Occurrence of flash drought in reservoirs in the semi-arid area of the Ceará State, Brazil (Postprint)

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Abstract

Precipitation is scarce in semi-arid areas, which results in serious drought. Occurrence of flash drought is quite often in these areas, and flash drought may also cause significant disasters. However, monitoring flash drought is still weak and remains a challenge. This study aims to identify, evaluate, and monitor flash drought events that occurred from 1961 to 2020 in reservoirs of the Ceará State, Brazil. The Christian’ s method, standardized precipitation index (SPI), standardized precipitation evapotranspiration index (SPEI), and evaporative demand drought index (EDDI) were used to assess the severity and persistence of flash drought. Moreover, analyses conducted in 2001, 2008, 2011, 2012, 2016, and 2020 revealed the complexity and interaction of flash drought with environmental and meteorological factors. The results indicated that in dry years such as 2001, 2012, and 2016, drought indices pointed to the intensification of drought conditions, with impacts on major reservoirs in the area, such as Banabuiú, Castanhão, and Orós. Low precipitation, associated with high evaporative demand, intensified water stress, reducing water availability for the population and local ecosystems. In wet years such as 2008, 2011, and 2020, SPEI and EDDI indicated higher moisture levels and drought relief, favoring the recovery of reservoirs. It was also observed that most flash drought episodes evolved into conventional droughts, highlighting their persistence and potential long-term impact. Moreover, the months of May and November presented a higher frequency of flash drought during the wet and dry periods, respectively, negatively impacting most of the studied reservoirs. These findings underscore the need for effective drought monitoring and mitigation strategies to reduce its impacts on agriculture and water resources in the semi-arid area. Early detection and analysis of flash drought are important for improving water resource management and for continuous adaptation to changing drought conditions.

Full Text

Preamble

Occurrence of Flash Drought in Reservoirs in the Semi-Arid Area of Ceará State, Brazil

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Abstract: Precipitation is scarce in semi-arid areas, resulting in serious drought conditions. Flash drought occurs quite frequently in these regions and may cause significant disasters. However, monitoring flash drought remains weak and continues to pose a challenge. This study aims to identify, evaluate, and monitor flash drought events that occurred from 1961 to 2020 in reservoirs of Ceará State, Brazil. Christian' s method, the Standardized Precipitation Index (SPI), Standardized Precipitation Evapotranspiration Index (SPEI), and Evaporative Demand Drought Index (EDDI) were used to assess the severity and persistence of flash drought. Moreover, analyses conducted for 2001, 2008, 2011, 2012, 2016, and 2020 revealed the complexity and interaction of flash drought with environmental and meteorological factors.

The results indicated that in dry years such as 2001, 2012, and 2016, drought indices pointed to intensifying drought conditions, with impacts on major reservoirs in the area, such as Banabuiú, Castanhão, and Orós. Low precipitation, associated with high evaporative demand, intensified water stress, reducing water availability for the population and local ecosystems. In wet years such as 2008, 2011, and 2020, SPEI and EDDI indicated higher moisture levels and drought relief, favoring reservoir recovery. It was also observed that most flash drought episodes evolved into conventional droughts, highlighting their persistence and potential long-term impact. Moreover, the months of May and November presented a higher frequency of flash drought during the wet and dry periods, respectively, negatively impacting most of the studied reservoirs. These findings underscore the need for effective drought monitoring and mitigation strategies to reduce impacts on agriculture and water resources in the semi-arid area. Early detection and analysis of flash drought are important for improving water resource management and for continuous adaptation to changing drought conditions.

Keywords: water resources; evaporative demand; drought indices; monitoring; precipitation

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1 Introduction

Drought is a prolonged period of precipitation deficit that leads to significant water shortages in a given area, affecting not only water resources but also agriculture, public health, economy, and environment. According to the classification established by Wilhite and Glantz (1985), drought can be categorized into different types, each with distinct characteristics, such as meteorological drought, agricultural drought, hydrological drought, and socioeconomic drought. The impacts of drought can be amplified by factors such as temperature anomalies and changes in atmospheric patterns (Chang and Wallace, 1987; Wilhite, 2000; Wilhite et al., 2007; McCabe et al., 2008; Basara et al., 2013; van Loon, 2015; Pessini, 2017; Pontes Filho et al., 2019; Gonçalves et al., 2021; Hamidifar, 2024).

Droughts are often slow-developing events, taking years to become fully established within the mutual influence of environmental, social, and economic factors. However, among different manifestations of these phenomena, there is flash drought, which represents a new category of drought with quick (few weeks or months) and intense (high severity) development. This type of drought is challenging due to its rapid intensification, which may occur unpredictably and negatively impact human activities, as well as water and food security. Flash drought often starts as a meteorological drought and progresses to an agricultural drought as environmental conditions worsen. If factors such as lack of precipitation, heavy wind, high solar radiation (caused by the absence of clouds), high temperature, and heat wave last for several weeks, the drought process can be triggered and develop quickly (Hobbins et al., 2016; Mo and Lettenmaier, 2016; Ford and Labosier, 2017; Otkin et al., 2018a; Christian et al., 2019a, b, 2024).

Climate phenomena such as thermal variability (El Niño and La Niña) of the tropical oceans, the presence of areas of high atmospheric pressure (hot and dry air masses over specific areas), and the Madden-Julian Oscillation (MJO) have the potential to influence the occurrence of flash drought. These events can alter weather patterns by abnormally heating or cooling the Pacific Ocean, hinder cloud formation by keeping air stationary under high pressure, and modify global atmospheric circulation, thus affecting precipitation distribution in various parts of the planet (Christian et al., 2020; Mishra et al., 2021; Noguera et al., 2021; Parker et al., 2021; Kang et al., 2022; Mohammadi et al., 2022; Christian et al., 2024).

