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Research papers

At the extremes: Assessing interrelations among the impacts of and responses to extreme hydroclimatic events in Ceará, Northeast Brazil

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ABSTRACT

As climates continue to change, semi-arid rainfall regimes are projected to become increasingly more extreme, with longer dry periods and fewer, but more intense, heavy rainfall events. This process of hydroclimatic intensification increases the risk associated with successive extreme climate hazards, such as drought and then heavy rainfall, in the same area. However, the development of effective adaptation strategies to drought, heavy rainfall, and flood hazards is hampered by the lack of integrated analyses that consider the interactions among these hazards and responses to them. To increase understanding of these interactions, this paper examines impacts of and adaptive actions taken in response to prolonged drought (2012–2018) and subsequent extreme rainfall and flooding (March and April 2023) in the semi-arid region of Ceará, Northeast Brazil. We find that policies and adaptive measures focus primarily on drought hazard, while preparation for extreme rainfall events and flooding is scant. Management plans and long-term adaptive strategies are being developed for drought and not other extreme hydrometeorological events. Additionally, emergency measures for extreme rainfall and flooding are much less structured than those for drought. As such, the paradigm "Convivência com o semiárido" ("Living with the semi-arid region") remains limited to adapting to drought hazard, ultimately hindering adequate extreme rainfall and drought responses. To promote more effective adaptive strategies in the context of hydroclimatic intensification in semi-arid regions, drought, heavy rainfall, and flood responses must be considered in a more integrated manner to create management plans to prepare for the potential impacts of these hazards into the future.

1. Introduction[1]

Rainfall regimes in semi-arid regions are becoming ever more extreme, with longer dry periods and fewer, but more intense, heavy rainfall events—a process called hydroclimatic intensification (de Oliveira et al., 2014; Medeiros et al., 2022). Semi-arid regions are particularly vulnerable to hydroclimatic intensification, given characteristic rainfall levels below potential evapotranspiration rates throughout most of the year and severe runoff during rainfall events (Panthou et al., 2018). Extreme rainfall and flooding are essential for surface water and ground water recharge in semi-arid regions (Geris et al., 2022; Liu et al., 2011), but these extreme events often result in

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[1] Abbreviations: Northeast Brazil (NEB); Banabuiú River Basin (BRB); State Water Resource Management Company of Ceará (COGERH); Intertropical Convergence Zone (ITCZ); Research Institute for Meteorology and Water Resources - Ceará State (FUNCEME); Secretariat of Water Resources of Ceará (SRH); Superintendency of Hydraulic Works of Ceará (SOHIDRA); Water and Sewage Company of Ceará (CAGECE); Municipal Alert Index (IMA); Company of Mineral Resource Research (CPRM); Proactive Drought Management Plan (PDMP); National Meteorological Institute of Brazil (INMET); Center for Weather Forecasting and Climatic Studies (CPTEC).

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catastrophic consequences—including socioeconomic loss, erosion and land degradation, infrastructure damage, and loss of life—in semi-arid regions globally (Sumi et al., 2022).[2] As exposure to drought and heavy rains and flooding increases, areas that are unable to recover from one disaster may be more likely to experience compound disasters, with adverse outcomes greater than the sum of two isolated events (McGreevy and Adrien, 2023). Yet, few studies analyze risk and adaptation measures related to drought in conjunction with those associated with heavy rainfall and flooding, which limits understanding of possible interactions and hinders the development of adaptation strategies to minimize risk to extreme events (Ward et al., 2020). To help fill this gap, this paper examines outcomes of and responses to extreme rainfall and flooding in 2023 in the semi-arid region of Ceará, Brazil and their relationships to adaptation measures to severe drought from 2012 to 2018 and prolonged drought impacts in the region. Integrative approaches to address the impacts of and responses to hydrometeorological extreme events is imperative given the current and projected increases in intensity, frequency, and overlapping consequences of drought, heavy rains, and flooding.

Ceará forms part of Northeast Brazil (NEB), known for suffering due to drought and the modernist paradigm of "*Combate contra a seca*" ("Fight against drought") that guided drought policies focused on large infrastructure projects in the region throughout the 20th century (Alves da Silva, 2007). In the late 20th century, a new paradigm, "*Convivência com o semiárido*" ("Living with the semi-arid region"), developed with a greater focus on local, sociotechnological solutions (Alves da Silva, 2007). Despite the shift in perspective from fighting against drought to coexisting with the semi-arid region, both paradigms center drought and drought impacts.

