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A New Approach for Assessing the Drought Risk Management Capacity at the Municipal Level in Brazil

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Abstract

Long-term drought has occurred in all regions of Brazil, and its effects have been more intense in recent decades. Poor management of drought can exacerbate significant consequences, severely compromising water, food, energy, economic security, natural systems, and high fire risk that can affect biomes. It also slowly and indirectly affects the society living on vulnerable geographic space. This article discusses a methodology for assessing the drought risk management capacity at the municipal level in Brazil, and this new approach is statistically based using environmental data provided by the municipalities, from observational networks to data banks and remotely sensed data. It presents a method to indicate the steps of priority actions for the phases of drought management. It also characterized the long-term drought in Brazil (hydrological drought) between 1982 and 2022. The proposed approach provides a better understanding and the use of various drought indices to develop the most appropriate action steps for mitigation and adaptation. The final goal is to increase the resilience for those affected by drought. The work was developed based on the actions defined by the Brazilian Federal Government (Preparation, Prevention, Mitigation, Response, Recovery, and Restoration). This aims to improve the management of risk and disaster typified as drought in Brazil and to contribute with scientific knowledge to legislators regarding adaptation and resilience policies to drought extremes in parts of the country. At the end, we expect to highlight to managers and decision-makers the critical points in the government's proactive and reactive actions to drought that need to be better managed.

Keywords

Drought Management, Brazil, Drought Indices, Vulnerability

1. Introduction

For Wilhite and Glantz (1985), the classification of meteorological drought, agricultural drought, and hydrological drought deals with the deficit as a physical phenomenon. In contrast, socioeconomic drought addresses it in terms of supply and demand, following the effects of water scarcity as it propagates through socioeconomic systems. The definitions of drought categorization are Meteorological drought: which occurs when precipitation is below typical averages for a region for an extended period (Wilhite & Glantz, 1985; Mishra & Singh, 2010; Wilhite et al., 2014; Van Loon, 2015; Ravelo et al., 2016). If the lack of rain lasts longer, other forms of drought can occur with a more significant social and economic impact (Ravelo et al., 2016). Precipitation deficit can extend and lead to meteorological and agricultural droughts (Tallaksen & Van Lanen, 2004); Agricultural drought: occurs when there is a prolonged deficit of water in the soil and consequently causes water stress of plants, harming the different stages of vegetation development and harvest (Mishra & Singh, 2010; Sivakumar et al., 2011); Hydrological drought: refers to the effects of the prolonged deficit of precipitation on the supply of surface and underground reservoirs, including reflecting in low flows of rivers, low levels of lakes and aquifers, impacting the water supply (Wilhite, 2000; Tallaksen & Van Lanen, 2004). Generally, this drought class is a consequence of the most severe meteorological and agricultural droughts (Wilhite, 1992); Socioeconomic drought: is related to the impacts resulting from the previously mentioned classes of drought when the water supply negatively affects the demands of human activities, whether directly or indirectly, such as ecological or health impacts, agricultural production, water security, food, energy, economics, and navigation (Wilhite, 2000; Van loon, 2015).

Other types of droughts have also emerged, such as groundwater drought, which begins with reduced groundwater recharge and then reduced discharge levels, and generally lasts from months to years (Mishra & Singh 2010), and ecological drought, which is a water deficit that pushes ecosystems to their limits of vulnerability, stressing natural and human systems (Crausbay et al., 2017). There are sudden droughts, of short periods, “flash droughts”, usually less than three months, resulting from an increase in evapotranspiration and rapid drying of the soil due to high temperatures and strong winds (Mo & Lettenmaier, 2016).

These drought events concomitant with heatwaves, low air humidity, strong winds, or high temperatures are called compound events (Zscheischler et al., 2018, 2020). For instance, the drought that affected Pantanal in 2020 was classified as a heat-drought event where the drought and high temperatures increased the fire risk (Marengo et al., 2021; Libonati et al., 2022). The Pantanal is one of the world's largest wetlands. According to Wilhite and Glantz (1985); Wilhite et al. (2014); Van Loon (2015); Ravelo et al. (2016); and NDMC (2023), the types of droughts are meteorological; agricultural; hydrological; and socioeconomic. A drought event could have more severe impacts as it propagates and persists in the hydrological cycle (UNDRR, 2021).

Droughts substantially impact the economy, society, and affected ecosystems, with the risk of degradation or desertification (Cherlet et al., 2018; UNDRR, 2021). According to Article 1 of the UNCCD (2022), desertification is "land degradation in dryland areas resulting from various factors, including climatic variations and human activities." When human pressures cause excessive and unsustainable long-term structural instability in water resources, water scarcity is an imbalance (Tallaksen & Van Lanen, 2004; UNDRR, 2021). While drought is a natural event limited in time, aridity is a characteristic of a dry permanent climate (Wilhite, 2000; Tallaksen & Van Lanen, 2004; UNDRR, 2021).

Brazil has a history of droughts, some dating back hundreds of years in Northeast Brazil (Marengo et al., 2021). In recent years, severe droughts have affected all Brazilian regions (Cunha et al., 2019; Cuartas et al., 2022), with highlights to the unprecedented drought that occurred in the Southeast Region between 2014 and 2015 (Otto et al., 2015; Nobre et al., 2016; Cunha et al., 2019), as well as the drought between 2015 and 2016 in the Amazon, which was considered the most severe in the last 100 years (Cunha et al., 2019) and the multiyear drought (2012-2018) in the Northeast region, being the most extreme in the Brazilian Semiarid region (Marengo et al., 2018; Alvalá et al., 2019a; Cunha et al., 2019, Cuartas et al., 2022), and the current drought affecting the Parana-La Plata basin (Naumann et al., 2021). In fact, between 2019 and 2022, the prolonged drought in the Pantanal Region, with subsequent fires that reached hundreds of thousands of hectares, affected natural biodiversity, agribusiness, livestock, and low river levels compromised several stretches of waterway transport (Marengo et al., 2021; Libonati et al., 2021, 2022).

Among the priorities of the Sendai Framework 2015-2030, it is proposed to strengthen governance to manage disaster risk. Therefore, it is necessary to promote collaboration and partnership between mechanisms and institutions to implement relevant instruments for reducing disaster risk and sustainable development (UNISDR, 2015). Risk management includes proactive actions that precede the disaster, including the drought disaster, with the objective of managing. This is directed at avoiding or reducing future impacts, tackling complex issues, including actions associated with early warning and monitoring, planning, reducing vulnerability, and developing national risk-based drought management policies (Wilhite, 2000; CGEE, 2016). Disaster or crisis management comprises only reactive actions after the effects and impacts of drought, which occur as a direct or indirect consequence of drought events.

Therefore, the general objective of this article is to propose a methodology for assessing drought risk management. This methodology constitutes a new approach representing a strategic procedure to indicate the steps of priority actions for the phases of drought management. This is done at the municipal level, together with a characterization of drought (hazard) in Brazil between 1982 and 2022. The new approach involves institutions working on drought disaster management, particularly highly exposed vulnerable populations. The methodologies can be operationally implemented to generate helpful information for monitoring and decision support for drought risk and disaster management actions. It also offers valuable information to support the formulation of public policies applied to better coexistence and resilience to the drought disaster in Brazil. Our focus is on hydrological droughts since they affect food, water and energy security in the country.

2. Drought in Brazil, Historical Aspects and Current Monitoring

The Brazilian government defines drought as a "naturally occurring phenomenon when registered rainfall is significantly lower than normal values, causing a serious water imbalance that negatively affects production and consumption systems" (Brasil, 2015). In this sense, the Brazilian Classification and Codification of Disasters (COBRADE) defines "drought as a prolonged period of dryness, for some time sufficient for the lack of precipitation to cause serious hydrological imbalance" and that dryness is a "prolonged period of low or no rainfall, in which the loss of soil moisture is greater than its replacement" (Brasil, 2012, 2013, 2014, 2022). However, this article will deal with drought or dryness as drought. The Intergovernmental Panel on Climate Change—IPCC defines drought as an abnormally dry period long enough to cause a severe hydrological imbalance (IPCC, 2012).

According to CEPED/UFSC (2020), the drought disaster was responsible for the most significant damages and total economic losses in recent years in Brazil. Information on material damage and total economic losses comes from the Database of the Integrated Disaster Information System (S2iD, 2023) and CEPED/UFSC (2023). Official statistics show that in the period of the multiannual drought in the semiarid region, from 2011 to 2018, the financial impact in the Northeast Region alone was R$ 87.2 billion (about US$ 18.2 billion). Between 2019 and 2022, the economic losses associated with the drought in the South Region were R$ 79 billion (about US$ 17 billion). In the drought situation in the Southeast Region, between 2014 and 2015, the losses were R$ 9.5 billion (US$ 2.1 billion), and between 2020 and 2021, they were R$ 8.8 billion (US$ 2.0 billion). During the drought in the Pantanal, between 2019 and 2022, the losses were 12.2 billion in the Mid-West Region, and in the North Region, between 2015 and 2016, economic losses were R$ 186.7 million (about US$ 40 million) (**Figure 1**).