To study flash drought around the world, researchers use different variables in different areas. In Australia, Southeast Asia, and India, soil moisture is the main variable used. In Russia, analyses focus on evaporation and potential evapotranspiration (PET), while in Europe and Brazil, precipitation is the main parameter analyzed. In the United States of America (USA), the vegetation reaction to soil drying is examined. These variables reflect regional climatological characteristics, suggesting that the definitions and analyses of these events should be adjusted to the local environment (Christian et al., 2020; Mishra et al., 2021; Parker et al., 2021; Kang et al., 2022; Mohammadi et al., 2022; Noguera et al., 2022; Christian et al., 2024).

Monitoring flash drought can be complemented and enhanced through specific drought indices. These include precipitation-related indices such as the Standardized Precipitation Index (SPI) and Standardized Precipitation Evapotranspiration Index (SPEI). The SPI directly assesses precipitation deficits, providing information on the intensity and duration of droughts based on precipitation availability. The SPEI incorporates both precipitation and evaporative demand, offering a more comprehensive analysis of drought conditions and considering water losses due to PET (Park et al., 2018; Hoffmann et al., 2021; Ford et al., 2023; Christian et al., 2024).

Indices related to evaporative demand play a strong role in the early identification and dynamic monitoring of flash drought, such as the Evaporative Demand Drought Index (EDDI). Evaporative demand is used to quickly detect variations in soil and atmospheric moisture with EDDI, and the index is effective in signaling early drought. However, its high sensitivity can generate false alarms in areas with variable climates (Hobbins et al., 2016; McEvoy et al., 2016; Christian et al., 2024). Several studies have investigated the distribution and intensity of flash drought in distinct parts of the world. Christian et al. (2021) analyzed flash drought events in 15 areas from 1980 to 2015 based on evaporative stress anomalies (Christian et al., 2019a). They found that six areas (the USA, the Iberian Peninsula, Asia Minor, Brazil, the Sahel, and southeastern Australia) tended to experience an increase in flash drought, while three areas (India, the Great Rift Valley, and northern Australia) recorded a decrease in their frequency. Getahun and Li (2024) studied the Awash River Basin, an area prone to severe and recurring droughts in Ethiopia from 2002 to 2017. They used the methodology of Christian et al. (2019a) and the indices of SPI, EDDI, and Evaporative Stress Index (ESI) to enhance their analysis. They found that areas such as pastures and agricultural lands were vulnerable to flash drought. In their study, the EDDI proved to be more effective than SPI and ESI in detecting flash drought.

In Brazil, drought is a frequent phenomenon due to its climatic diversity. While the southern and southeastern areas have milder climates, the northern and northeastern areas experience high temperatures, often exceeding 30°C. Drought in the northeastern area is common and intense, resulting in severe impacts on agriculture and water supply (De Nys et al., 2016). Recent studies have analyzed the patterns and impacts of flash drought in Brazil, especially in the northeastern areas of the country. Barbosa (2023) used 18 years of satellite data to show that these droughts significantly affect the Caatinga vegetation, rapidly altering plant dynamics in response to the lack of precipitation. Ballarin et al. (2024) highlighted the increase in droughts in river basins, emphasizing the challenges in water and land management and the importance of adaptive and sustainable strategies to deal with these phenomena. The findings highlight the complexity and importance of flash drought in Brazil, especially in the northeastern area, where climate variability and precipitation scarcity represent ongoing challenges for agriculture, society, and environment. The state of Ceará, located in northeastern Brazil, often deals with water scarcity, aggravated by prolonged droughts. A multi-year drought from 2012 to 2018 caused great damage to agriculture, livestock, and local communities (Marengo et al., 2016; Martins et al., 2017; Marengo et al., 2018; Gonçalves et al., 2023a).

Despite efforts to identify and monitor drought, current scientific studies are still limited regarding flash drought, since monitoring is mostly centered on larger scales, such as monthly, quarterly, and annual scales. As such, there is a lack of research dedicated to assessing and monitoring these phenomena on a smaller scale, such as pentadic or fortnightly monitoring, in order to provide more complete information for the development of mitigation and adaptation strategies. Therefore, the objective of this research is to identify and monitor flash drought events in reservoirs of Ceará State, Brazil from 1961 to 2020.

2 Methodology

The methodology applied in this study was conducted through seven steps (Fig. 1 [Figure 1: see original paper]). First, the study area was defined by selecting 155 reservoirs monitored in Ceará State. Next, the time series of precipitation and PET were separated and analyzed. With these variables, the methodology of Christian et al. (2019a) was applied to identify and classify flash drought, followed by the calculations of SPI, SPEI, and EDDI drought indices.

2.1 Study Area

The state of Ceará is known for its vulnerability to drought, partly due to its semi-arid climate and low water storage, which could be exacerbated by ongoing climate changes. The climate of the study area is characterized by four periods related to precipitation: pre-rainy season (December–January), rainy season (February–May), post-rainy season (June–July), and dry season (August–November). Mean annual precipitation is about 600 mm. The climatic condition, combined with predominantly Caatinga vegetation and arid soil, contributes to the challenges faced by the population in terms of water supply and agricultural sustenance (Nimer, 1989; Nunes, 2012; Gutierrez et al., 2014; Marengo et al., 2018).

The area has 12 hydrographic basins, each with a specific number of reservoirs, which together make a total of 155 reservoirs monitored by the Ceará

Water Resources Management Company (COGERH): Acaraú (15), Banabuiú (19), Coreaú (10), Curu (14), Alto Jaguaribe (23), Médio Jaguaribe (15), Baixo Jaguaribe (1), Litoral (10), Metropolitana (22), Salgado (15), Sertões de Crateús (10), and Serra da Ibiapaba (1) (De Medeiros et al., 2012; COGERH, 2024). These reservoirs store water during the rainy season to use it during periods of drought, helping to mitigate the impacts of water scarcity and ensure the supply of drinking water and irrigation (Lopes and Santos, 2002; De Melo, 2005). Thus, it is important to monitor droughts that occur in this area, as they affect water availability and storage (Nunes, 2012; Gutierrez et al., 2014; Coutinho et al., 2017; Marengo et al., 2018). The 155 reservoirs monitored by COGERH were analyzed in this study, with locations shown in Figure 2 [Figure 2: see original paper].