The focus on drought in policies reflects the persistence of drought and drought-related disasters in the region. The droughts of 1877–1879, 1915, 1931, 1973, 1983, 1993, and 1998 evoke memories of unequal suffering in the Cearense sertão, as well as the implementation of large-scale infrastructure solutions in response to drought. The most recent drought (2012–2018) is considered the worst drought in Ceará's history, impacting various sectors and posing challenges for urban and rural human water supply (Marengo et al., 2017; Pontes Filho et al., 2020). Despite the historical emphasis on drought, deficiencies in drought management greatly exacerbated drought impacts and the water crisis (Martins et al., 2018). Long-term drought impacts were observed in the Banabuiú River Basin (BRB) of Ceará through February 2023 (Monitor de Secas, 2023).[3]

From 2007 to 2023, the majority of emergency declarations in Ceará were related to drought, with the highest number of declarations registered from 2012 to 2017 (CEDEC, 2023; Fig. A.1).[4] However, 2008, 2009, and 2023 stand out given the elevated number of declarations due to heavy rain or flooding. In 2009, there was a greater number of declarations due to extreme rainfall or flooding than to drought. During the most recent heavy rainfall events in March and April 2023, flooding due to heavy rain and the failure of small dams (i.e., the uncontrolled release of water from a reservoir through a dam due to structural failures) led to distress throughout the region, particularly in rural areas and more impoverished urban neighborhoods. Between March 22 and April 5, 2023, three of the 15 municipalities in the BRB (Piquet Carneiro, Senador Pompeu, and Pedra Branca) declared states of emergency due to heavy rains and one municipality (Milhã) declared a state of public calamity (Table A.1).[5] At that time, eight municipalities, including Milhã, were already under declared states of emergency due to short or long-term drought (Table A.1). As emergency declarations last 180 days, Milhã became simultaneously under a state of emergency due to long-term drought (declared November 10, 2022) and a state of public calamity due to heavy rains (declared March 28, 2023).

Given the gravity of flood impacts in years with extreme rainfall events in Ceará and other semi-arid regions, the "living with the semi-arid region" paradigm should be expanded to include extreme events related excess water (i.e., flooding and heavy rainfall). Under the current paradigm, semi-arid is often conflated with drought, and policies and technologies stress "living with drought" (e.g., Lindoso et al., 2018; Silva et al., 2021). In parallel, "living with flood" strategies have centered flood-related adaptations, particularly in temperate and continental riverine environments (Cuny, 1991; Ferreira et al., 2020). Both sets of approaches emphasize the importance of governance and infrastructure-focused adaptations, but drought and flood remain analytically isolated. To better adapt to both hydrometeorological extremes in semi-arid regions into the future, the interrelations between these events must be recognized in policy and action.

2. Study area

The Banabuiú River Basin (BRB) forms part of the semi-arid region of Ceará, NEB (Fig. 1). The tropical semi-arid region is characterized by distinct rainy and dry seasons; low average annual rainfall (<800 mm); and high temperatures (maximums around 36 °C), evapotranspiration rates (around 2000 mm/year), and spatial and temporal rainfall variability. More than 70 % of Ceará is characterized by a crystalline rock basement and shallow soils, which limit groundwater storage potential. Deep wells are often dry or have water with high salinity. As such, constructing small to large reservoirs for surface-water storage is a popular strategy to increase water supply, despite the region's high evapotranspiration rates.

The BRB forms part of the Jaguaribe River Basin and has a drainage area of 19,647 km^2 (13.4 % of the area of Ceará). Nineteen state-monitored reservoirs and more than 17,000 other private and municipal reservoirs serve important roles for human consumption, animal husbandry, and agricultural practices. Across the 15 municipalities that compose the BRB, 61.5 % of households live in urban areas and 38.5 % in rural areas, according to the 2010 Brazilian Census (IBGE, 2023). Rural households depend primarily on rainfed agriculture, and milk production in the region has greatly increased over the past decade (Section 4.2.1). According to the Municipal Alert Index of Ceará (IMA), 10 of the 15 municipalities of the BRB were considered to have high or medium–high levels of vulnerability over the past 10 years, where vulnerability was assessed based on 12 agricultural, meteorological, and

[2] For regional examples, please see: Northeast Brazil (de Oliveira et al., 2014), Northern Africa (Werren et al., 2016), the Sahel (Panthou et al., 2018), Sub-Saharan Africa (Geris et al., 2022), the Mediterranean (Hooke, 2019), the Middle East (Rahman et al., 2016), China (Zhang et al., 2018) and Southwest United States (Yang and Smith, 2018).

