



The Brazilian drought monitoring in a multi-annual perspective

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Abstract Droughts, which consist of natural and transient water deficits, endanger the water, food, and energy security of ecosystems. An effective drought preparedness strategy must focus on mitigating socioeconomic vulnerabilities to the phenomenon. In this context, the article aims to analyze the multi-annual characteristic of droughts in the Northeast region of Brazil. The study identifies each pixel under a spatial-temporal perspective of the phenomenon's severity, based on data from the Drought Monitor, providing a multi-annual and cumulative view of the extreme event. The approach aggregates a series of spatial-temporal drought severity data in a single product with clusters of monthly data referring to 5 years of outputs from the Drought Monitor. The results reveal that from July 2014 to June 2019, over 75% of the Northeast region of Brazil (NEB) area registers exceptional drought for, at least,

1 month along the 5 years. This result means impacts on water supply and crops that correspond respectively to the water dams collapsing volumes and widespread agricultural losses. Despite the natural recurrence and constancy of drought phenomena in the region, water management policies have often based the building of disproportionate and costly water infrastructure works. Cumulative multi-annual analysis of the outputs of drought monitoring can be an early warning system for water basins, regions, or municipalities, notably those who usually live with recurrent highly severe droughts, and remain neglected upon a remarkable vulnerability. This approach also supports proactive and preventive drought management instead of the usual emergency crisis management model.

Keywords Drought categories · Pixel trajectory · Spatial analysis · Cumulative approach · Northeast region Brazil

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Introduction

Droughts, from an operational definition, consist of natural, temporary, and recurrent water imbalances that extend over a minimum period of one season. They originate from rainfall deficits, whose characteristics such as severity, frequency, and duration change from one event to another. This phenomenon is related to parameters such as temperature, precipitation, the humidity of the air and soil, and distribution of rain and can occur in areas that register both low and high rainfall intensities. Its impacts are unfavorable to the

environmental, social, and economic aspects of society and can last for an extended period after the end of the event (Wilhite 2000; Mishra and Singh 2010; Brito et al. 2018).

In the arid and semi-arid regions of the world, primarily in the Northeast region of Brazil (NEB), which has 72.7% of its territory defined as a semi-arid area, having access to water is limited by several factors, among which is water scarcity, whether physical or economic. The water supply for people, livestock, and crops occurs through an extensive network of surface water reservoirs built along the basins. However, they face a series of controversies, highlighting the irregularity of rainfall, rainfall below 800 mm per year, and high rates of water runoff due to shallow crystalline soils, which also results in the predominant intermittency of their rivers, in addition to evaporation rates that exceed 2000 mm per year (Magalhães 2016; Lindoso et al. 2018).

In the Brazilian semi-arid region (SAB), such dilemmas are accentuated by the large resident population, the largest of the semi-arid regions in the world, which puts even more pressure on limited resources. Other ways of obtaining water, such as underground water reserves, have their use limited by both geophysical and economic scarcity. The populations most vulnerable to drought events in the NEB are those who live in rural areas and depend on family farming, the first being affected when droughts arise. There are losses in agricultural production, livestock, and jobs, and this culminates in a social crisis caused by water and food insecurity of those areas (Lindoso et al. 2018; Magalhães and Magalhães 2019).

The phenomenon is characterized as a natural disaster when it reaches areas of high population density and in which management follows a reactive cycle. In these regions, drought causes significant material and human damage, in addition to socioeconomic losses (Alvalá et al. 2019). The impacts resulting from drought are directly related to society's vulnerability to the event (Cunha et al. 2019). However, according to Wilhite (2000), the vulnerability recedes when proactive management comes into play, and thus, there is planning for future extreme events.

Risk management is based on three pillars of drought preparedness, according to Wilhite et al. (2005): (i) monitoring and forecasting/early warning; (ii) vulnerability/resilience and impact assessment; (iii) planning and mitigation, and response measures. The

constant monitoring and forecasting of droughts constitute an essential process for the implementation of previous actions when the phenomenon is still at the beginning of occurrence. Thus, there is a more exceptional ability to avoid or mitigate adverse effects arising from drought (Pontes Filho et al. 2019).

Brazil, however, adopts the reactive cycle as a way to manage the frequent droughts that affect mainly the Northeast region of the country. This paradigm, structured in crisis management, begins to change slightly with the implementation of the "Drought Monitor" mechanism. The Brazilian Drought Monitor (from Portuguese: Monitor de Secas do Brasil (MSB)) provides the mapping of the occurrence, severity, and extent of different intensities of drought, using monthly or weekly time scales, such as the United States Drought Monitor (USDM) as well the Mexico Drought Monitor (MSM).

MSB emerged from an international collaboration between the World Bank, National Drought Mitigation Center (NDMC) in the United States, and the Comisión Nacional del Agua (CONAGUA) in Mexico. They have extensive and pioneering experience in monitoring droughts in their respective countries. In conjunction with Brazilian federal, state, and municipal institutions, MSB emerged in 2014. The tracking maps are produced monthly, with data from different data sources related to meteorological and hydrological droughts. The indicators reflect short (last 3, 4, and 6 months) and long-term (last 12, 18, and 24 months) effects. The web portal's objective is to facilitate the monitoring of drought conditions, such as severity, space-time evolution, and possible impacts, to give outstanding support to decision-makers regarding the management actions of each drought category. The MSB uses the same categorization of the US monitor: abnormally dry (D0), moderate drought (D1), severe drought (D2), extreme drought (D3), and exceptional drought (D4) (Martins et al. 2015).