Drought are recurrent in regions of Brazil, and **Figure 2** illustrates the records of occurrences of drought by municipalities, carried out by the municipal and state civil defenses, between 1991 and 2022. Most of these records occur mainly

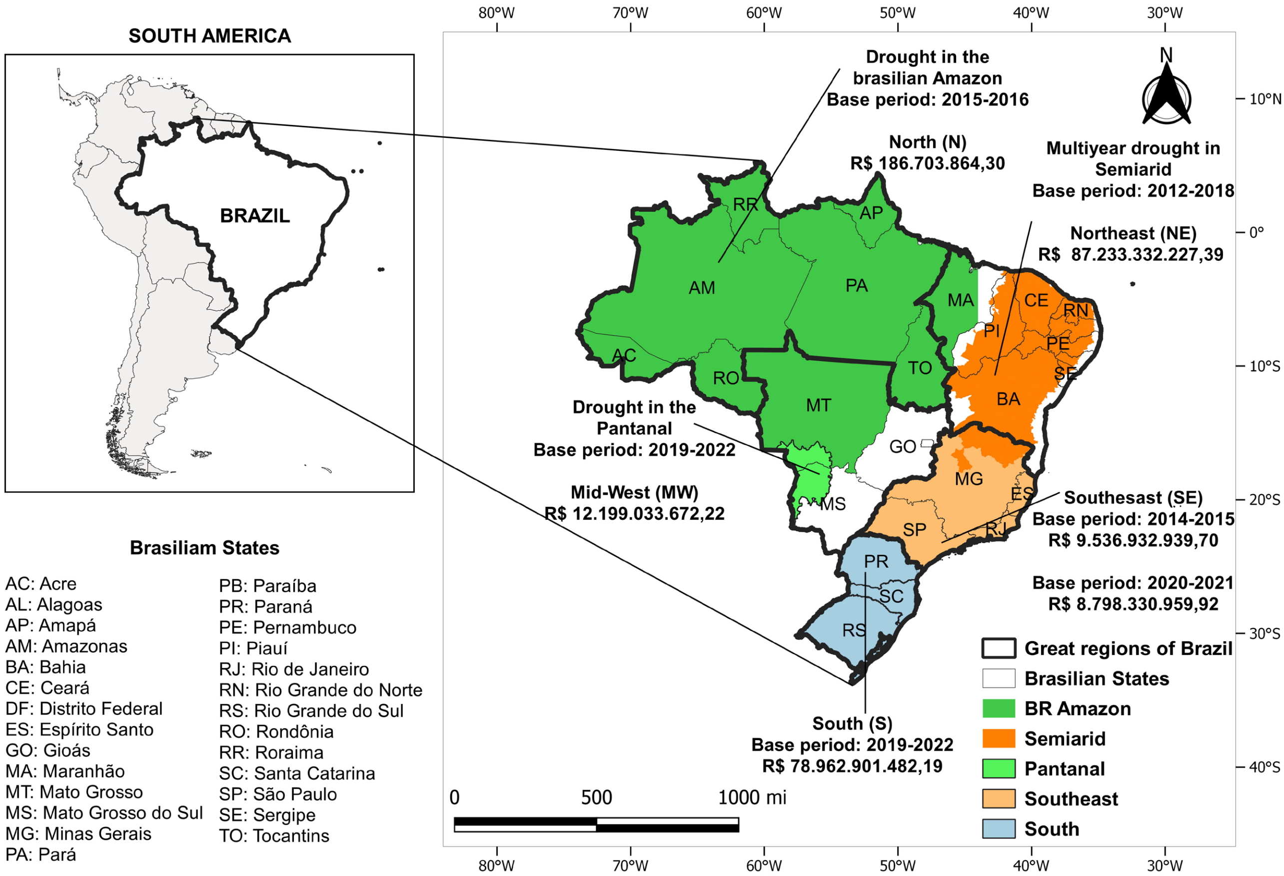

Figure 1. Economic losses consequence of recent drought in Brazil between 1991 and 2022. Source: Prepared from data up to 2021—CEPED/UFSC (2023); Data from 2022—S2iD Database (S2iD, 2023).

in the Semiarid region but also in the South region and municipalities in other regions of Brazil.

Unfortunately, in Brazil, the approach to drought historically is predominantly based on reactive crisis management (disaster management). Meaning, what to do when a new episode of drought occurs, and this paradigm needs to change, as Brazil needs to move towards a more proactive policy (disaster risk reduction) to face the impacts from the drought (CGEE, 2016). In Brazil, considering the action-defined measures in Decree No. 10,593 on 24 December 2020 (Brasil, 2020a), the elements of risk and disaster management, including the drought disaster, are presented in **Table 1**.

The Brazilian Drought Monitor (*Monitor de secas*), coordinated by the National Water and Basic Sanitation Agency (ANA, 2023) in partnership with several federal and state government institutions, represents one of the efforts for drought intensity in Brazil. This Monitor is a platform that provides a mapping of the occurrence, severity, and extent of different drought intensities, with indicators that reflect the short-term (last 3, 4, and 6 months) and long-term (latest 12, 18, and 24 months), and began in 2014 with a focus on the Northeast Region and expanded from 2018 onwards, with the inclusion of 20 states and the Federal District, therefore, with participation in all regions of the country, being

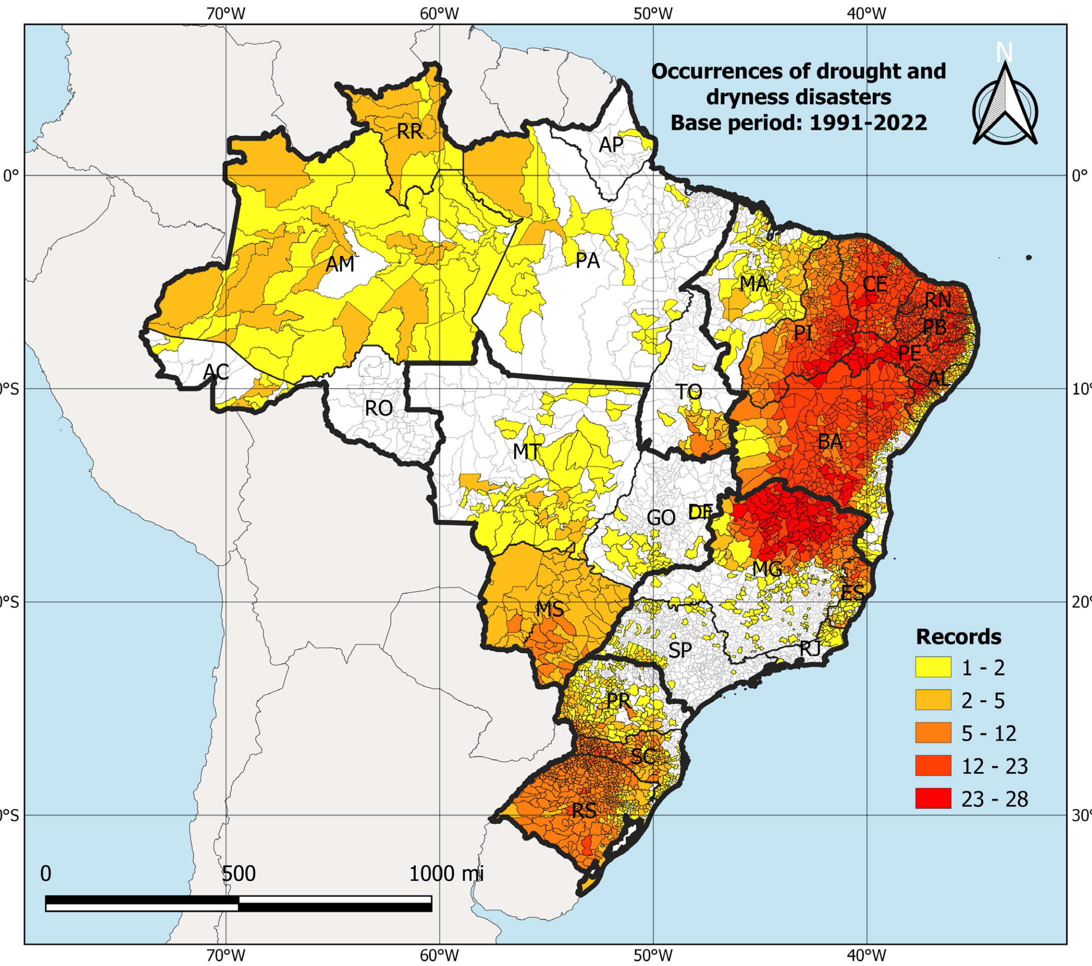

Figure 2. Municipalities with occurrences of drought disasters between 1991 to 2022. Source: Prepared from data up to 2021—CEPED/UFSC (2023); Data from 2022—S2iD Database (S2iD, 2023).

Table 1. Risk and disaster management cycle based on the actions defined by Decree No. 10,593, on 24 December 2020.

Cycle	Action	Stage	Stage definition
Risk management	Proactive	Mitigation	Measures designed to reduce, limit or avoid disaster risk.
		Prevention	Priority measures aimed at avoiding the conversion of risk into a disaster or the installation of vulnerabilities.
		Preparedness	Measures aimed at optimizing response actions and minimizing damage and loss resulting from the disaster.
Crisis management	Reactive	Response	Emergency measures carried out during or after the occurrence of the disaster, aimed at helping and assisting the affected population and restoring essential services.
		Recovery	Measures developed after the occurrence of the disaster aimed at restoring social normality include the reconstruction of damaged or destroyed infrastructure and the recovery of the environment and the economy.
		Restoration	Emergency measures aimed at restoring safety and habitability conditions and essential services to the population in the area affected by the disaster.

Source: Based on Brasil (2020a).

three in full: Northeast, South, and Southeast (ANA, 2023). The diagnostic map as a tool for the regular and periodic monitoring process, with monthly updates, of the Drought Monitor is based on three indexes: Standardized Precipitation Index—SPI, McKee et al. (1993), Standardized Precipitation Evapotranspiration Index—SPEI, Vicente-Serrano et al. (2010), and Standardized Runoff Index—SRI, Shukla & Wood (2008). The final product is mapping with the categorization: no relative drought, abnormally dry (S0), moderate drought (S1), severe drought (S2), extreme drought (S3), and exceptional drought (S4) (ANA, 2023). We have to remember that risk is a function of a hazard, vulnerability and exposure. The drought indices represent a quantification of a hazard (less rainfall and higher temperatures that induced drought).

The National Center for Monitoring and Early Warning of Natural Disasters (CEMADEN) continuously monitors droughts. It provides seasonal and sub-seasonal drought impacts for Brazil, with monthly updates. The diagnosis of drought conditions considers the synoptic climatology analysis and the monitoring by drought indexes, such as the Integrated Drought Index—IDI (Cunha et al., 2019), to analyze drought impacts over the past three and six months. The IDI combines precipitation, vegetation, and soil moisture information. From IDI, the drought can be categorized as usual, abnormally dry, moderate drought, severe drought, extreme drought, and exceptional drought (Cunha et al., 2019). CEMADEN also systematically monitors the hydrological drought throughout Brazil, periodically presenting the diagnoses and scenarios of the main reservoirs in the country, comprising, therefore, the analysis of the current situation of the main reservoirs, rain forecast with a focus on the main watersheds, weather forecast based on numerical modeling, as well as the projection of flow and storage for the coming months and also stands out in its drought risk monitoring with a focus on family farming (CEMADEN, 2023).