2.2 Database

Brazilian Daily Weather Gridded Data (BR-DWGD) were used to calculate drought indices and identify flash drought. Meteorological variables such as precipitation, maximum and minimum temperatures, PET, wind speed at 2 m height, relative soil humidity, and solar radiation with 0.1°$×$0.1° resolution were selected from BR-DWGD. To create this dataset, Xavier et al. (2022) used approximately 3600 weather samples. We applied inverse distance weighted (IDW) interpolation, which considers the influence of data points closest to the grid point to be estimated, weighing them according to distance. This model integrates information from Brazilian federal and state monitoring institutions, such as the National Institute of Meteorology (INMET) and the National Water and Sanitation Agency (ANA). To estimate actual evaporation (ET) data, we used the water balance proposed by Thornthwaite (1948), which considers available water capacity (AWC), precipitation, and temperature data (Chikabvumbwa et al., 2024). AWC values were obtained from the Harmonized World Soil Database (HWSD), available from the Food and Agriculture Organization (FAO) of the United Nations (Wieder et al., 2014; Lima et al., 2020).

2.3 Flash Drought

We referenced the method from Christian et al. (2019a) to identify flash drought, which is based on evaporative stress. This index refers to the increase of PET in response to drought conditions, where the evaporative demand of the atmosphere exceeds the soil' s ability to provide enough water. This phenomenon results in a water deficit in the soil, leading to increased surface temperature and decreased humidity, which intensifies drought conditions. To understand the formation and impacts of flash drought, it is useful to visualize the components involved in the Venn diagram (Fig. 3 [Figure 3: see original paper]), which highlights three main elements: rapid development (speed at which drought is established), drought (water deficit that does not meet the evaporative demand of the atmosphere), and impacts (adverse effects caused by drought, such as agricultural loss and water stress on ecosystems). The intersection of these elements defines the flash drought event (Christian et al., 2024).

The value of evaporative stress ratio (ESR) is inversely proportional to the intensity of evaporative stress in the environment. According to Christian et al. (2019a), the use of ESR in the analysis of flash drought is due to its ability to integrate several near-surface variables, as recommended by Otkin et al. (2018a). The ESR was calculated from daily ET and PET data (Eq. 1):

$$ESR = \frac{ET}{PET}$$

where ET is evapotranspiration (mm/d) and PET is potential evapotranspiration (mm/d).

ESR ranges from 0 to 1. Values close to 1 mean that the moisture and vegetation present in the soil satisfy the atmospheric demand for evapotranspiration. For values close to 0, the surface responds with a minimal or zero amount of evaporation.

Christian et al. (2019a) recommend the use of pentadic period (5 d) or longer to calculate the standard ESR (SESR), which can minimize the variability of daily ESR data. Computing the values of pentadic period mitigates short-term fluctuations and makes the methodology more effective. Thus, SESR values were accumulated using Equation 2:

$$SESR = \frac{ESR - \overline{ESR}}{ESR_\sigma}$$

where $\overline{ESR}$ is the average ESR and ESR_σ is the standard deviation of ESR.

The identification of flash drought involves the element "flash," which indicates the rapid intensification of drought. This method is achieved by calculating the variation in SESR values between each pentadic period. Thus, the normalized variation of the SESR ($(\Delta SESR)_Z$) is presented in Equation 3 (Christian et al., 2019a):

$$(\Delta SESR)_Z = \frac{\Delta SESR - \overline{\Delta SESR}}{\Delta SESR_\sigma}$$

where $\Delta SESR$ is the average change in SESR; $\overline{\Delta SESR}$ is the average change in SESR values for a specific pentad at a specific grid point for all available years in the dataset; and $\Delta SESR_\sigma$ is the standard deviation of $\Delta SESR$.

Four criteria are used to identify flash drought events. Criterion 1 requires a minimum duration of six pentads (30 d) to exclude short events with no significant impact. Criterion 2 stipulates that the final SESR value must be below the 20th percentile, ensuring that only severe events are considered. Criterion

3 evaluates the rapid intensification of the drought, where $\Delta SESR$ between consecutive pentads must be at or below the 40th percentile and the overall trend is continuous intensification. Criterion 4 requires that the mean change in SESR during the entire length of the flash drought must be less than the 25th percentile of the climatological changes in SESR for that grid point and time of year (Christian et al., 2019a).

The classification of flash drought events (Table 1) is based on the rate of intensification, measured by the average change in SESR, and is divided into four categories: FD1 represents moderate flash drought (20th–25th percentiles); FD2 represents severe flash drought (15th–20th percentiles); FD3 represents extreme flash drought (10th–15th percentiles); and FD4 represents exceptional flash drought (<10th percentiles) (Christian et al., 2019a).

Table 1 Classification of flash drought events according to their intensities

Flash drought intensity index	Classification	Average SESR change (ΔSESR)
FD1	Moderate flash drought	20th–25th percentiles
FD2	Severe flash drought	15th–20th percentiles
FD3	Extreme flash drought	10th–15th percentiles
FD4	Exceptional flash drought	<10th percentiles

Note: SESR, standard evaporative stress ratio. The classification in this study was cited from Christian et al. (2019a).

2.4.1 EDDI

EDDI, developed by Hobbins et al. (2016) and McEvoy et al. (2016), is used to monitor agricultural and hydrological droughts. It stands out for analyzing anomalies in the evaporative demand of the atmosphere and detecting drought, as it does not depend on precipitation. It is useful for identifying the onset and intensification of drought, providing alerts that assist with agricultural monitoring, seasonal forecasting, and risk management (Pendergrass et al., 2020; Noguera et al., 2021).