The MSB is based on three indicators, in addition to a series of support products: (i) SPI (Standardized Precipitation Index), a short-term and easy-to-use meteorological sign, whose input parameters are precipitation data, widely used for drought monitoring, developed by McKee et al. (1993); and (ii) SPEI (Standardized Evapotranspiration Index by Precipitation), which is also a long-term meteorological indicator whose input parameters are precipitation and temperature. However, this index requires a complete series of data sets (more complex) based on the SPI calculation procedure

(Vicente-Serrano et al. 2010); (iii) SRI (Standardized Runoff Index), a short-term hydrological indicator developed by Shukla and Wood (2008), which applied the same concepts used by McKee et al. (1993), replacing precipitation with runoff data (Martins et al. 2015; Svoboda and Fuchs 2016).

Data is available monthly in the Brazilian Monitor. The proposed methodology is a “cumulative approach” which consists of incorporating all monthly outputs from the MSB into a single product that expresses drought from a multi-annual perspective. In the case study, a time frame of 5 years is considered, which corresponds to 60 months of monitoring from the MSB.

This proposal has as its principal motivation to evaluate the intensities of severe, extreme, and exceptional drought that affected the NEB from 2014 to 2019, in an integrated multi-annual perspective. This period under analysis corresponds to an interval of the most significant drought ever recorded in the country and its transition to a non-dry year. As a result, the spatial cross-related and cumulative analysis determines which are the areas and municipalities kept under intense drought levels for a more extended period within the 5 years of investigation.

Materials and methods

Study area—Northeast Brazilian region

The first register of droughts in the NEB is from the sixteenth century during the colonization of the country. The Indians migrated from the hinterlands (interior regions) to the coast fleeing from droughts. Although with less frequent events, coastal areas also face agricultural and livestock losses. Over the years, the hinterlands were gradually occupied, and droughts start to have socioeconomic impacts of higher intensity and duration. The population and herds grew; however, the water infrastructure did not grow at the same rate. This fact made NEB society very vulnerable, until the multi-annual drought (from 1877 to 1879), which decimated herds and killed thousands of people. At the end of the drought, many dams were built making reservoirs that ensured the water supply for the inhabitants of the NEB, and, consecutively, in the twentieth century, an institutional framework emerges focused on management, financial investments, and development of public

policies to deal with droughts (Campos 2014; Campos 2015).

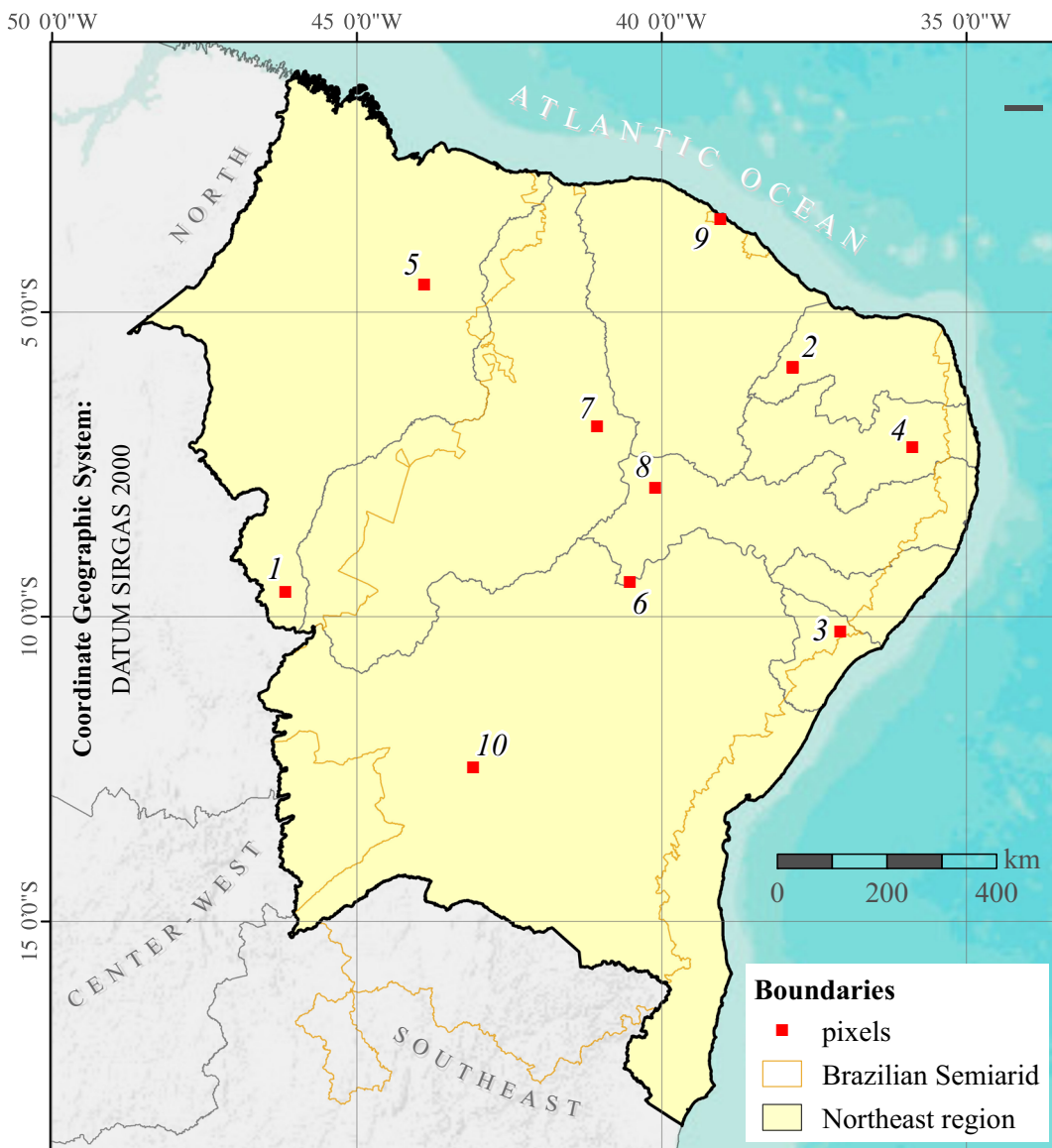
Despite advances in public policies aimed at coping with recurrent droughts in the Northeast, the planning and respective management of this climate phenomenon, in the twenty-first century, is still based on facing the drought only when the event already occurs and its impacts are visible. In the last long-term drought from 2012 to 2018, most of the supply reservoirs collapsed, reaching the dead volume (Souza Filho et al. 2018). Municipalities started to depend on water supply by tanker trucks, and agriculture register critical losses (Marengo et al. 2016; INSA 2020). The impacts of droughts in the NEB over the years are, in particular, the migration of people from the interior to the coast, drop in agricultural production, hunger, and drop in the volumes of the reservoirs (De Nys et al. 2016). Figure 1 shows the NEB and the location of the most populated cities (over 100 thousand inhabitants)