The drought monitoring performed by ANA and CEMADEN characterizes the carrying out of fundamentally important preparation actions as a similarity of participation in risk management (proactive management cycle). The people most vulnerable to drought the small farmers in the semiarid region of Brazil and those who live along the margins of Amazonian River channels (*ribeirinhos*). That population and their livelihoods, assets, resources, services are the most directly and/or indirectly exposed affected by a drought event.

In other countries, similar drought monitoring efforts are also in place. In Mexico, the National Commission of Water (CONAGUA- https://smn.conagua.gob.mx/es/climatologia/monitor-de-sequia/monitor-de-sequia-en-mexico) monitors drought intensity since 2014 for the whole Mexican territory. It is based on obtaining and interpreting different indices or drought indicators such as the SPI and various indicator of vegetation robustness derived from satellite (see Section 3). In Bolivia, the National Meteorological Service SENAMHI drought monitor (http://monitorsequias.senamhi.gob.bo/#/) was implemented in 2020. Both Mexican and Bolivian drought monitors follow the United States Drought USDM—Monitor (https://www.drought.gov/data-maps-tools/us-drought-monitor) using a five-category system. As in the ANA drought monitor of Brazil, categories show experts' assessments of conditions related to dryness and drought including observations of how much water is available in streams, lakes, and soils compared to usual for the same time of year.

3. Methodology

In Figure 3 we have the general flowchart of the methodology.

3.1. Drought Indices

Hydrological droughts are related to a more extended water deficit in the hydrological system (Van Loon, 2015). In this study, we used the Integrated Drought Index—IDI (Cunha et al., 2019) to characterize the drought and exposure of Brazil's most affected by prolonged droughts. For this purpose, we used the composite index on the 12-month time scale as a significant time scale in the context of hydrological drought (WMO; GWP, 2016), which we will now refer to as a long-term drought. The period considered was from January 1982 to December 2022. We also used SPI and other indices that are explained in following.

Integrated Drought Index (IDI)

The IDI consists of a combination of the Standardized Precipitation Index—SPI (McKee et al., 1993) with the Vegetation Health Index—VHI (Kogan, 1990, 1997, 2001), which in turn is based on the Normalized Difference Vegetation Index—NDVI (Tarpley et al., 1984; Kogan, 1995), and Land Surface Temperature—LST, and has been related to moisture availability and canopy resistance, indicating vegetation stress and soil water stress. In contrast, SPI is related to precipitation deficit (drought trigger). However, although precipitation is the main driver for drought development, negative precipitation anomalies do not

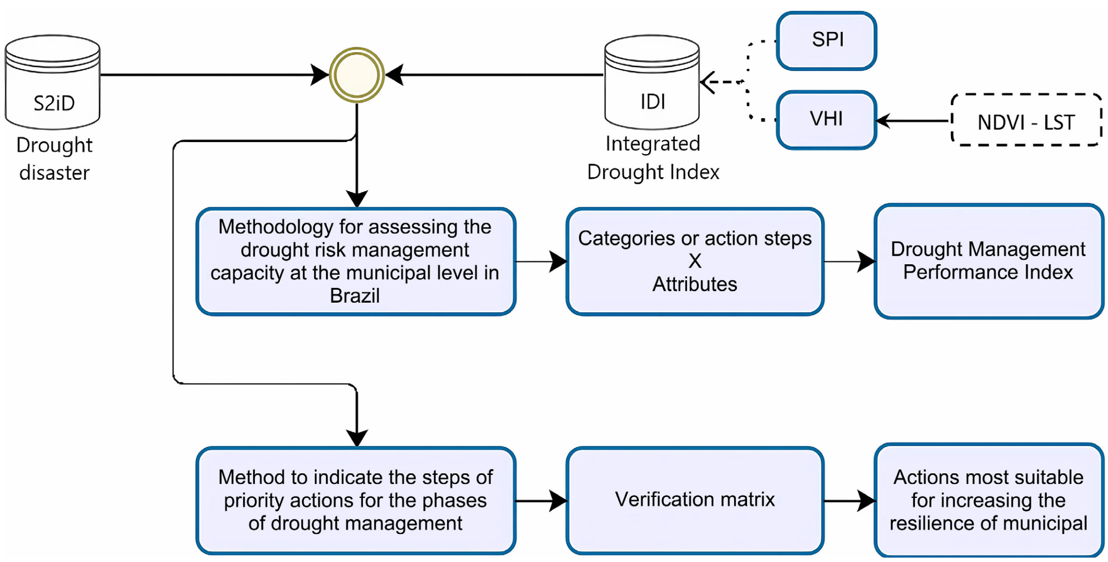

Figure 3. Flowchart of the methodology.

always correspond to the drought, as it does not consider the impact. In contrast, the VHI represents the surface response to water deficit from the vegetation. Therefore, these two indices provide complementary information for identifying areas affected by the drought (Cunha et al., 2019; Marengo et al., 2021), making the IDI a robust index to assess areas with drought impacts.

The first step in calculating the IDI is categorizing each drought index according to **Table 2** (ranging from 1 to 6). Then, the arithmetic mean between the variables organized from 1 to 6 results in the IDI varying from 1 to 6. In Summary, the SPI12 represents the already established long-term drought (rainfall deficit), while the VHI indicates areas where drought already impacts vegetation. Thus, the IDI enables the classification of the drought event based on these characteristics of the evolutionary process of the phenomenon.

1) Standardized Precipitation Index (SPI)

The SPI identifies and quantifies dry (negative values) and wet (positive values) events (McKee et al., 1993). The SPI is recommended as a standardized index applied in any region (WMO; GWP, 2016). The historical rainfall record is fitted to a probability distribution and then transformed into a normal distribution (McKee et al., 1993), calculated as:

$$\text{SPI} = \frac{X_{ij} - X_{im}}{\sigma} \quad (1)$$

where, X_{ij} corresponds to normalized precipitation. X_{im} corresponds to average precipitation. And, σ standard deviation.

According to Cunha et al. (2019), to compose the IDI, the SPI was calculated from the accumulated monthly precipitation made available by the Climate Hazards Group InfraRed Precipitation (Funk et al., 2015; Souza et al., 2020).

2) Vegetation Health Index (VHI)

The combination of visible (VIS) and infrared (IR) satellite imagery has been widely used to monitor plant changes and water stress (Marengo et al., 2021). Based on the Normalized Difference between Vegetation Index and Land Surface Temperature (NDVI-LST), the VHI has been related to moisture availability and canopy strength, indicating vegetation stress or soil water stress, and is defined as the mean of the Temperature Condition Index—TCI and the Vegetation

Table 2. Index values and drought intensity ratings according to various drought indices.

SPI	VHI	IDI	Drought Classification
>−0.5	>40	6	Normal
−0.5 a −0.8	30 a 40	5	Abnormally Dry
−0.8 a −1.3	20 a 30	4	Moderate Drought
−1.3 a −1.6	12 a 20	3	Severe Drought
−1.6 a −2.0	6 a 12	2	Extreme Drought
<−2.0	<6	1	Exceptional Drought

Source: Based on Cunha et al. (2019).

Condition Index—VCI (Kogan, 1990, 1995, 1997, 2001; Kogan et al., 2005), calculated as:

$$VHI_i = \alpha VCI_i + (1-\alpha) TCI_i \quad (2)$$

where, α e (1 − α) are coefficients to determine the contribution of each index, which is usually assigned a value of 0.5, assuming equal contribution of both variables to the VHI. VCI is obtained from the ratio of land surface reflectivity in visible and near-infrared wavelengths, and the NDVI is used to assess the coverage of healthy vegetation, calculated as:

$$VCI = 100 * \frac{NDVI - NDVI_{min}}{NDVI_{max} - NDVI_{min}} \quad (3)$$

being that, NDVI is the smoothed weekly NDVI, and $NDVI_{max}$ and $NDVI_{min}$ are the multiyear minimum and maximum observed NDVI in the same week.

TCI is used to identify vegetation stress caused by high temperature and excessive wetness. It is calculated from thermal emissions measured at infrared wavelengths, according to Equation (3):

$$TCI = 100 * \frac{BT_{max} - BT}{BT_{max} - BT_{min}} \quad (4)$$

where BT is the smoothed brightness temperature for the week and BT_{max} and BT_{min} are the multiyear maximum and minimum brightness temperature observed for that week. The process involves physical and physiological suppression of evaporation and transpiration when less water is available (Andujar et al., 2017).

These indices are obtained from the NOAA STAR Global Vegetation Health Products website (NOAA STAR, 2023). VHI, VCI, and TCI are considered Blended Vegetation Health Products (VHP) derived from remote sensing commonly used for drought assessment (Marengo et al., 2021).

3.2. Data from Records of Occurrences Affected by Drought and Variation in Harvests

In this study, to verify the evolution of disaster records with a focus on drought, we used data from disaster occurrences recorded by the Civil Defenses of Brazilian municipalities and states, and these were obtained from 1982 to 1990 from the National Center for Risk and Disasters Management (CENAD), from 1991 to 2021 from the Digital Atlas of Disasters in Brazil (CEPED/UFSC, 2023), and from 2022 of the Integrated Disaster Information System—S2iD (S2iD, 2023). Data on affected people from 2000 to 2021 was also obtained from the Digital Atlas of Disasters in Brazil and from 2022 from S2iD. For application in areas of other countries, drought disaster data can be found through national civil defense or the area of interest.

3.3. Drought Risk Management Capacity Index

Based on Decree No. 10,593, on 24 December 2020 (Brasil, 2020a), the government established six categories of actions: mitigation, prevention, preparedness, response, recovery, restoration also described on Wilhite (2000) to analyze drought risk management capabilities. These measures can be applied in institutions that carry out their proactive and reactive actions in a municipality in a drought situation. A weighted checklist was developed to score each of the six categories of drought management actions. For the negative attributes, the following were established: inexistence of competence to act in action measures (No 1), and act but not yet perform (No 2), which is when the action in the category is of competence to work, but there is the total inexistence of performance at the time of verification. For the positive attributes, it was established: acts and executes in part (Yes 1), which is when there is the execution of part of the action measure, however, efforts were made to implement entirely in the foreseen future, and it acts and executes completely (Yes 2) when there is complete execution of the action measure in the category in question. **Table 3** presents the characterization of the attributes for the classes of measures of drought management.

