicability beyond our study area, as it can be transferred to investigate spatial drought connectedness in other regions of the world. For Brazil, we identified five drought regions with similar drought characteristics and spatial dependencies. The Amazon's Northwest and Brazil's South and Southeast regions experience the most severe droughts in terms of intensity and frequency, while the semi-arid region stands for its long drought duration. The Central-Northeast region reveals a significant spatial drought connectedness, making it highly susceptible to spatially compounding droughts.

The insights gained from such spatial investigations have the potential to improve drought management and facilitate the development of strategies to reduce drought risks. For example, they enable the development of risk-pooling strategies, which aim to share drought risks among regions that are not usually jointly affected by droughts. Future studies should focus on sector-specific drought impacts within the identified drought similarity regions to further evaluate the potential of risk pooling across these regions. Another important next step in the analysis of spatially compounding droughts is the consideration of climate change projections, which is essential to anticipate widespread droughts in a warming world and to develop adaptation strategies. Considering spatial dependencies in drought occurrence in drought management and climate impact assessments will enhance society's capacity to alleviate negative drought impacts.

Data Availability Statement

All data and scripts used to replicate the analysis in this paper and the figures are openly available. The data can be accessed in Gesualdo (2024), and the codes are detailed in Gesualdo et al. (2024).

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