The Northeast region of Brazil (NEB) encompasses 1794 municipalities, distributed in nine states that constitute an area of 1,552,167.009 km². It is characterized by intense solar radiation, low cloud cover and relative humidity, and high rates of potential evapotranspiration. Precipitation is irregularly distributed throughout the region. The dry (semi-arid) zone, which is in the interior, registers less than 800 mm of rain per year, which is concentrated in the months from February to May. In contrast, the tropical area, located on the coast and in part of the regional borders, reaches more than 1500 mm of annual precipitation distributed between April and July. Approximately 72.7% of its territory is legally known as semi-arid (Fig. 1) for policy initiatives (Alvares et al. 2013; Cunha et al. 2015; IBGE 2017; Tomasella et al. 2018).

The semi-arid region of Brazil (SAB) occupies a total area of 1,128,697 km² and holds a population of around 28 million inhabitants in 1292 municipalities. Federal policies established an official boundary for the SAB based on three criteria: (i) average annual rainfall equal to or less than 800 mm; (ii) Thornthwaite dryness index equal to or less than 0.50; and (iii) daily water deficit similar to or greater than 60%, considering all days of the year (SUDENE 2017).

Cumulative approach

In the MSB, each drought class is associated with its drought impacts, as shown in Table 1. In this analysis,



Pixel location: municipality (state)

- | | |
|------------------------|----------------------------|
| 1. Alto Parnaíba (MA) | 6. Juazeiro (BA) |
| 2. Apodi (RN) | 7. Monsenhor Hipólito (PI) |
| 3. Aquidauana (SE) | 8. Ouricuri (PE) |
| 4. Campina Grande (PB) | 9. Paracuru (CE) |
| 5. Codó (MA) | 10. Paratinga (BA) |

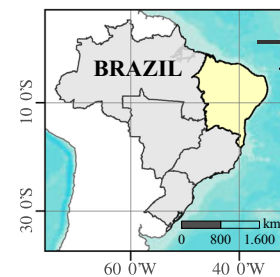


Fig. 1 Location of the Northeast region of Brazil with the overlap of the Brazilian semi-arid region and the municipalities with a population of over 100,000 inhabitants. Source: Elaborated from IBGE (2017), and SUDENE (2020)

three drought typologies were chosen from the five classes available in the monitor outputs: severe (D2), extreme (D3), and exceptional droughts (D4). This

selection is due to the highest impact levels, such as water restrictions (severe drought) and the creation of states of emergency (exceptional drought).

Table 1 represents the impacts associated with each existing category in the MSB regarding water (W) and agricultural (A) sectors. The first corresponds to the hydrological impacts on the human supply system. The second corresponds to the effects on agricultural activities, which include crops, pastures, and mosaics of agriculture and fields (Svoboda et al. 2002; NDMC 2020). It is worth mentioning that, according to the Water Law in Brazil (Law n° 9.433/1997), “when there is a shortage, priority in the use of water resources is given to human consumption and the watering of animals” (Brasil 1997).

Monthly data from July 2014 to June 2019, totaling 5 years of drought analysis, are systematized in a GIS environment (ArcGIS Desktop 10.6), as well as submitted to spatial analysis operations and the consequent structuring of accumulated drought maps. The entire procedure is described graphically in Fig. 2. The data provided by the MSB are available in vector format (shapefile). In this approach, all data is converted in spatial grids with a resolution of 1000 m. This operation aims to facilitate the map algebra of cumulative drought categories for the entire period considered. The Spatial

Table 1 The impacts associated with water supply and agricultural activities for the Monitor’s drought categories

Category	Water (W)	Agriculture (A)
D0	Coming out of drought: some lingering water deficits	Going into drought: short-term dryness slowing planting, growth of crops or pastures Coming out of drought: pastures or crops not fully recovered
D1	Streams, reservoirs, or wells low, some water shortages developing or imminent; voluntary water-use restrictions requested	Some damage to crops and pastures
D2	Water shortages common; water restrictions imposed	Crop or pasture losses likely
D3	Widespread water shortages or restrictions	Major crop/pasture losses
D4	Shortages of water in reservoirs, streams and wells creating water emergencies	Exceptional and widespread crop/pasture losses

Source: Adapted from Svoboda et al. (2002), ANA (2020a), NDMC (2020)

Analyst Tool from ArcGIS makes possible an overlay of 60 monthly raster files, based on a cumulative function (Fig. 2).