The weighting of the lists was done by operating an arithmetic progression (AP) of six terms (the same number of risk and disaster management action categories). Therefore, it was possible to generate weighting for the attributes based on the principle of attractiveness between the options (a > b > c ... > n) and generation of scores (scale from 0 to 100) to infer the degree of institutional performance of drought disaster management, by ordering and defining performance levels for each established criterion. However, we have to assume levels of uncertainty in this list. This methodology for weighting the lists is similar to the software MACBETH (Measuring Attractiveness by a Category Based Evaluation Technique, Bana e Costa et al. (2003, 2017). The highest weights were associated with risk management actions. For Wilhite (2000), a greater emphasis on forecasting, monitoring, mitigation, and preparation, which are proactive

Table 3. Verification attributes for drought risk management analysis.

Categories or action steps	Examples of measures based on Decree No. 10,593 on 24 December 2020	Attributes			
		No 1	No 2	Yes 1	Yes 2
Preparedness	Preparedness, monitoring, and alert measures	Does not act (Lack of competence to act)	There is the competence to act, but there is a total lack of an action at the time of verification	Acts and executes in part (Indicates that there is some execution in the action category, however, efforts have been made to complete execution in the foreseeable future)	It works and runs completely (Indicates that there is full execution of the action in the category in question)
Prevention	Risk reduction measures				
Mitigation	Measures to avoid the risk				
Response	Relief measures and humanitarian assistance				
Recovery	Reconstruction, environmental and economic recovery measures				
Restoration	Emergency measures to restore security, habitability, and essential services				

Source: Prepared by the authors.

actions, can reduce the frequency and severity of disasters, and according to the Centro de Gestão a Estudos Estratégicos CGEE (2016). The highest score was associated with preparation actions involving monitoring and alert measures since, according to Alvalá et al. (2019b), alert systems have been proposed to reduce the vulnerability of populations living in risk areas.

For the attributes of the checklists, positive, proportional, and attractive differences were established following the ordering of the pre-established options: Yes 2 > Yes 1 > No 2 (Yes 2 is more attractive than Yes 1, which is more attractive than No 2).

Attribute No 1 is neutral when there is no competence to act with action measures. Still, it should be scored with 100 to not penalize the category of action in question and not to reflect negatively on the degree of global drought management performance of an institution involved in drought management. Furthermore, as institutions have different actions or competencies in only some of the activities of the drought risk management cycles, the Drought Management Performance Index should not be used for intercomparison with other institutions but their monitoring and individualized decisions. For this ordering and considering positive (proportional) differences in attractiveness between the attributes, we first have the hierarchically weighted score of the performance index of the details (**Table 4**).

The weighting among the six categories of actions of drought risk management is done similarly. For the preliminary ordering of the six categories of actions to obtain the weights generated by AP, the differences in attractiveness between the categories of actions are considered positive (proportional). Then, considering the AP of six terms, the sum of which results in one, the ratio (r) was obtained as follows:

$$r + 2r + 3r + 4r + 5r + 6r = 1 \quad (5)$$

which results in:

$$r = 1/21 \quad (6)$$

where the solution is:

$$r = 0.0476 \quad (7)$$

therefore, the six terms were obtained as follows:

$$AP = (a = r, b = a + r, c = b + r, d = c + r, e = d + r, f = e + r) \quad (8)$$

Table 4. Verification attributes for drought risk management analysis.

Attribute	Score
Yes 2	100
Yes 1	50
No 2	0
No 1	100

Source: Prepared by the authors.

Thus, the hierarchically weighted score of the performance index of the categories is generated. Table 5 presents the weighted ordering of the criteria and respective weights obtained through the AP.

Completing and tabulating the lists for a final score is obtained based on the number of categories identified as present but adjusted for their weights. Thus, it is possible not only to measure the performance in the classes or categories actions of drought management but also to establish the measurement of the institutional performance index based on the defined criteria. The following expression presents the general formula for calculating the drought management performance index:

$$\text{Drought Management Performance Index} = \Sigma \left(Is \cdot Pw \right) \quad (9)$$

"*Is*" is the individual score received for each attribute, with values of 100, 50, or 0. "*Pw*" is the weight value corresponding to the category of drought management actions. Then, the Drought Management Performance Index is calculated by summing the results of the weighted score of each attribute corresponding to the types of drought management actions. Therefore, the measurement of the indices, within a scale from 0 to 100 for the categories, is later crossed in a matrix to infer the degree of drought management performance.

3.4. Priority Action Pointer for Drought Risk Management

Considering the six actions contained in Decree No. 10,593 on 24 December 2020 (Preparation, Prevention, Mitigation, Response, Recovery, and Restoration) (Brasil, 2020a), Table 6 proposes the investment priority degrees by actions of stages of risk management of drought to point out the classes of actions or stages most suitable for increasing the resilience of municipalities. Once the priority levels of risk management actions are distributed, the sum of points by municipalities is obtained, mapped for better visualization of the results, and/or tabulated in management reports. The lower the sum of the degrees of priority, the higher the priority of action, with a greater indication for the investment of public resources to minimize impacts.

Table 5. List of share categories and respective weights.

Categories (AP terms)	Progressive weights
(a) Preparedness	0.2858
(b) Prevention	0.2381
(c) Mitigation	0.1905
(d) Response	0.1428
(e) Recovery	0.0952
(f) Restoration	0.0476
Σ	1

Source: Prepared by the authors.

Table 6. Tabulation of municipal checklists for priority drought management actions.

Condition	Disaster				Management cycle						Degree	
					Risk management			Crisis management				
					Classes de ações ou etapas							
	Drought?	Human damage?	Deaths?	Economic or other damages?	Mitigation	Prevention	Preparation	Response	Recovery	Restoration	Risk and disaster management (Σ)	Priority
1	Yes	Yes	Yes	-	1	1	1	1	1	1	6	1
2	Yes	Yes	No	-	1	1	1	1	2	1	7	2
3	Yes	No	No	Yes	1	1	1	1	2	2	8	3
4	No	No	No	No	2	2	1	3	3	3	14	4

Source: Prepared by the authors.

Of the six categories of actions, "preparedness" is the best identified, as it is a drought preparedness, monitoring, and alert measures, as the disaster varies from year to year, and the management of drought should not be surprised. For an eventual unforeseen drought, preparation is based on proactive actions. Thus, top priority (1) is assigned to the preparation action in all municipalities. According to Alvalá et al. (2019b), alert systems have been proposed to reduce the vulnerability of populations living in risk areas.

In mitigation, prevention, preparedness, and response actions, the municipalities impacted by the drought were given top priority (1), as they suffered from some human damage. It also promotes a break from the paradigm of a historically more reactive approach to crises in Brazil to move towards a more proactive policy to face the impacts of drought (CGEE, 2016), also based on strengthening the three pillars of drought preparedness: monitoring and early warning; vulnerability and impact assessment; and preparedness, mitigation, and response planning and measures (CGEE, 2016; UNDRR, 2019, 2021).

The focus of this approach is the human damage resulting from drought. So, municipalities with priority 1 (very high) for resources are those impacted by drought with human damage, including deaths, with or without material, environmental, economic, and other damages. For municipalities that fit this priority, priority investment is indicated in all disaster risk management actions.

Municipalities with priority 2 (high) are those with impacts caused by drought, human damage, no record of deaths associated with the disaster, and with or without material, environmental, economic, and other damages. For municipalities with high priority, the most indicated actions, in the first place, are response, restoration, mitigation, prevention, and preparation. The recovery action is in the background for municipalities with priority 2.

The municipalities with priority 3 (medium) are those that suffer economic or other damage associated with drought but without human damage and without deaths associated with the disaster. For municipalities that fall within the medium priority, response, mitigation, prevention, and preparedness actions are the most suitable for resources in the foreground, and recovery and restoration actions are in the background.

Municipalities with priority 4 (monitoring) are the municipalities that are not under the drought disaster but must always remain the priority of the preparedness action since permanent monitoring and alert is essential for all municipalities. Therefore, with the application of this methodology, the verification matrix was tabulated in Table 6 to point out the most indicated actions to increase the resilience of the municipalities.

4. Results and Discussion

Based on Equation (5), Tables 7-9 present in a practical way how the indexes of

Table 7. Tabulation of drought risk management checklists from institution "A" to municipality "B" (Base period: 2010).

Categories	Attributes				Scoring attributes (Ap)	Progressive weights (Pw)	Performance index (PI) $PI = Ap \cdot Pw$
	No 1	No 2	Yes 1	Yes 2			
	-	0	50	100			
Preparedness		●			0	0.2858	0
Prevention					0	0.2381	0
Mitigation		●			0	0.1905	0
Response			●		50	0.1428	7.14
Recovery		●			0	0.0952	0
Restoration		●			0	0.0476	0
Drought Management Performance Index $\Sigma(Ap \cdot Pw)$							7.14

Source: Prepared by the authors.

Table 8. Tabulation of drought risk management checklists from institution "A" to municipality "B" (Base period: 2015).

Categories	Attributes				Scoring attributes (Ap)	Progressive weights (Pw)	Performance index (PI) $PI = Ap \cdot Pw$
	No 1	No 2	Yes 1	Yes 2			
	-	0	50	100			
Preparedness			●		50	0.2858	14.29
Prevention			●		50	0.2381	11.91
Mitigation		●			0	0.1905	0
Response			●		50	0.1428	7.14
Recovery			●		50	0.0952	4.76
Restoration			●		50	0.0476	2.38
Drought Management Performance Index $\Sigma(Ap \cdot Pw)$							40.48

Source: Prepared by the authors.

Table 9. Tabulation of drought risk management checklists from institution "A" to municipality "B" (Base period: 2020).