Its calculation (Eqs. 4 and 5) uses PET data. Then, empirical probability is used to compare each reference month of the series with the complete series of that month, obtaining the positional value of the month in relation to the year. This value is transformed into a series of probabilities using Tukey' s test. After these statistical analyses, each probability value is approximated by the inverse of normal distribution (Hobbins et al., 2016).

$$W = \begin{cases} -\sqrt{2\ln[1-P(E_0)]} & \text{if } P(E_0) \leq 0.5 \\ \sqrt{2\ln[P(E_0)]} & \text{if } P(E_0) > 0.5 \end{cases}$$

$$Z = W - \frac{C_0 + C_{1W} + C_{2W}^2}{1 + d_{1W} + d_{2W}^2 + d_{3W}^3}$$

where W is the standardized variable derived from the cumulative probability $P(E_0)$; P is precipitation (mm); E_0 is the reference evaporation (mm); and C_0, C_1, C_2, d_1, d_2, and d_3 are constants equal to 2.515517, 0.802853, 0.010328, 1.432788, 0.189269, and 0.001308, respectively.

EDDI values equal to 0.00 indicate that the amount accumulated during the aggregation period in the year and month of interest is equal to the value of the average of the series. Negative values of EDDI indicate a wet anomaly and positive values indicate a condition drier than normal. Thus, the higher the positive value, the higher the intensity of drought (Hobbins et al., 2016). Table 2 shows the EDDI classification.

Table 2 EDDI (evaporative demand drought index) classification according to drought severity

Classification	Stage of drought
\$ \$2.00	Extreme drought
1.50 to 1.99	Severe drought
1.00 to 1.49	Moderate drought
0.50 to 0.99	Low drought
-0.49 to 0.49	Normal
-0.99 to -0.50	Poor humidity
-1.49 to -1.00	Moderate humidity
-1.99 to -1.50	Severe humidity
$\leq$ -2.00	Extreme humidity

Note: The classification of EDDI is referenced from the National Oceanic and Atmospheric Administration (NOAA, 2021).

2.4.2 SPI

The SPI, developed by McKee et al. (1993), quantifies the precipitation deficit on several time scales and assists in the assessment of drought severity. The calculation of SPI (Eqs. 6 and 7) involves the use of monthly data of accumulated precipitation for an interval of n months. These data are fitted to a gamma function to calculate the probabilities of occurrence of each precipitation value. Next, the inverse of the normal distribution is applied to determine the deviations of precipitation in relation to the average of analyzed intervals (Patel et al., 2007; Martins et al., 2015; Santos, 2020; Gonçalves et al., 2021; Gonçalves et al., 2023a).

$$SPI = -\left(t - \frac{c_0 + c_{1t} + c_{2t}^2}{1 + d_{1t} + d_{2t}^2 + d_{3t}^3}\right), \text{ if } 0.0 < H(x) \leq 0.5$$

$$SPI = +\left(t - \frac{c_0 + c_{1t} + c_{2t}^2}{1 + d_{1t} + d_{2t}^2 + d_{3t}^3}\right), \text{ if } 0.5 < H(x) \leq 1.0$$

where t is the auxiliary variable calculated from the cumulative probability $H(x)$; and $H(x)$ is the cumulative probabilistic distribution. In Equations 6 and 7, t corresponds to $\sqrt{2\ln[H(x)]}$ for $0.0 < H(x) \leq 0.5$; and t corresponds to $\sqrt{2\ln[1-H(x)]}$ for $0.5 < H(x) \leq 1.0$. Table 3 shows the classification of SPI according to the auxiliary variable calculated from the severity of cumulative probability $H(x)$, where positive values indicate humidity and negative values indicate droughts.

Table 3 Classification of SPI (standardized precipitation index) according to severity

SPI Value	Classification
$ $2.00	Extreme precipitation
1.50 to 1.99	Severe precipitation
1.00 to 1.49	Moderate precipitation
0.50 to 0.99	Light precipitation
-0.49 to 0.49	Almost normal
-0.99 to -0.50	Low drought
-1.49 to -1.00	Moderate drought
-1.99 to -1.50	Severe drought
≤ -2.00	Extreme drought

Note: The classification of SPI is referenced from McKee et al. (1993).

2.4.3 SPEI

The SPEI, developed by Vicente-Serrano et al. (2010), uses PET and precipitation data to calculate the water balance, allowing a comprehensive analysis of the effects of drought. This index is multiscale and integrates the climatic aspects essential to understanding drought conditions, considering both the availability of water and the effects of temperature on evapotranspiration.

The calculation (Eq. 8) is based on the climatic water balance, determined by the difference between P and PET for the month, which provides a simple measure of water surplus or deficit of the period analyzed.

$$D = P - PET$$

where D is the water deficit in the month analyzed (mm).

Then, the gamma distribution is selected to standardize the series and obtain SPEI, following the method of Abramowitz and Stegun (1965) (Eqs. 9 and 10).

$$W' = \begin{cases} -\sqrt{2\ln[P']} & \text{if } P' \leq 0.5 \\ \sqrt{2\ln[1-P']} & \text{if } P' > 0.5 \end{cases}$$

$$SPEI = W' - \frac{C_0 + C'_{1W} + C_2{W'}^2}{1 + d'_{1W} + d_2{W'}^2 + d_3{W'}^3}$$

where W' is the standardized variable derived from P'; and P' is the probability. Positive SPEI values indicate above-average humidity conditions, while negative values indicate drier conditions. A drought event is defined when SPEI value is less than or equal to -1.00 in a given period (Vicente-Serrano et al., 2010; Li et al., 2015). Table 4 presents the drought categories according to SPEI values.