A range value expresses all output data from 0 to 60, where “0” means that the pixel in an area which has not under any severe drought (D2, D3, or D4) during any of the months within the time interval analysis (5 years). In other hands, the value “60” expresses that the area was severely critical during the whole 5-year review period, uninterruptedly.

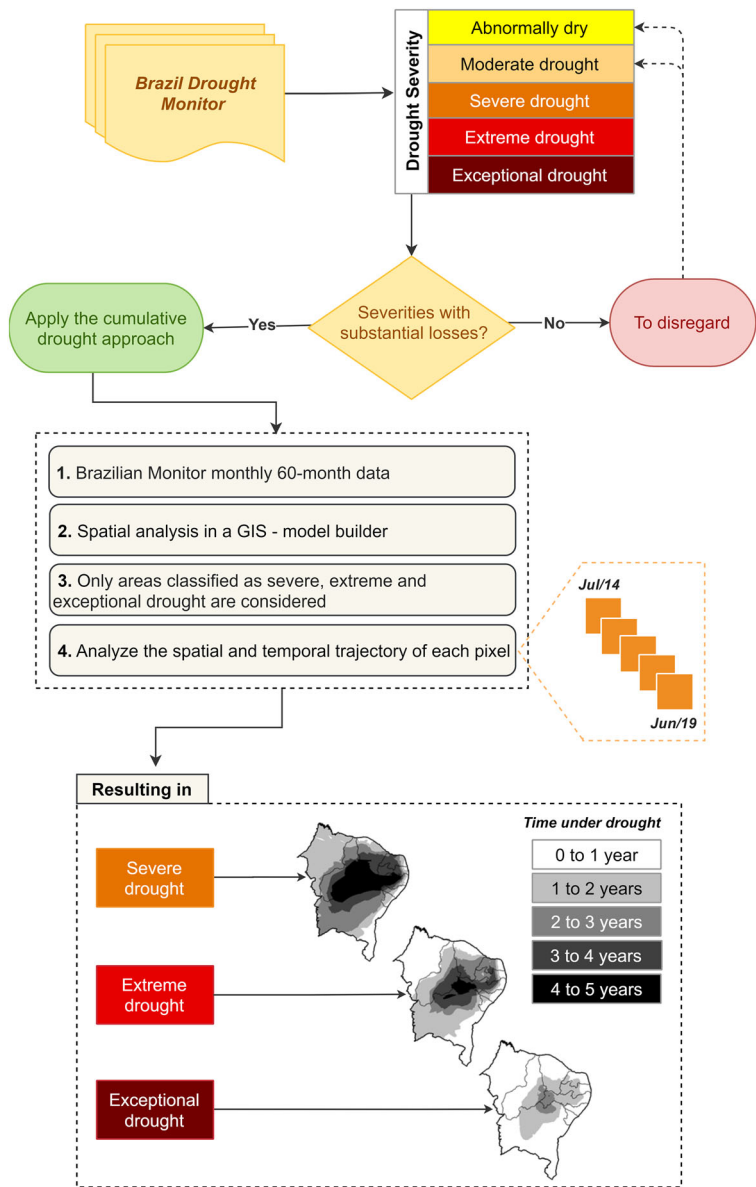
For better visualization of the results, the cumulative output interval (0 to 60) is structured into intervals, considering that these values correspond to the total number of months in which a given area was under severe drought conditions in 5 years. The categories (established by intervals) are described in the following, and they are strongly related to the most significant priority areas for mitigation and crisis management actions (Fig. 2).

- (a) Interval 1: pixels under severe drought conditions for up to 12 months during the evaluated period (0 to 1 year).
- (b) Interval 2: pixels under severe drought conditions for more than 12 months and up to 24 months during the evaluated period (1–2 years).
- (c) Interval 3: pixels under severe drought conditions for more than 24 months and up to 36 months during the evaluated period (2 to 3 years).
- (d) Interval 4: pixels under severe drought conditions for more than 36 months and up to 48 months during the evaluated period (3 to 4 years).
- (e) Interval 5: pixels under severe drought conditions for more than 48 months during the estimated period (4 to 5 years).

The cumulative approach aims to analyze the spatial and temporal trajectory of each pixel and, consequently, determine which ones are under severe, extreme, or exceptional drought conditions in different periods and the permanency and continuity time of these conditions. The study is based on the accumulated approach applied to 13 years of US drought maps developed by Rufino et al. (2014). Those authors developed a cumulative map from 2000 to 2012 using outputs from the US Drought Monitor, applied to 678 available maps.

In the end, the diagnostic mapping can be cross-related with 1794 municipalities boundaries in the NEB. Zonal statistics allows quantifying how much area

Fig. 2 Cumulative approach: methodological framework



of a municipality still in drought conditions and for how long. One city can be classified in more than one interval, and it is an essential planning tool for different horizons of time (see Table 2) because of the possibility to policymakers having different management actions according to not only to the severity of the drought but also to the permanency time along last 5 years.