Categories	Attributes				Scoring attributes (Ap)	Progressive weights (Pw)	Performance index (PI) $PI = Ap \cdot Pw$
	No 1	No 2	Yes 1	Yes 2			
	-	0	50	100			
Preparedness				●	100	0.2858	28.58
Prevention			●		50	0.2381	11.91
Mitigation		●			0	0.1905	0.00
Response				●	100	0.1428	14.28
Recovery				●	100	0.0952	9.52
Restoration				●	100	0.0476	4.76
Drought Management Performance Index $\Sigma(Ap \cdot Pw)$							69.05

Source: Prepared by the authors.

each category and the drought management performance index are obtained with application to a hypothetical institution "A" for the periods 2010, 2015, and 2020, also shown in Figure 4.

4.1. Characterization of Drought Intensity and Associated Impacts

The Integrated Drought Index IDI was used to characterize the exposure and areas affected by drought, which combines the lack of precipitation and the surface response to water stress (Cunha et al., 2019). Figure 5 shows the IDI calculated for 1982 to 2022 in Brazil (Figure S1 IDI-12 maps in the Supplementary Materials) and the records of drought occurrences during the same period.

Prolonged and more intense droughts have increased in recent decades in all major Brazilian regions (N, NW, MW, SE, and S), with an increase in the number of occurrences of impacts due to drought (socioeconomic and environmental impacts) recorded by the Municipal and State Civil Defenses from all Brazilian regions. Much of the country (Figure 5(a)) faced a high frequency of drought after 2012, mainly due to the multiyear drought in the Brazilian Semiarid region and the south of the country, with the years 2015 and 2016 being the most critical, where the extent of drought in the Brazilian territory was 97.2% and 93.3% respectively, with a high in the records of drought. Known for its highest rainfall rates among Brazilian regions (Cunha et al., 2019), the North Region (Figure 5(b)) showed an increase in the frequency of severe drought between 2014 and 2015, reflecting the rise in occurrence records.

In the Northeast Region (Figure 5(c)), the highlight was the high frequency of drought between 2012 and 2018, with a sharp decline in 2020, with the years 2012 and 2015 being the most extreme in terms of drought categories, reflected in the increase of records of damages and survey carried out with a drought disaster. In 2015, the drought covered 99.9% of the region, with 69.26% of the area experiencing severe or extreme drought and 8.04% experiencing exceptional

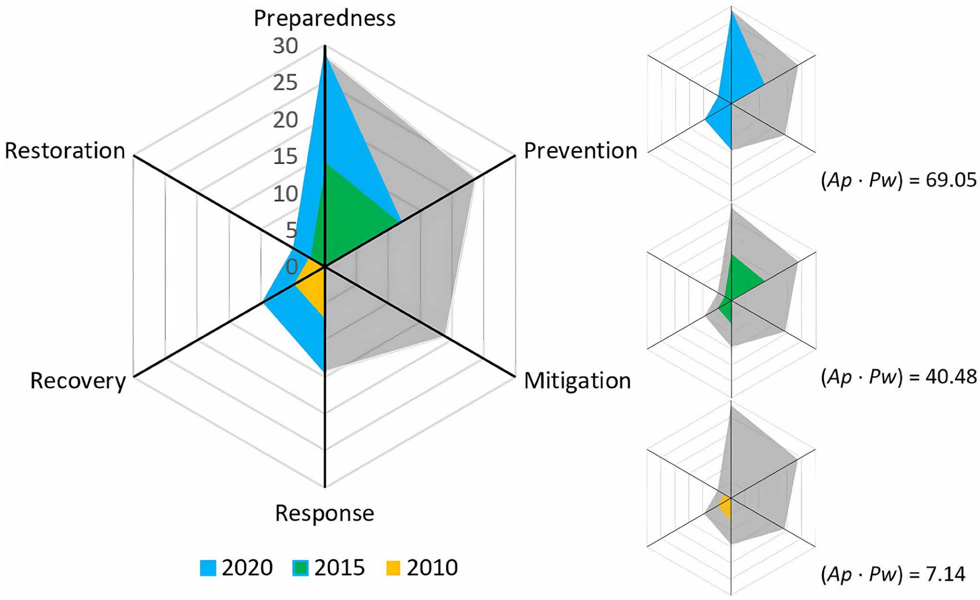

Figure 4. Drought risk management performance index of institution "A" to municipality "B" (Base periods: 2010, 2015, and 2020). The gray area indicates the maximum score that can be obtained in each category of actions. Source: Prepared by the authors.

drought. After the increase in the number of occurrences recorded during the multi-annual drought (2012 to 2018), this number dropped again in 2020 when 13.7% of the region was in the normal condition class, but with a new upward trend in these occurrences' records in 2021.

The Mid-West Region (**Figure 5(d)**) showed an increase in the frequency of drought between 2019 and 2022, and in 2020 the drought was severe in 19.1% of the region, extreme in 18.5%, and exceptional in 13.9. The number of records of drought occurrences peaked in 2020. The Pantanal region suffered severe drought in 2019 (Marengo et al., 2021).

2014 and 2015 in the Southeast Region (**Figure 5(e)**) had a high drought frequency. In 2014, a severe drought occurred in 56.7% of the region and an extreme drought in 6.8%. In 2014, a severe drought occurred in 34.9% of the region, extreme in 20%, and 5% in exceptional drought, culminating in the water crisis that mainly affected the city of São Paulo and the metropolitan region and an increase in the number of drought occurrences records. The Southern Region (**Figure 5(f)**) peaked at 99.9% of the area in a drought situation in 2020. Severe drought occurred in 30.8% of the region, extreme drought in 38%, and 16.9% in exceptional drought.

The analysis also corroborates Cuartas et al. (2022), who highlighted that hydrological drought events have been more frequent and intense in recent decades in Brazil, particularly in the last decade (2010-2021); droughts have also occurred concomitantly in several regions of the country, with noticeable impacts on different socioeconomic sectors, which are still being experienced.

Until 2019, droughts were responsible for the largest number of people affected (**Figure 6**). From 2020 onwards, the totals affected by other disasters were

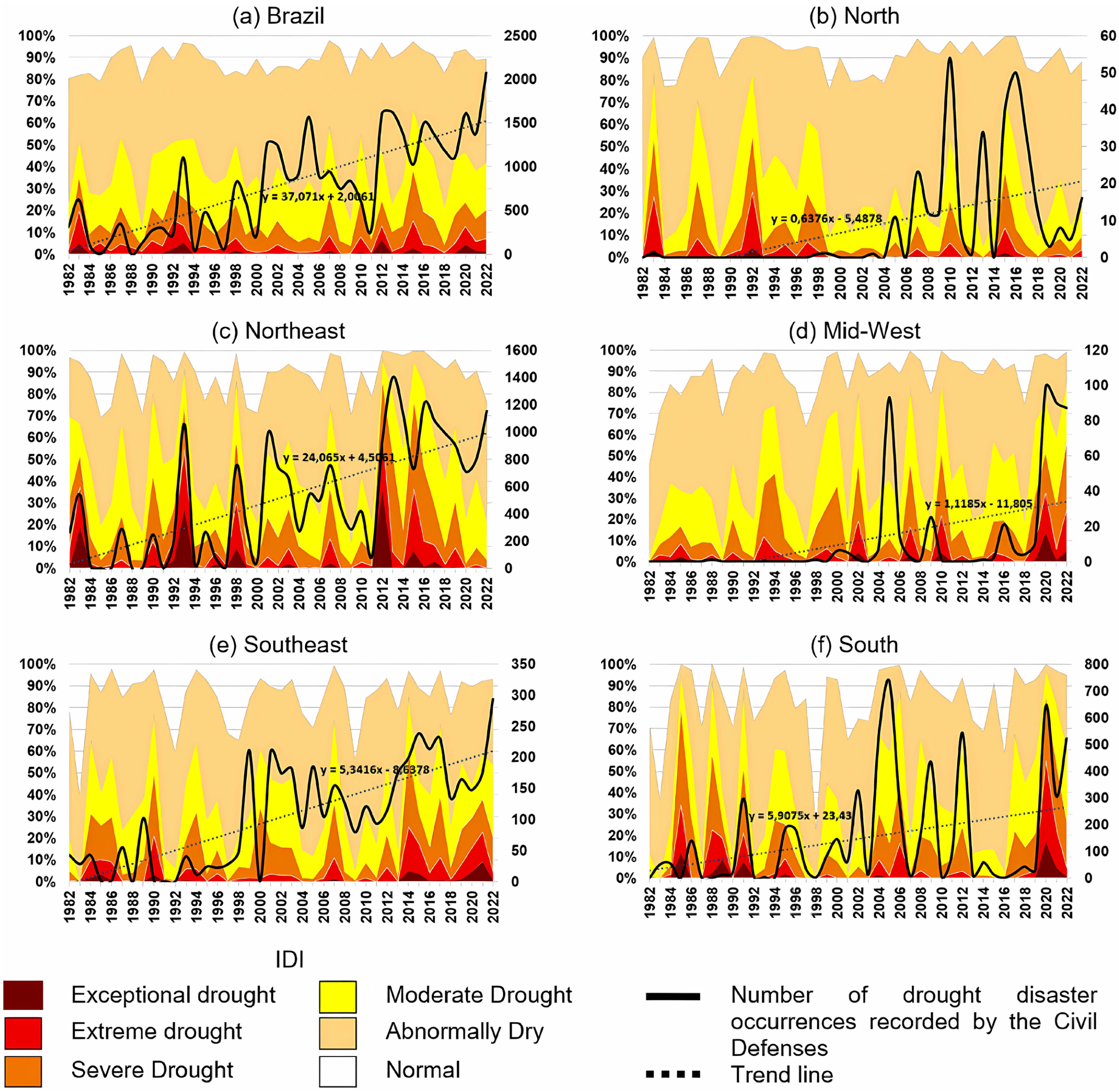

Figure 5. Annual distribution of IDI-12 frequency and records of drought occurrences in Brazil and Regions from 1982 to 2021: (a) Brazil; (b) North; (c) Northeast; (d) Mid-West; (e) Southeast and (f) South. Horizontal axis: years from 1982 to 2021; Left vertical axis: area or region in IDI-12 classes (%); right vertical axis: number of drought disaster occurrences recorded by the Civil Defenses (black line). Prepared from data: CEMADEN; CENAD; CEPED/UFSC; S2iD.

higher, inflated by the number of people affected by COVID-19 infections, which consequent increase in the total number of people affected by all disasters. The Northeast Region (Figure 6(c)) has the highest number of people affected by drought. Furthermore, the South Region (Figure 6(f)) had this number high as of 2020.