Table 4 Classification of SPEI (standardized precipitation evapotranspiration index) according to wet or drought severity

SPEI Value	Classification
$ $2.00	Extremely wet
1.50 to 1.99	Very wet
1.00 to 1.49	Moderately wet
-0.99 to 0.99	Almost normal
-1.49 to -1.00	Moderate drought
-1.99 to -1.50	Severe drought
≤ -2.00	Extreme drought

Note: The classification of SPEI is referenced from Vicente-Serrano et al. (2010).

3 Results

3.1.1 Identification of Flash Drought

The methodology for identifying flash drought was applied to quantify the number of years that experienced a flash drought event (expressed as a percentage) in the monitored reservoirs of Ceará State, Brazil, for each time of year (Fig. 4 [Figure 4: see original paper]). For the pre-rainy season (December–January), the hydrographic areas of the state with the highest records of flash drought events, above 60%, were the Metropolitana basin (Amanary, Catucinzenta, Germinal I, and Itapebussu reservoirs), the Sertão de Crateús basin (Barragem do Batalhão), the Alto Jaguaribe basin (Caldeirões, Orós and Rivaldo de Carvalho), the Coreaú basin (Diamante, Itaúna, Martinópole, and Tucunduba), the Médio Jaguaribe basin (Riacho da Serra and Tigre), and the Salgado basin (Rosário). These events were also evidenced in other basins, with 30%-50% of the years containing at least one episode of flash drought.

The rainy season (February-May) presented the highest percentages of flash drought, ranging from 65% to 70%, in the reservoirs Acaraú Mirim, Araras, Ayres de Sousa, Sobral, and Taquara (Acaraú basin); Angicos, Diamante, Gangorra, Martinópole, Premuoca, Trapiá III, and Tucunduba (Coreaú basin); Acarape do Meio, Catucinzenta, Gavião, Germinal, Malcozinhado, Pacajus, Pacoti, Penedo, Pesqueiro, and Tijuquinha (Metropolitana basin); Caxitoré, Desterro, Frios, Itapajé, Pentecoste, Salão, and Tejuçuoca (Curu basin); Gameleira, Mundaú, Poço Verde, and Quandú (Litoral basin); and Jaburu I (Serra da Ibiapaba basin). The other reservoirs presented lower percentages of flash drought, ranging from 25% to 50%.

Regarding the post-rainy season (June–July), the frequency of flash drought occurrences varied between 30% and 50% in most reservoirs. Some reservoirs, such as Acarape do Meio, Amanary, Aracoiaba, Arneiroz II, Banabuiú, Bonito, Castanhão, Itapebussu, Santo Antônio de Russas, and Tijuquinha presented a higher percentage of flash drought, above 55%. The dry season (August-November) presented a high percentage of flash drought in all reservoirs, with values above 55%.

3.1.2 Intensity of Flash Drought

The annual frequencies of different intensities of flash drought are shown in Figures 5 and 6. The category FD1 (Fig. 5a [Figure 5: see original paper]) presented a higher frequency of occurrence for all seasons and reservoirs studied, with percentage values above 25%. The categories FD2 (Fig. 5b) and FD3 (Fig. 6a [Figure 6: see original paper]) presented lower frequencies for all seasons, with percentage values below 15%. Finally, category FD4 (Fig. 6b) exhibited values less than 25%.

3.2 Flash Drought and Drought Indices

For the analyzed period (from 1961 to 2020), 12 reservoirs were chosen considering their strategic importance within each river basin. This selection included the largest reservoirs according to drainage area and water accumulation capacity, highlighting their potential in the context of water management in the following areas: Castanhão (Médio Jaguaribe basin), Orós (Alto Jaguaribe basin), Banabuiú (Banabuiú basin), Jaburu I (Serra da Ibiapaba basin), Pacoti (Metropolitana basin), Araras (Acaraú basin), Santo Antônio de Russas (Baixo Jaguaribe basin), Itaúna (Coreaú basin), Pentecostes (Curu basin), Atalho (Salgado basin), Santo Antônio de Aracatiaçu (Litoral basin), and Barragem do Batalhão (Sertão de Crateús basin). This strategic selection aimed to enable a more detailed analysis of the results obtained, since evaluating all 155 reservoirs would be complex and could result in superficial observations, thus compromising the depth of discussion.

In addition, a survey was carried out of the years considered wet (with above-average precipitation) and dry (with below-average precipitation) for the study area, using data from the Ceará Foundation of Meteorology and Water Resources (FUNCEME, 2024). Three years—2001, 2012, and 2016—were selected as dry years; and 2008, 2011, and 2020 as wet years, which were used to analyze the application of methodology for identifying flash drought and the behavior of EDDI, SPI, and SPEI drought indices when monitoring these events.

3.2.1 Analysis of Flash Drought The methodology for identifying flash drought uses the standardized SESR index, which is made for each spot, with adjustments of the average and standard deviation for each location and period of analysis. This approach makes it possible to compare evaporative stress in different areas and climates. The classification limit for flash drought (FD1, FD2, FD3, and FD4) is defined from the percentiles of the distribution of standardized SESR values for each study area and specific period, which means that the intensity of flash drought is categorized by the speed of intensification of drought conditions in relation to the history of that area, adjusting to the local and temporal values of the data used, not being a fixed scale for all areas studied. This adjustment to local percentiles allows the analysis to capture local and period-specific variations. Thus, each reservoir has its own thresholds for the classification of flash drought events. This method differs from the classification of SPI, SPEI, and EDDI drought indices, where the same severity scale is applied universally to all areas.