An ascending scale of “temporal severity” is established: interval 1 corresponds to areas with less severity, which experienced drought conditions for a maximum period of 1 year (even if there is no continuity along the time); On another hand, interval

5 presents areas that require priority actions or a closer look from drought management agencies. It is worth mentioning that the three drought intensities are independently assessed to verify how long (time intervals 1 to 5) each pixel of the NEB was under different types of drought. The next step is to carry out the spatial contingency analysis, overlapping the accumulated drought maps with the municipality boundaries and identifying and quantifying areas for definitions of policies and funding support. After all, this approach shows up Brazilian semi-arid municipalities which have been more vulnerable to drought

Table 2 Summary of the number of municipalities in each type of drought and their area percentages based on the cumulative approach

Drought categories	Interval 1 0 to 1 year)	Interval 2 (1 to 2 years)	Interval 3 (2 to 3 years)	Interval 4 (3 to 4 years)	Interval 5 (4 to 5 years)
Number of municipalities (1794 total)					
Severe drought	197 (11.0%)	499 (27.8%)	301 (16.8%)	375 (20.9%)	421 (23.5%)
Extreme drought	735 (41.0%)	405 (22.6%)	344 (19.2%)	253 (14.1%)	53 (3.0%)
Exceptional drought	807 (45.0%)	488 (27.2%)	78 (4.3%)	1 (0.0%)	0
Percentage of NEB area (total of 1,552,167.009 km ²)					
Severe drought	8.1%	28.0%	22.9%	18.5%	22.4%
Extreme drought	37.5%	29.9%	14.4%	14.6%	3.2%
Exceptional drought	48.9%	23.5%	4.7%	0.0%	0.0%

(higher frequency of exposure to drought events) by overlapping municipal boundaries.

Results

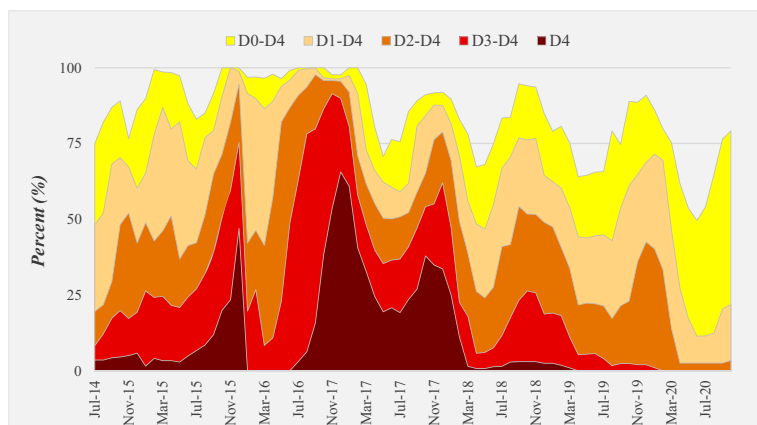
The Drought Monitor in Brazil classifies droughts based on degrees of severity that are associated with a series of expected impacts on activities that depend on the regional water supply. What differentiates MSB from other indexes is the systematic elaboration process, which involves the participation of several actors, among which are the authors of the monthly maps and the validators, which are located throughout the entire geographic region, which makes the process more robust, as indicated by ANA Resolution No. 31 of July 13, 2020, which institutes the Drought Monitor Program.

To show the drought behavior, in the Northeast region of the country, we have Fig. 3, which represents a tabular area graph with a time scale that extends over just over 6 years of drought analysis. Records for all

MSB categories—abnormally dry, moderate, severe, extreme, and exceptional—from July 2014 to October 2020 are represented. The most critical month corresponds to December 2016, in which 65.64% of the region points to exceptional drought in its territory. The quarter from November 2016 to January 2017 indicates the peak of the highest drought intensity, with records that mark the collapse of the water supply, recorded in 132 NEB municipalities. This water crisis scenario extends until mid-2018 when the main water reservoirs in the Northeast reach their dead volume. From 2019, the multi-annual drought scenario that extends from 2012 to 2018 decelerates, entering a stage considered normal for the Northeast region of Brazil, which demonstrates the beginning of a recovery cycle.

MSB integrates several meteorological and hydrological drought indices in a single product, which makes it accessible to the entire population, especially to decision-makers. Thus, the proposed methodology, entitled cumulative approach (Rufino et al. 2014), further simplifies this decision-making process, like all monthly

Fig. 3 Area graph referring to tabular drought data from the MSB. Source: Elaborated from ANA (2020a)



maps—raw data—are integrated into a single file that indicates, for each drought category, how long each municipality or other geographical area of interest has been in drought for a given period of analysis.

The study presents the most austere events—which are severe, extreme, and exceptional drought—when, usually, the reservoirs are not sufficient to mitigate all the impacts described in Table 1, thus resulting in a water crisis. The municipalities that register, in the course of the complete analysis, the highest classes of the interval—which are 3, 4, or 5 (legend of Fig. 4)—in their territory, are the most critical situations, because it means that the localities are in more intense droughts for more than 2 years among the five that are analyzed. This fact means that these regions did not have enough time to recover crops and pastures, or even to reduce rationing actions in urban areas, as the drought lasted for years.

In this regard, when analyzing the result shown in Fig. 4, it is noted that the NEB east coast and a small portion of the Ceará state coast did not register droughts for more than a year, during the entire period analyzed (Fig. 4a). However, as the interiorization takes place, reaching the northeastern hinterland region, it appears that the phenomenon is becoming more intense, which

can be easily seen by the increase in color intensity, which starts from white on the coast (minimum time in dry condition) to black in the “Sertão” (more than 4 years under dry state).

The same approach is analyzed from the perspective of extreme drought (Fig. 4b). Almost 15% of the Northeast extension of the country has registered this condition for more than 3 years, which is equivalent to 60% almost analysis period. Reference is made to this percentage of 60% of the time, as it corresponds to a region that registered more severe degrees of drought severity for a significant time. What gives evidence of the difficulty of mitigating the impacts arising from the extreme event, since the SAB, already in its normal climatic conditions, has an irregular rainfall regime and high rates of evaporation in its reservoirs, in addition to a population in a state of vulnerability, especially concerning supplying the suburbs and rural supply.