4.2. Drought Risk Management Capacity Index—Case of the SEDEC Performance in the Drought Disaster in São Francisco de Assis do Piauí City (State: PI), Base Period 2022

In this case study, the attributes were verified through exploratory research, with

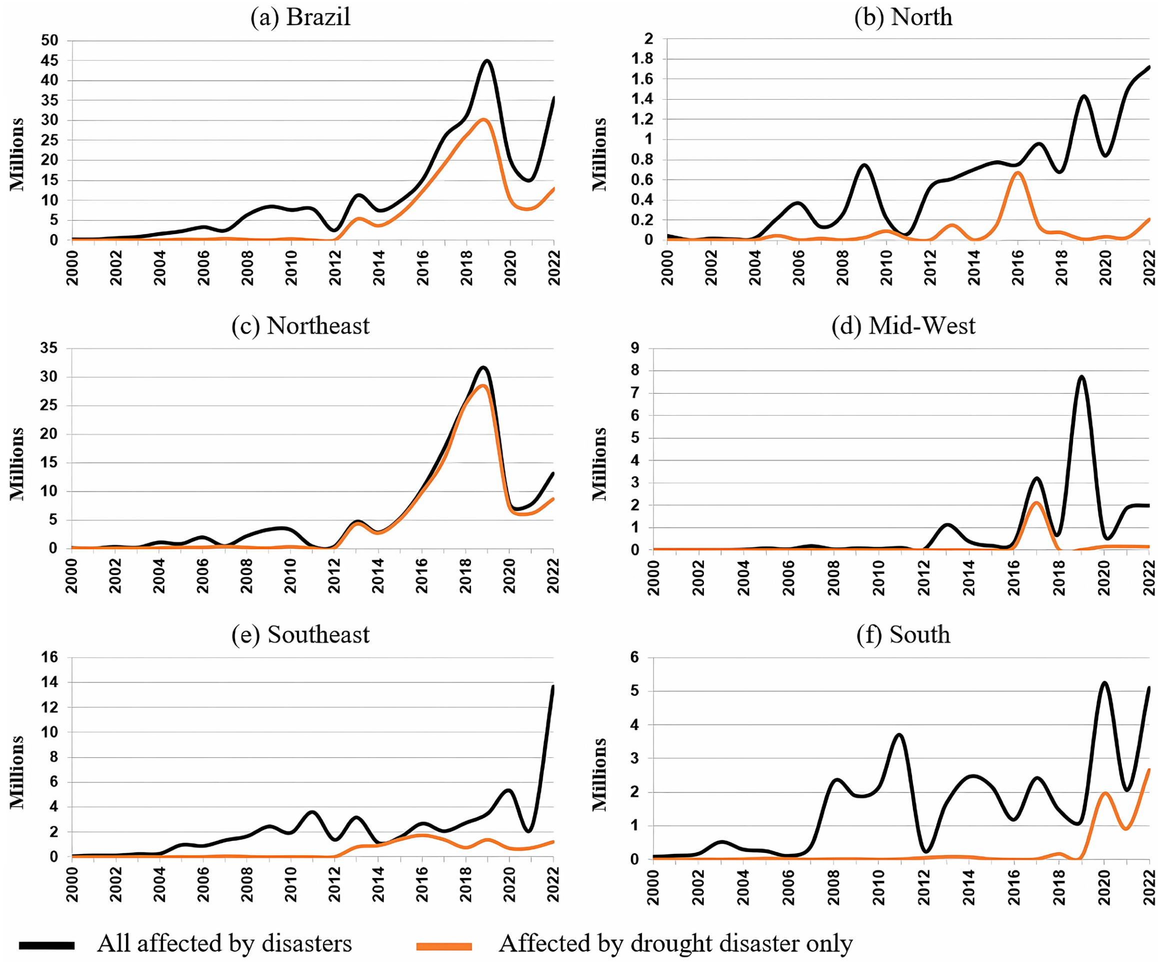

Figure 6. Annual frequency distribution of people affected by drought in Brazil and Regions, from 2000 to 2021: (a) Brazil; (b) North; (c) Northeast; (d) Mid-West; (e) Southeast and (f) South. Horizontal axis: years 2000 to 2022; Vertical axis: affected (millions of people) by drought (orange line), and affected by all disasters (black line). Sources of data: CEPED/UFSC (2023); S2iD (2023).

searches in the S2iD (S2iD, 2023) and public information accessible on official government websites. According to data in S2iD (S2iD 2023), the municipality of São Francisco de Assis do Piauí, in Piauí state, registered the drought disaster on 18 May 2022, with details in Disaster Information Form—FIDE of the protocol PI-F-2209658-14110-20220518, and again on 6 December 2022, with a description informed in the FIDE of the protocol PI-F-2209658-14110-20221206.

For 2022, no action was identified in the mitigation stage, part of the risk management cycle. There also needed to be action in the recovery and restoration stages, part of the disaster management cycle. These can be considered SEDEC's activities since it is up to SEDEC to "establish strategies and guidelines for the actions of Civil Defense and Protection, risk, and disaster management." These were not verified regarding the execution in the mitigation, recovery, and restoration stages regarding the drought disaster in São Francisco de Assis do Piauí city.

The municipality was served by Operation Water Truck-*Carro-Pipa* (http://sedec.5cta.eb.mil.br/, accessed on 1 June 2023) as a measure of humanitarian assistance actions and characterized assistance in the response class within its scope of activity. The Carro-Pipa Operation is technical cooperation funded by the Ministry of Regional Development/SEDEC and Defense. Promoting joint articulations with bodies that are part of the National Civil Defense and Protection System (SINPDEC) also characterizes preparation actions.

Given the verifications in the categories of actions of preparation, prevention, mitigation (risk management cycle), response, recovery, and restoration (disaster or crisis management cycle), it was possible to mark in the attribute column of **Table 10** and score according to the methodology in Section 2.3 and **Table 3**, to obtain the performance index in each category of shares. Finally, the case's Drought Management Performance Index (global score) value was 66.67, also represented in **Figure 7**.

4.3. Categories of Priority Actions for Drought Risk Management —A Strategic Methodological Proposal for Municipalities

The procedures and criteria for analyzing requests for federal recognition are established in Normative Instruction No. 36, on 4 December 2020 (Brasil, 2020b), and Ordinance No. 260, on 2 February 2022 (Brasil, 2022) and are based on the verification of the documentation sent through the S2iD (S2iD, 2023), which corresponds to the correct completion of the FIDE, Municipal or State Declaration of Emergency Action, photographic report, opinion of the civil defense agency, a decree declaring an emergency or state of public calamity, application for federal recognition, documents that clarify data and information presented in FIDE, in the Municipal Declaration of Emergency Action and State Decree of Emergency Action. However, no more indicated or priority disaster management actions exist in each municipality.

Table 10. Tabulation of the drought risk management checklists of the National Secretariat for Civil Defense and Protection - SEDEC, to the São Francisco de Assis do Piauí city (Base period: 2022).

Categories	Attributes				Scoring attributes (Ap)	Progressive weights (Pw)	Performance index (PI) $PI = Ap \cdot Pw$
	No 1	No 2	Yes 1	Yes 2			
	-	0	50	100			
Preparedness				●	100	0.2858	25.58
Prevention				●	100	0.2381	23.81
Mitigation		●			0	0.1905	0
Response				●	100	0.1428	14.28
Recovery		●			0	0.0952	0
Restoration		●			0	0.0476	0
Drought Management Performance Index $\Sigma(Ap \cdot Pw)$							66.67

Source: Prepared by the authors.

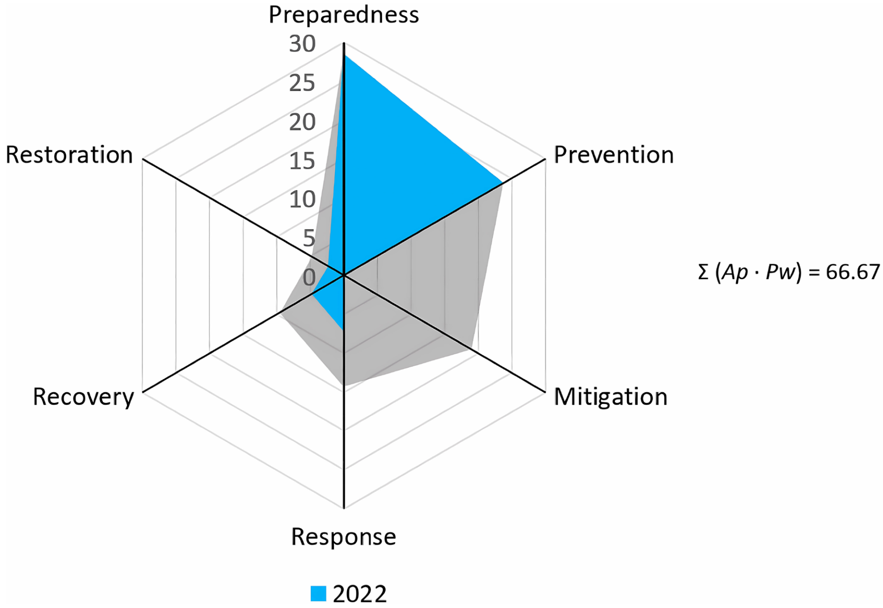

Figure 7. Drought risk management performance index of the National Secretariat for Civil Defense and Protection—SEDEC, in the municipality of São Francisco de Assis do Piauí city (Base Period: 2022 São Francisco de Assis do Piauí). The gray area indicates the maximum score that can be obtained in each category of actions. Source: Prepared by the authors.

Thus, the application of the proposed methodology made it possible to rank the municipalities with the highest investment priority, both in the actions of the risk management cycle and in the actions of the disaster management cycle, focusing mainly on proactive efforts to minimize the impacts of drought, reduce the vulnerability of those affected and increase the resilience of municipalities that suffer from the disaster.