Figure 7 [Figure 7: see original paper] presents the monthly classification of flash drought events from 1961 to 2020 for the Araras, Atalho, Banabuiú, Barragem do Batalhão, Castanhão, Itaúna, Jaburu I, Orós, Pacoti, Pentecoste, Santo Antônio de Aracatiaçu, and Santo Antônio de Russas reservoirs. From these results, it could be observed that most flash drought events were concentrated in FD1 and FD4 categories, although there were also variations in other severity levels that were less frequent. The year 2001, marked by below-average precipitation, presented an increase in the occurrence of FD1 category in reservoirs such as Atalho, Barragem do Batalhão, and Itaúna. Meanwhile, the Banabuiú, Orós, and Santo Antônio de Aracatiaçu reservoirs experienced episodes in FD4 category, indicating that the impact of drought might be considerable in these areas. In contrast, above-average precipitation occurred in the years 2008 and 2011, with low occurrence of flash drought, where most events fell into FD1 category, with only a few episodes reaching higher classification.

For the year 2012, the dry situation was worse than previous years, as there was a significant increase in flash drought events, with FD2 category for Itaúna, Jaburu I, and Santo Antônio de Russas reservoirs, FD3 category for Atalho and Barragem do Batalhão, and FD4 category for Castanhão, Jaburu I, Orós, and Pacoti reservoirs, indicating a worsening of drought conditions in these areas. In 2016, flash drought events reached critical levels in many reservoirs, with higher drought frequency of FD3 and FD4 categories, especially in Castanhão, Banabuiú, Orós, and Pentecoste reservoirs. In 2020, a year considered wet, the FD1 category was observed, with a lower frequency of other severity classes, which indicated that this year presented favorable water conditions for the recovery of reservoirs.

Based on the above analysis, we identified relevant seasonal patterns, highlighting the monthly variability of drought events. However, for a deeper understanding of critical periods, it is necessary to identify the months that presented the highest number of flash drought episodes in each monitored area. This analysis allows not only characterization of the most extreme years, but also highlights which months within each season presented a greater tendency for the occurrence of these events.

Table 5 shows the detailed results for each reservoir, containing the months with the highest occurrence of flash drought in each period of the year. This information is important to understand the distribution of drought events and identify the months that are more likely to evolve into more severe drought, contributing to more effective planning in water resource management. When analyzing the months with the highest frequency of flash drought in each period, it is noted that for the pre-rainy season, January appeared as the most critical for all reservoirs evaluated, suggesting that the beginning of the year may be vulnerable to drought events even before the rainy season begins. This may indicate insufficient precipitation or depletion of water resources at the end of the previous year due to the dry season and other atmospheric factors involved, such as high temperatures and high evaporative demand.

Table 5 Month with the highest occurrence of flash drought for each season

Reservoir	Pre-rainy season	Rainy season	Post-rainy season	Dry season
Araras	January	May	July	November
Atalho	January	May	July	November
Banabuiú	January	May	July	November
Barragem do Batalhão	January	May	July	November
Castanhão	January	May	July	November
Itaúna	January	May	July	November
Jaburu I	January	May	July	November
Pacoti	January	May	July	November
Pentecoste	January	May	July	November

Reservoir	Pre-rainy season	Rainy season	Post-rainy season	Dry season
Santo Antônio de Aracatiaçu	January	May	July	November
Santo Antônio de Russas	January	May	July	November
Orós	January	March	July	November

During the rainy season, the months that stood out most were May, February, and March, where the first exhibited a higher number of occurrences, followed by March and February. This variability reflects differences in the distribution and intensity of precipitation throughout the months. May was considered a transition month, that is, it was between the peak of rainy season (March–April) and the months with relatively lower precipitation (June–July). In the post-rainy season, the month of July was predominant in several reservoirs. This result indicated that even after the end of rainy season, there was a significant trend toward flash drought occurrence, possibly due to the quick decrease in soil moisture and high evapotranspiration rates, which was typical during the transition to the dry season. Finally, in the dry season, November emerged as the most critical in all reservoirs. The consistent presence of this month indicated that near the end of the annual dry cycle, reservoirs were vulnerable due to the accumulation of water deficits over previous months and the additional pressure of high evapotranspiration, along with high temperatures and low soil moisture.

3.2.2 Analysis of SPI, SPEI, and EDDI Drought Indices In addition to the analysis of flash drought, conventional drought from 1961 to 2020 was examined using the SPI (Fig. 8 [Figure 8: see original paper]), SPEI (Fig. 9 [Figure 9: see original paper]), and EDDI (Fig. 10 [Figure 10: see original paper]) to determine if flash drought evolved into complete conventional drought. Thus, the monthly values of the indices were used to classify drought events in the selected reservoirs.

Although the year 2001 was considered dry, the SPI, SPEI, and EDDI values presented conditions of low drought and almost normality for all reservoirs, indicating that despite low precipitation, the impacts were not as severe in terms of extreme drought. This result suggested a certain resilience of the reservoirs during this period or a more gradual impact of the lack of precipitation. For 2008, a year classified as rainy, SPI values were expected to fall within wet categories. However, the presence of low drought episodes suggested that precipitation distribution might be irregular or that other factors, such as high evapotranspiration rate and temperature, influenced drought conditions. On the other hand, both SPEI and EDDI values indicated conditions closer to hydric normality. The year 2011 was considered a wet year, and variability in SPI values was observed, including drought episodes in some reservoirs, such as Castanhão and Orós. This result suggested that despite annual precipitation amount being above average, there were periods of water deficit that resulted in low drought episodes. Similar to 2008, SPEI and EDDI values indicated wet conditions for most reservoirs, with only low to moderate droughts in the Castanhão and Orós reservoirs.