The most severe cumulative map (Fig. 4c), in turn, does not indicate areas in this condition for more than 3 years (60% of the time). The municipalities that register the exceptional drought intensity are the most affected by the event’s multitemporal and spatial impacts, which correspond to an area of 48.9% that indicates this type of drought for at least 1 month among the 5 years.

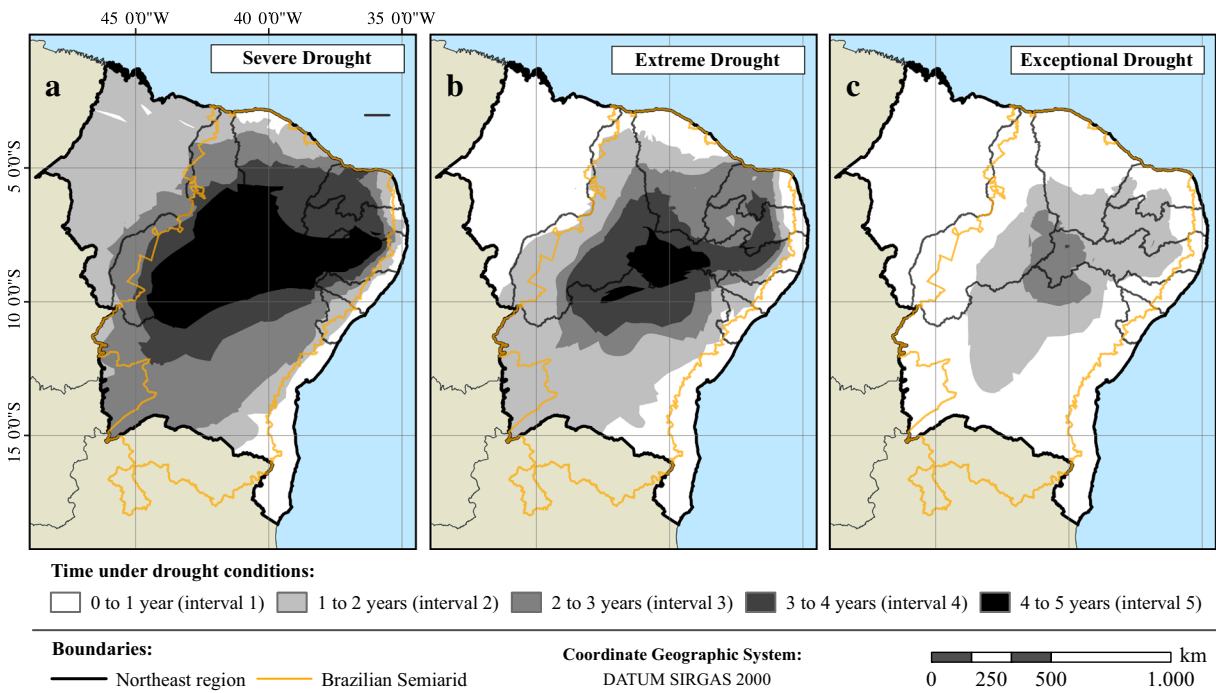


Fig. 4 Maps are resulting from the cumulative drought approach for NEB. From the lowest to the highest intensity are (a) severe drought, (b) extreme drought, and (c) exceptional drought. Source: Elaborated from ANA (2020a), IBGE (2017), and SUDENE (2020)

The municipality of Ouricuri is the most extreme case. Located in the hinterland of Pernambuco, it stands out as the only place that has been under the most severe drought intensity for over 3 years.

The most severe drought categories (severe, extreme, and exceptional) are those that also have the most severe impacts, as shown in Table 1. Severe drought generates prevalent water scarcity, with restrictions on human supply (rationing), while exceptional drought results in decrees on the state of emergency. In extreme cases of a short duration of water, the resource is provided utilizing tanker trucks, a crisis solution that, in most cases, remains in use for a more extended period, since the recovery of the volume of water in the reservoirs after drought is slow. According to ANA (2018), this type of palliative measure is characterized as a form of emergency supply that occurs when all other supply solutions are exhausted.

In order to quantify the municipalities and the NEB area percentages reached by the drought, we have Table 2. The first part corresponds to the number of localities, among the 1794 existing in the Northeast, which records the most intense droughts examined and by how much time remained the condition, while the other component refers to the percentage of area under each type of drought assessed. It is noteworthy that only 4.4% of the total number of municipalities recorded exceptional drought for more than 12 months. Such an investigation reflects a positive outlook, since the expected impacts for this condition are highly critical, with generalized consequences for all sectors dependent on water resources.

It is worth mentioning that as the severity becomes intense, the municipalities return to the milder temporal categories. This fact does not mean, however, that all rural and urban areas are under milder impacts. Although the most severe class (exceptional drought) lasts for the shortest time, its consequences are the most complex and challenging to recover. Managing these effects is an arduous task, particularly in the Brazilian context, where drought management is generally reactive, and there is a lack of synergy between the levels of municipal, state, regional, and national planning (Gutiérrez et al. 2014; Awange et al. 2016; Marengo et al. 2019).