Using the reported damage data from the drought disaster from 2021, available in S2iD, the methodology in Section 2.4, and the verification matrix in **Table 9**, it was possible to categorize the priority municipalities for drought risk management actions and present these georeferenced municipalities (**Figure 8**).

Table 11 presents the total number of municipalities by region and their priorities in managing drought disaster actions.

As in the period considered (2022), no deaths were directly associated with the drought disaster, and no municipality received the categorization of priority one—very high. However, 1667 municipalities suffered human damage (except deaths), with or without material, environmental and economic damages. Thus, these municipalities received the categorization of priority 2—high, a situation in which the highest priority is indicated in response and restoration actions and all proactive measures, with recovery actions with priority two.

The Northeast Region had 519 municipalities with priority two for disaster management actions. 460 municipalities were categorized as a high priority in the South Region. The Southeast Region had 145 municipalities with high priority. The Mid-West Region had 33 municipalities with priority two. Furthermore,

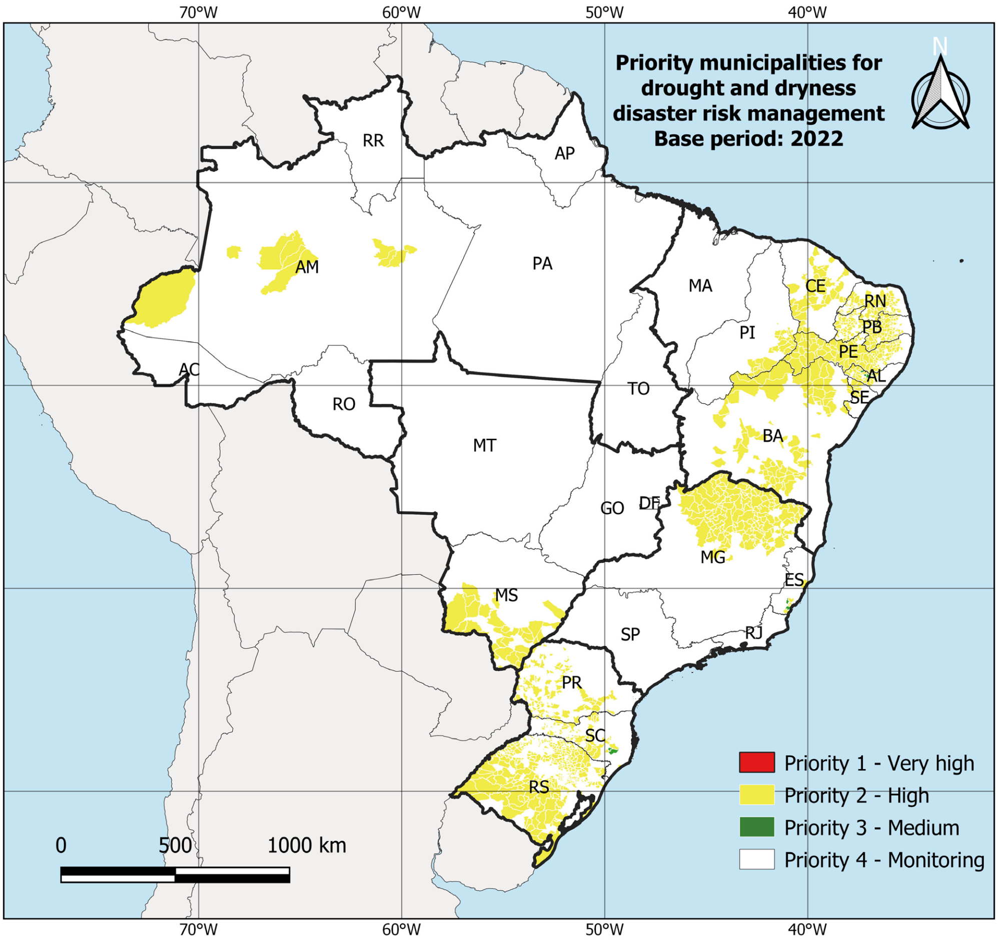

Figure 8. Priority municipalities to the drought risk management actions, base period: 2021. Source: Prepared by the authors.

Table 11. Total of priority municipalities, by regions, for the stages of drought management actions. Base period: 2021.

Region or area	Priorities			
	1 Very High	2 High	3 Medium	4 Monitoring
North	0	10	0	440
Northeast	0	519	4	1271
Mid-West	0	33	0	434
Southeast	0	145	2	1521
South	0	460	3	730
Brazil	0	1667	9	3896

Source: Prepared by the authors.

10 municipalities in the North Region had high-priority categorization. Of the 9 municipalities that did not have human damages but had economic or other damages associated with drought, categorized with priority 3—medium, 4 were

in this condition in the Northeast Region, the South Region had 3, and the Southeast Region had 2. These municipalities are given the highest priority in response actions, and all proactive measures and recovery and restoration actions were given priority two.

It is essential that the municipalities that did not suffer the drought disaster, 3896 municipalities, categorized with priority 4 or monitoring, always remain with the preparation actions in priority 1, since, currently, the alert systems, which are among the preparation of the measure, have been proposed as a strategy to reduce the vulnerability of populations living in risk areas (Alvalá et al., 2019b). These municipalities were given priority two for the other actions of the disaster management cycle and priority three for measures of activities in the most reactive process.

It is also important to highlight that, to produce data through the proposed methodology; it is possible to operate it automatically, to obtain the data in tables and georeferenced for use in a more practical, objective, and updated way. Furthermore, in this sense, **Figure 9** presents an example of a block diagram for the proposed methodology's operational implementation, whose data indicates priority municipalities in managing risk of drought.

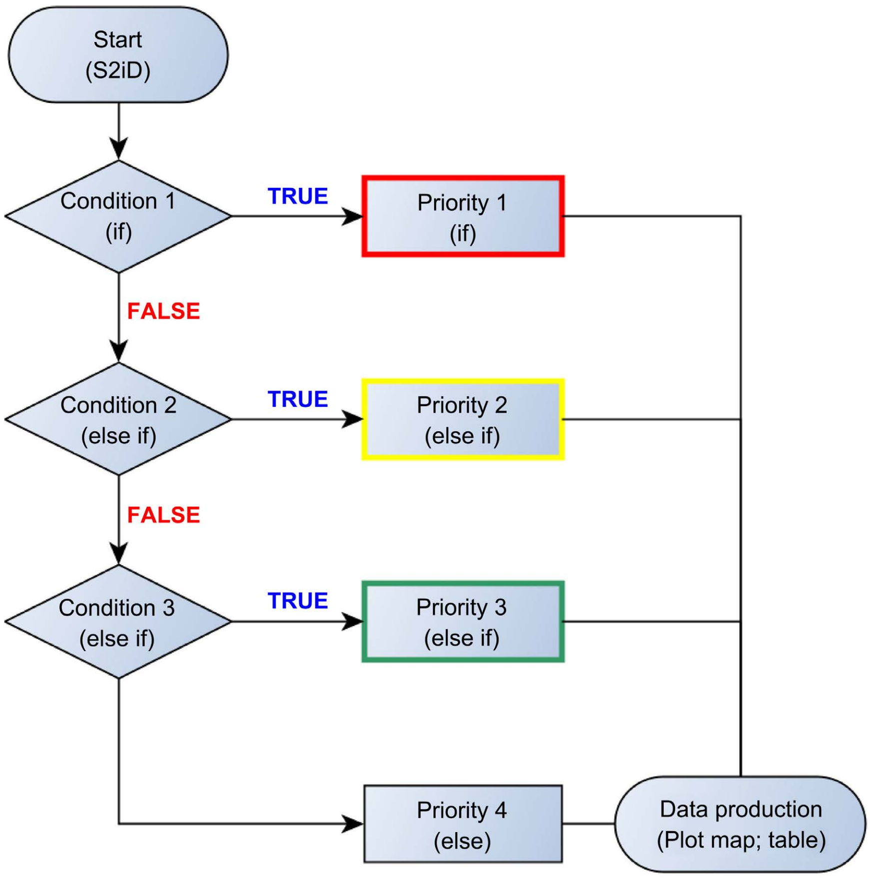

Figure 9. Block diagram representation for automating the proposed methodology for indicating priority municipalities in the drought management actions. Source: Prepared by the authors.

Thus, the production of data can be made available with each update of the input database, processed based on the verification matrix (**Table 9**), where the data produced correspond to the indication of priority municipalities in the management of risk and drought disaster, obtaining the georeferenced information (e.g., **Figure 9**), and in management reports in the format of tables, which can be processed to aid investment decision and monitoring focusing of the risk and disaster management, as well information for the researchers and other interested parties.

5. Conclusions and Recommendations

Long-term drought has occurred in all regions of Brazil, including infrequent areas, and has been more intense in recent years. This article proposed a methodology for assessing drought risk management, which can be applied for drought management at the municipal level. This is directed to develop priority actions at the level of cities, and according to the Brazilian Federal Government. The idea is to provide support decision-making for the optimization of the application of resources, according to each class of priority actions, and to increase the resilience of municipalities as part of drought management. Our work's application is directed to measure the capacity of the stages of proactive and reactive actions of the institutions involved in drought management. Thus, the application of the proposed method to indicate the classes of priority actions for the municipalities, can significantly contribute to the decision aid for efforts more focused on preparation and better coexistence in the face of drought disasters throughout Brazil, it also offers scientific basis for the improvement of public policy actions related to drought in the country. The novel approach of this work is the development of the Drought Risk Management Capacity Index methodology, that can be applied for drought management at the municipal level.

The proposed methodologies' success depends on the input data's quality. So, the idea is that in the application of the Drought Risk Management Capacity Index methodology, the verification of the attributes is checked with the manager of the institution involved in the management of drought in each municipality. Regarding the methodology Categories of Priority Actions for Drought Management, with the data collection from the S2iD, some problems of consistency of input data appeared. Among them, death data associated with drought may not represent the reality, and such inconsistency is decisive for the classification of the municipality in the very high priority, given that the methodology focuses on human damage. It is recommended that the information of deaths resulting directly and indirectly associated to drought be attested and recorded in the national system called the Department of Informatics of the Unified Health System (DATASUS). Later om and these could be included in the S2iD as consistent data on drought-associated deaths

Another point that deserves to be highlighted is that the bibliographic and documentary review showed that emergency actions or programs to cope with drought impacts are mainly aimed at the Brazilian Semiarid Region. However, in this study, it was possible to recognize that all Brazilian regions have suffered from the impacts associated with drought disasters. Therefore, the challenge of launching a National Policy for Coexistence with Drought is already evident. This Policy should avoid falling into political projects of government programs, which may end with a change in government, and this policy should be constantly monitored and opportunely re-evaluated. Eventual adjustments of the moment should be performed, always valuing the best governance.