The year 2012 showed a strong correspondence between below-average precipitation and SPI values that fell into the categories of moderate, severe, and extreme droughts, which reinforced the relationship between low precipitation rates and the occurrence of severe drought, including flash drought. SPI values pointed to a rapid degradation of humidity conditions. As with the SPI, SPEI and EDDI values also indicated more severe and extreme droughts in almost all reservoirs; however, according to the indices, the Banabuiú, Castanhão, Orós, Santo Antônio de Russas, Pacoti, Pentecostes, and Santo Antônio de Aracatuaçu reservoirs were the most affected by the severity of drought. The Atalho, Araras, Barragem do Batalhão, and Itaúna reservoirs remained in low drought conditions, with no signs of extreme drought. In 2016, drought conditions were severe, with SPI values indicating moderate, severe, and extreme droughts. This pattern was consistent with the classification of 2016 as a year of below-average precipitation, highlighting the severity of drought and the presence of flash drought due to the rapid intensification observed.

The SPEI and EDDI indices also displayed more severe and extreme droughts, agreeing with the SPI values. The droughts were widespread and intense, and once again the Castanhão, Orós, Banabuiú, Santo Antônio de Aracatiaçu, Pentecoste, and Santo Antônio de Russas reservoirs were the ones most negatively affected.

Although the year 2020 was considered wet, the persistence of SPI values in ranges of low and moderate droughts suggests that even in years with high annual precipitation, there might be episodes of drought, possibly linked to seasonal precipitation variability and the rapid transition to drought conditions. SPEI and EDDI values, on the other hand, were predominantly wet for all reservoirs analyzed, pointing to a possible recovery and increase in humidity.

3.2.3 Relationships Among SPI, SPEI, and EDDI Indices Table 6 displays Pearson' s correlation values (expressed as percentages) among SPI, SPEI, and EDDI indices. The high correlation between SPI and SPEI, with all values above 85%, indicated a strong association between the variations of indices, reflecting the same climatic condition, drought or humidity. Thus, when the SPI detected a meteorological drought in that period, the SPEI value followed this variation; in other words, they also tended to reduce.

The correlations between SPI and EDDI, and between SPEI and EDDI, resulted in values above 50%, indicating a moderate positive relationship between these indices. This result suggested that although the indices were correlated, they captured different aspects of weather conditions, such as evapotranspiration, which was more directly associated with EDDI. This index was more sensitive to atmospheric water demand and reflected the water stress of plants, while SPI and SPEI focused more on precipitation and water balance, respectively.

Table 6 Relationships among SPI, SPEI, and EDDI indices

Reservoir	SPI and SPEI (%)	SPI and EDDI (%)	SPEI and EDDI (%)
Araras	85	55	58
Atalho	87	52	54
Banabuiú	89	61	63
Barragem do Batalhão	86	53	55
Castanhão	88	59	61
Itaúna	85	51	53
Jaburu I	87	57	59
Pacoti	86	54	56
Pentecoste	88	58	60
Santo Antônio de Aracatiaçu	89	60	62
Santo Antônio de Russas	87	56	58
Orós	88	59	61

4 Discussion

4.1 Flash Drought

The results obtained indicated that flash drought occurred in all seasons, although their frequency and intensity varied according to the precipitation regime and the prevailing atmospheric conditions in each period. The presence of precipitation during the pre-rainy season (December–January) could, in many cases, alleviate drought conditions, helping to moisten the soil and recover water levels in reservoirs. However, if the precipitation was not sufficient or evenly distributed, drought conditions could persist, since both the soil and water body needed a significant amount of precipitation to fully recover from the losses incurred during the dry season.

During the rainy season (February–May), there was the highest accumulation of precipitation of the year, especially in March and April. This period was important for refilling reservoirs and increasing soil moisture, which tended to reduce the frequency of flash drought. In addition, the intensity of the winds in the area usually decreased between February and March, due to the proximity of the Intertropical Convergence Zone, which favored the formation of convection and more constant precipitation (Silva, 2003). However, adverse environmental conditions, such as below-average precipitation, high temperature, high solar radiation, and high evaporative demand, could lead to rapid drying of the soil, contributing to an increase in drought events. Although precipitation still occurred during the post-rainy season (June–July), the accumulation was lower than that of the rainy season. In addition, the trade winds began to increase in intensity from June onwards, which could speed up the process of soil drying. The combination of lower precipitation amount and the action of the trade winds could contribute to a reduction in soil moisture, increasing the vulnerability of these areas to flash drought.

During the dry season (August-November), the lack of precipitation combined with high temperature, strong wind, and high evaporative demand could effectively contribute to the rapid drying of the soil. During this season, the lack of rain meant that there was no water replenishment in the soil, while high temperature increased evaporation, removing even more water from the Earth' s surface. As the days went by, the soil' s water reserves were gradually depleted, leaving plants and other organisms vulnerable to the lack of moisture. In addition, the months of August and September were marked by the strength of trade winds, as they reached their maximum intensity and frequency at this time (Silva et al., 2002, 2003). This combination of factors in the dry season resulted in a higher occurrence of flash drought, as the rapid loss of soil moisture was not compensated by new precipitation, increasing drought conditions over a short period. These conditions could persist in the next seasons (pre-rainy season and rainy season) if precipitation was not sufficient to replenish soil water levels, thus causing drought to continue, negatively affecting vegetation, agriculture, and available water resources. Thus, soil moisture recovery became necessary to break the drought cycle and mitigate its prolonged impacts (Mo and Lettenmaier, 2016; Otkin et al., 2018a, b; Christian et al., 2019a, b).

Seasonal variability is reflected not only in the frequency of flash drought, but also in their intensity. In the dataset analyzed, the intensity of FD1 was the most frequent, followed by FD4, FD2, and FD3 categories. The predominance of FD1 suggested that although these events were common, most of them did not reach FD2 or FD3 category. However, the significant occurrence of FD4 indicated that when these events were more intense, they could be quite severe and prolonged, increasing the risk of evolving into agricultural or hydrological drought, given the difficulty in recovering from the impacts.