From July 2014 to June 2019, 2297 Emergency Situation (ES) and Public Disaster States (SPD) decrees were recorded across the NEB, distributed across 581 municipalities (S2iD 2020). The municipality with the

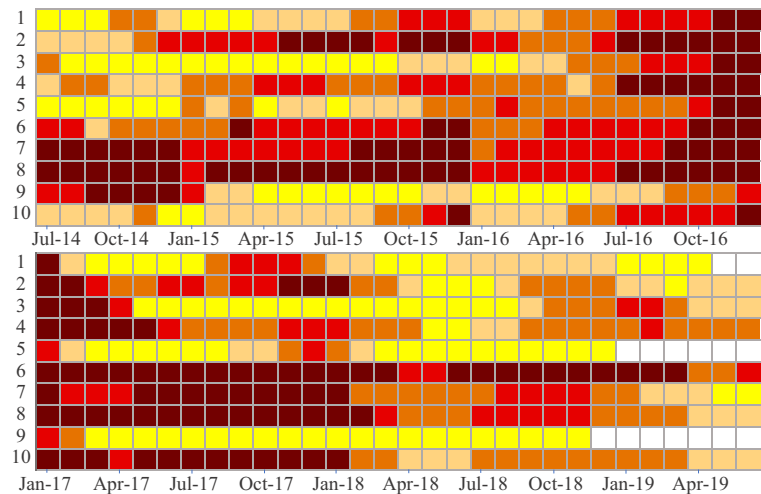
highest number of decrees was Macau (RN), located on the north coast of the Northeast. However, from the cumulative approach, Macau has not experienced exceptional drought for more than 12 months, over 5 years. On the other hand, it should be noted that Ouricuri, despite being the municipality under worst drought condition (in a multi-year perspective), did not register any emergency decree for the “drought” disaster during this period. However, 7 ES are registered for the “dry season” disaster, according to the Integrated Disaster Information System (S2iD).

Finally, it is necessary, as the last analysis, to understand the spatio-temporal evolution of the drought in the NEB, to visualize the trajectory of 10 pixels selected at random (Fig. 5), located according to Fig. 1. The GIS data obtained from the Brazilian Drought Monitor are presented in vector format of shapefile. However, to apply the proposed methodology, it is necessary to convert the maps to a matrix model composed of cells (pixels), which represent the minimum mapping unit of the area (Bajjali 2018). The pixels form a matrix of continuous data, and their size corresponds to the spatial resolution that, for this study, originated with a dimension of 1×1 km.

Campina Grande is a medium-sized city located in the semi-arid region of the State of Paraíba, represented by the trajectory of pixel number four. As can be seen in Fig. 5, it was in exceptional drought, uninterruptedly, between July 2016 and May 2017. However, the municipality decreed a state of emergency due to “dry season” 9 times between October 2014 and April 2019. The locality is supplied by the Epitácio Pessoa reservoir, which has a capacity of 466.53 hm³ and also supplies another 25 urban centers. The reservoir does not have enough water supply to reverse losses since September 2011, according to Rêgo et al. (2017), until, in December 2014, rationing measures are enacted, however, not enough to prevent a collapse in the water supply of the 26 locations, which occurs in early 2017, when it reaches the volume of only 2.9% of its full capacity.

Pixel number 8 is located in the municipality of Ouricuri, Sertão de Pernambuco, characterized as the worst drought condition recorded in NEB, according to the exposed cumulative methodology. Among the 60 months, the region was in exceptional drought for precisely 37 months. The municipality decreed an emergency due to drought seven times between April 2016 and March 2019 (S2iD 2020). This information is

Fig. 5 The trajectory of the 10 pixels selected in the study area for drought analysis from a temporal perspective



consistent with the criticality data of the stored water volume in the main reservoirs in the municipality, presented by the “Olho N’água” platform. The “Algodões” weir, which has a capacity of just over 58 hm³, collapsed in January 2016 and remained so until mid-2018 (INSA 2020).

Discussions

Drought monitoring can be done in several ways, using different types of data, indices, and mapping analysis, including meteorological time series and satellite data. Each method has its space-time and cost-specific resources. The Drought Monitor consists of one of these ways, and its differential is the participatory validation process that makes up the formulation of monitoring products with approval from interested parties on the drought intensities that affect each area (Martins et al. 2016; Zeri et al. 2018).

Multi-annual observation of drought events using the cumulative approach methodology allows verifying how long a pixel is under some drought intensity condition. This result is a data of high relevance for managers from the most diverse politic administrative since it serves as a reference for decision-makers for proposing and implementing actions and measures that aim to mitigate the impacts of the most diverse types of drought. The results are shown in Fig. 4 and Table 2 helping in the creation of space-time typologies that support decision-making in future drought phenomena. In a region like the Brazilian Northeast that has been

experiencing droughts for centuries, new approaches and methodologies are urgently needed to deal with droughts proactively, rather than reactively.

The categories of mild and moderate drought are disregarded from the analysis because they result in rapidly reversible and, therefore, recoverable impacts, as shown in Table 1. The NEB’s water supply is predominantly aimed at capturing water from surface reservoirs, which can supply the population with the necessary water demand in the face of such drought intensities.

However, when the drought comes more severely, extending multi-annually, the water supply declines in opposition to a demand that remains constant. Given this scenario, SAB, which comprises almost 65% of NEB, enters a state of water deficit. According to Magalhães (2016), the region starts registering annual rainfall below the historical average of 800 mm, concentrated in a short time, concomitantly with evapotranspiration rates that exceed 2000 mm/year. Such components of the water balance in the hinterland, associated with shallow crystalline-based soils, result in mostly intermittent watercourses.

Authors such as Cunha et al. (2017), Azevedo et al. (2018), and Brito et al. (2018) identify that the last long-term drought affected NEB with significant impacts. The event was characterized as the worst drought on record, drastically affecting the availability of water in the territory. According to the 2018 ANA Annual Report, 80% of people affected by droughts in 2017 live in the NEB. It is designated as the region most affected by multi-annual drought phenomena and with the most

vulnerable population from a socioeconomic point of view (Cunha et al. 2018).