It is suggested that the methodologies proposed in this article can be implemented to assist public managers in decision-making. The Drought Risk, Management Capacity Index methodology can be applied once every semester or year. The methodology for Priority action categories for Drought Management can be operationally implemented in an automated way, for quick and practical production of updated data with each new drought disaster record entered in the input database. It is noteworthy that although many institutions and bodies participate in stages of drought risk management in Brazil, monitoring and evaluation mechanisms are still necessary to measure their participation, as well as to infer which classes of shares are the most indicated for the management of drought in each reality of the municipalities. These solutions have already been presented in this paper for now.

As an opening for new research and future work using the methodology Categories of Priority Actions for Drought Management, it is recommended to include more criteria for evaluation, in addition to those currently existing if the municipality is in a drought situation and if it has damage human, deaths, economic or other damages associated with drought. For example: also delimiting if the municipality suffers from the water supply, if there are agricultural losses, among many others that can be included and verified. The new approach was innovated by offering a methodological proposal for institutional assessment of drought risk management and a strategic methodology to indicate priority action classes in drought management at the municipal level.

Author Contributions

Conceptualization, methodology, investigation, formal analysis, visualization, and drafted the manuscript, ALMEIDA, E. K. A.; supervision, writing—original draft preparation, project administration, ALMEIDA, E. K. A., MARENGO, J. A. and PAMPUCH, L. A.; software, resources and data curation, ALMEIDA, E. K. A. and CUNHA, A. P. M. A.; writing—review and editing, ALMEIDA, E. K. A., MARENGO, J. A., PAMPUCH, L. A. and CUNHA, A. P. M. A. All authors contributed to the article and approved the submitted version.

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Declarations

Conflicts of Interest

The authors declare no conflict of interest.

Data Availability

Data will be made available on request.

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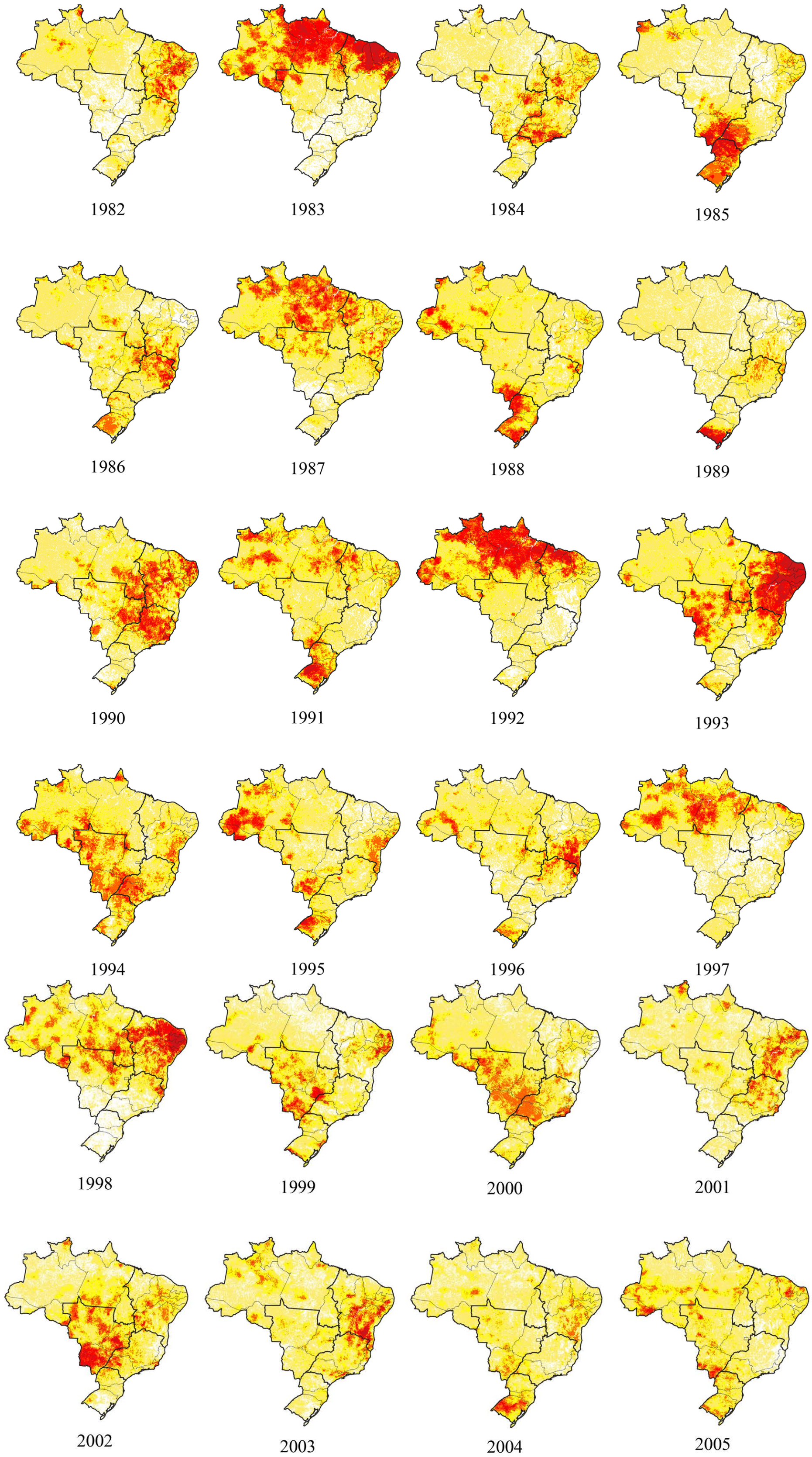
Supplementary Materials



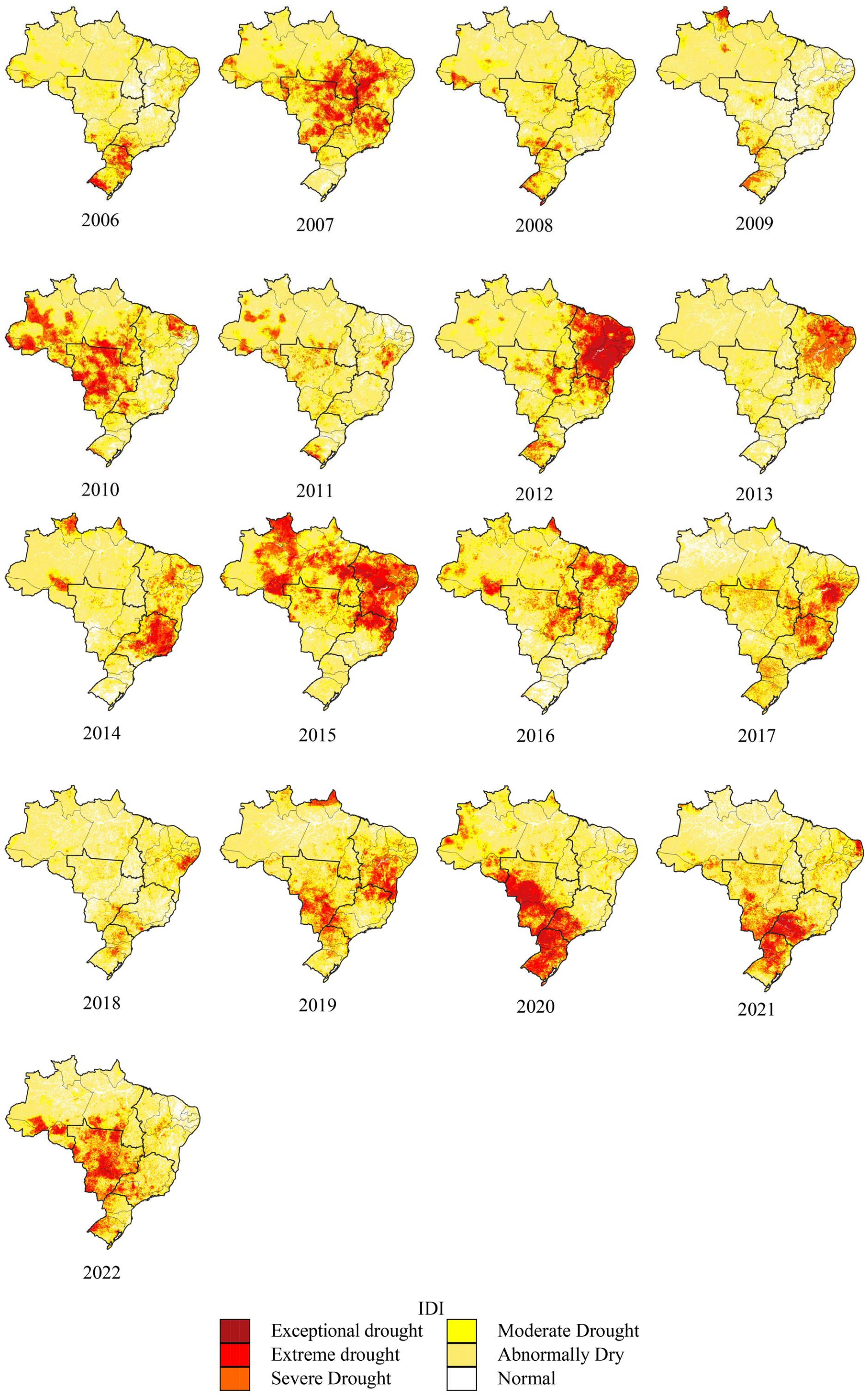


Figure S1. Integrated drought index (IDI-12) maps from 1982 to 2022. The maps show the characterization of drought and exposure of the areas most affected in Brazil.