4.2 Flash Drought and Drought Indices

The results showed that the frequency and severity of drought and flash drought in the reservoirs of Ceará State were related to the climatic characteristics of the area, the annual distribution of precipitation, and atmospheric systems. The year 2001, for example, was characterized by conditions of climate neutrality, with the transition from the weak phase of the La Niña phenomenon to the neutral phase (Assunção, 2011; NOAA, 2011; Yu et al., 2011). This behavior may have influenced precipitation and drought conditions in some areas. The response of the reservoirs to flash drought was uneven, as evidenced by the different indices used. The SPI indicated low droughts in some periods, while the

SPEI and EDDI displayed almost normal water levels. This result showed that the response of water systems to climate oscillations was not uniform and depended on regional variables such as water storage volume, water management, topography, and environmental aspects, which played an important role in the response to drought, leading to an uneven impact on severity.

The observed drying up of Ceará's reservoirs from 2012 to 2016 was due to a prolonged period of meteorological drought that began in 2012 and, in some areas, lasted until 2019. During these years, the state faced a significant shortage of precipitation, resulting in insufficient water supply to replenish the reservoirs in an adequate manner, affecting most of the areas. In addition, 2016 was marked by one of the strongest El Niños in recent decades, which severely impacted the distribution of precipitation, leading to a high frequency of drought events classified as severe to exceptional in practically all reservoirs in Ceará State (Martins et al., 2017; Marengo et al., 2018; Rodrigues et al., 2021; Gonçalves et al., 2023a, b).

In contrast to 2016, 2020 displayed favorable climatic conditions, with the influence of the La Niña phenomenon, along with the South Atlantic Convergence Zone and the proximity of the Intertropical Convergence Zone, which may have helped to maintain precipitation at adequate levels, mitigating the severity of drought in the reservoirs studied (NOAA, 2024). The observations made over the years agree with the studies carried out by Barbosa et al. (2024) and Barbosa (2023), where the first work pointed to a higher occurrence and accentuated severity of flash drought events in years considered dry, such as 2012 and 2016, in the northeast of Brazil. They identified that 28% of the area experienced FD1, while the other categories, FD2, FD3, and FD4, corresponded to 23%, 21%, and 21%, respectively. This result demonstrated the constant challenges faced by the area and the need for more proactive and interconnected water management. The second study indicated that flash drought has had an impact on ecosystems in Northeast Brazil, resulting in changes in the regional and seasonal dynamics of vegetation. In addition, their results pointed to a drying trend in the semi-arid area over the years analyzed (2002–2018). Christian et al. (2021) also identified in their analysis that northeastern Brazil was one of the most susceptible areas to the occurrence of flash drought from 1980 to 2015.

In addition, the research carried out by Santana and Santos (2020) and Gonçalves et al. (2023a) confirmed the results indicated by the drought indices (SPI, SPEI, and EDDI). Gonçalves et al. (2023a) carried out a comparative analysis of five drought indices, including SPI and EDDI, for the Banabuiú, Castanhão, and Orós reservoirs, located in Ceará State, Brazil. The results displayed that in years with below-average precipitation, such as 2012 and 2016, the indices indicated more extreme drought and that the SPI and EDDI were sensitive to capturing drought events in the area. Santana and Santos (2020) highlighted that the water shortages that occurred between 2012 and 2017 in northeastern Brazil, especially in the semi-arid area, compromised agricultural production and human supply, indicating the need for effective public policies to mitigate the effects of drought. The high correlations between SPI and SPEI indices were also observed in the study by Oliveira et al. (2023), and the results displayed that SPI and SPEI presented a high correlation, which suggested that these indices were sensitive to the same climatic variation. The correlations among EDDI, SPEI, and SPI indices displayed that EDDI could identify drought events associated with high evaporative demand, even when indices based on precipitation, such as SPI, indicate humid conditions, or when there are differences in the magnitude and duration of drought events detected by each index. This information is valuable because it reflects how drought can be manifested and perceived in different ways, depending on the index used (Gonçalves et al., 2023a; Oliveira et al., 2023).

5 Conclusions

This study applied a comprehensive methodological approach to identify and classify flash drought in the monitored reservoirs of Ceará State, Brazil. By jointly evaluating SPI, SPEI, and EDDI drought indices, it was possible to validate the effectiveness of the method and confirm the results obtained. It was observed that flash drought occurred more frequently in the pre-rainy season (above 60% in the Metropolitana and Sertão de Crateús basins), in the rainy season (65%-70% in the Acaraú, Coreaú, Curu, Metropolitana, and Litoral basins), and in the dry season, where high evaporation resulted in frequencies above 55% in all reservoirs. Dry years such as 2012 and 2016 faced severe and extreme flash drought events, affecting reservoirs such as Banabuiú, Castanhão, and Orós, highlighting regional water vulnerability. On the other hand, wet years such as 2008 and 2011 displayed a reduction in flash drought, although irregularities in precipitation distribution caused low and moderate droughts in some areas.

Most flash drought events evolved into conventional drought, with January being the critical month in the pre-rainy season, May in the rainy season, July in the post-rainy season, and November in the dry season (the most vulnerable period due to accumulated water deficits and high potential evapotranspiration rates). The strong correlation between SPI and SPEI (above 85%) validated consistency in the analysis of climatic conditions, while moderate associations with EDDI highlighted its complementary approach. The methodology used proved satisfactory for detecting flash drought, presenting sensitivity in representing seasonal variability, thus reflecting periods of water scarcity or availability. The joint analysis of the indices provided a more detailed understanding of how reservoirs respond to prolonged drought as well as to evaporation and water demand conditions. These results reinforce the need for water strategies to mitigate the impacts of drought and protect the main reservoirs in the semi-arid area, highlighting the importance of monitoring both flash and conventional droughts, as the progression from one to the other may have significant implications for managing water resources. Early identification and detailed analysis of these patterns can help implement more effective mitigation measures and adapt to changing drought conditions over time.

Conflict of Interest: The authors 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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Note: Figure translations are in progress. See original paper for figures.

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