According to Cunha et al. (2019), drought prevention actions in Brazil focus on the construction of large and expensive water infrastructure works, mainly in SAB. For example, in the first two decades of the twenty-first century, a significant river diversion project is under construction: the diversion of the São Francisco River. This project aims to complement the water supply of four NEB states (Rio Grande do Norte, Paraíba, Ceará, and Pernambuco). Together, they accounted for 75% of the country's drought records in 2018 (ANA 2019).

From an agricultural point of view, the categories of drought have different consequences. From the possibility of agricultural losses (severe drought category) to generalized agricultural losses (exceptional drought category), staying in a drought condition leads to impacts and losses. The crops of beans, corn, and cassava correspond to the main crops for the subsistence of life in SAB (Magalhães 2016). Corn, above all, is used as a base for human and also animal feed. However, when drought occurs, it causes soil moisture deficiency (agricultural drought), which causes a decrease—when they are not decimated—in agricultural production in the northeastern hinterland (Martins et al. 2018).

Given this, ANA (2020b) recognizes that the expansion of the MSB, for the whole country, would make the platform more consolidated, providing greater robustness to the system, from the uniform and integrated monitoring of drought, with a unified database. This statement was punctuated by Wilhite et al. (2000), when arguing that an indispensable component for preparing for droughts is the creation of a national system to help decision-makers, at all geographic levels (local, regional, and national), to manage their territory in the face of these events proactively.

Among the three pillars proposed by Wilhite et al. (2005), for effective drought risk management, the first, which consists of monitoring, has been adequately implemented at NEB since the emergence of MSB in 2014. In addition to the monthly data available on the platform, it is possible to analyze the trajectory of the phenomenon by different methodologies, as is the case of the cumulative approach proposed in this study. The second and third pillars, which correspond to vulnerability assessment and planning, respectively, are still weak points for the Brazilian reality. However, based on the systematic analysis of droughts from a multi-annual perspective, the triggers for the creation of

typologies of vulnerability to drought were created, making it necessary to elaborate integrated and participatory coexistence plans at the most diverse levels of planning.

Conclusions

Drought events and their different intensities, which are triggered by water deficit events, cause short-, medium-, and long-term impacts on the different sectors that make up a nation. Therefore, such events present one of the most severe natural risks, as their consequences remain even after the phenomenon ends. Drought events are natural phenomena that can become more damaging due to the vulnerabilities of society, i.e., this type of risk does not make easy the decision-making problem, since this cause is intrinsic to the geographic profile. Therefore, most of the solution is to be prepared to deal with the impacts resulting from droughts. It is called drought risk management.

Reactive drought management should give way to a proactive management system, since, according to the history of drought events in the NEB, these events are frequent and there is a natural weather variability in this Brazilian region; therefore, the cities and settlements (more than 1000) have no choice but to adapt to them. The ideal situation is to design a management system adapted to future drought events and thus to develop plans that cover all levels of geographic planning: national, river basin, regional, state, and municipal.

It is important to note that the country has taken a step forward in the implementation of the Drought Monitor, first implemented in the Northeast region in 2014, as well as the monthly monitoring of droughts, given the definition of drought stages, which change depending on drought severity. It is a tool capable of providing excellent support to decision-making processes, as it has a local validation phase in the map elaboration.

Based on current results, it is essential to evaluate drought events from a multi-annual point of view in order to determine the regions that remained most of the time in a high level of drought severity. If an area remains under exceptional (most intense) drought for a long time, it should be an indicator that the location requires more considerable attention from the drought management system than others.

It is agreed that the longer the drought period (in some months) under the most extraordinary cumulative

drought events, the more intense its impacts on the most diverse sectors, whether agricultural, social, or economic.

The cumulative maps for 5 years of MSB data provide new subsidies not limited in a monthly analysis—as available on the Monitor—but allowing to evaluate all data from the last 60 months in a big picture and uncomplicated manner. Besides, the results highlight the areas that require more significant concern for coping with drought which it is not possible or comfortable in a monthly analysis or even in a comparison analysis (month by month in different years as the most common use of the MSB).

The prevalence of longer time intervals was the criterion taken into account in the previous quantifications, that is, if a municipality falls within more than one interval, the one with longer duration prevailed over the other—more than 4 years prevails in all others—periods regardless of the area's coverage rate.

Observing the droughts from the perspective of the cumulative approach allows analyzing the event because of its multi-annual characteristics and thus making it possible to plan actions of living together with a phenomenon so recurrent in the NEB. This preparedness should establish hierarchical actions based on the intensity of the drought that affects a given area and its respective duration, according to the maps presented in Fig. 3. The management between the MSB and other information platforms mentioned must be integrated. For instance, for one area under severe drought for more than 2 years, the supply reservoir network begins to collapse, and, in order to manage them, in addition to the Drought Monitor, data related to the monitoring of water levels (from other monitoring systems) in dams is crucial.

It is noteworthy that the multi-annual drought that hits the Northeast of Brazil ended in mid-2018. Thus, the last year considered in the analysis was without severe drought in the whole NEB, which may have caused a milder drought scenario. From a cumulative perspective, droughts must always be analyzed in their respective temporal categories.

Authors' contributions Yáscara MA Brito: Conceptualization; data curation; formal analysis; investigation; methodology; validation; visualization; roles/writing - original draft; and writing - review and editing.

Iana AA Rufino: Conceptualization; formal analysis; funding acquisition; methodology; software; supervision; visualization; roles/writing - original draft; and writing - review and editing.

Cybelle FC Braga: Formal analysis; supervision; visualization; roles/writing - original draft; and writing - review and editing.

Kevin Mulligan: Conceptualization; investigation; and methodology.

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Compliance with ethical standards

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