[3] Long-term impacts are on timescales of more than 12 months and are usually hydrological or ecological, such as reservoirs at their inactive volume for prolonged periods (Monitor de Secas, 2023b). The inactive volume is reached when the reservoir level is below the level of the water abstraction infrastructure.

[4] The declaration of a state of emergency is a political process that occurs at the municipal, state, and federal levels. It is overseen by the State Civil Defense Agency, although emergency declarations are made at the municipal level and then ratified at the federal level. A declaration of emergency or calamity gives a municipality access to federal funding through the Civil Defense.

[5] According to the Brazilian Decree No. 7.257 (Brazil, 2010), a state of emergency is defined as an "abnormal situation, caused by disasters, causing damages and losses that imply the partial impairment of the response capacity of the public power of the affected entity." A state of public calamity is defined as an "abnormal situation, caused by disasters, causing damage and losses that imply a substantial impairment of the response capacity of the public power of the affected entity" (Brazil, 2010).

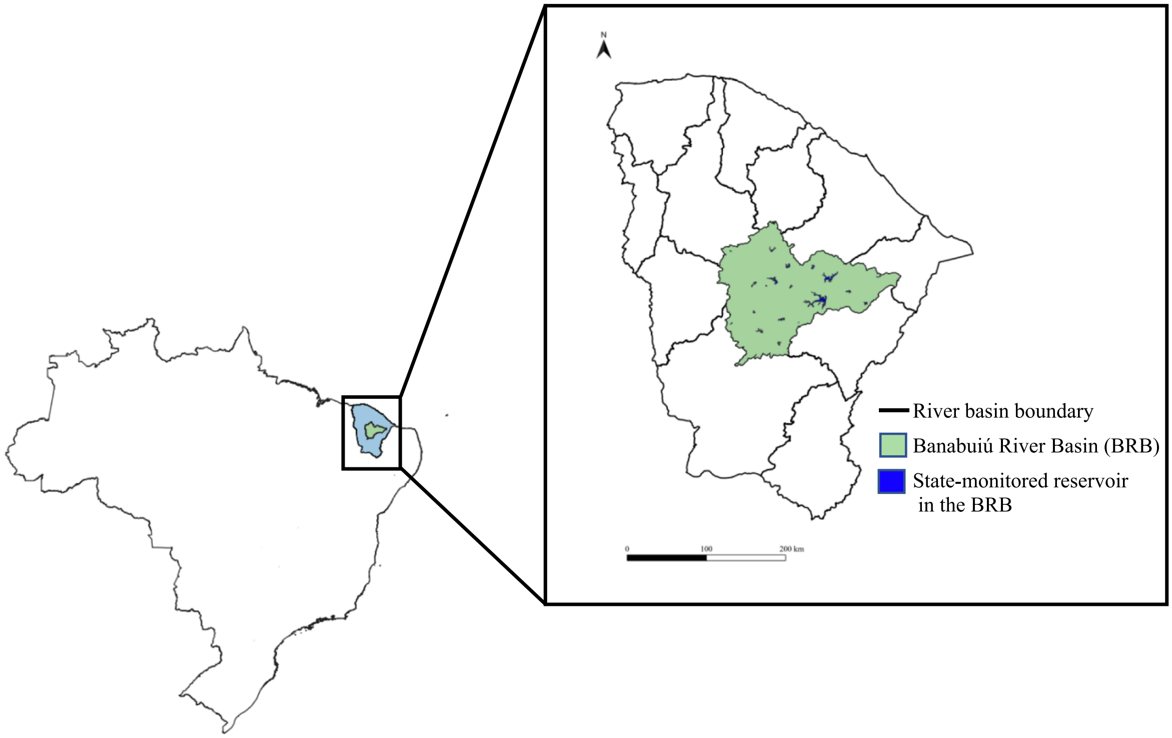

Fig. 1. The Banabuiú River Basin (BRB), Ceará, Northeast Brazil.

hydrological indicators (Fig. 2).[6]

Precipitation in Ceará is intricately influenced by a range of atmospheric and oceanic systems throughout the year. The primary driver of the rainy season (February to May) is the Intertropical Convergence Zone (ITCZ), with droughts during this period linked to anomalies in the Atlantic system (Hastenrath and Greischar, 1993; Hastenrath and Heller, 1977). The El Niño-Southern Oscillation (ENSO) also plays a crucial role, where La Niña typically brings above-average rainfall and El Niño leads to drought conditions (Kayano and Capistrano, 2014). Additionally, the Madden-Julian Oscillation (MJO) has intraseasonal impacts (Valadão et al., 2017; Vasconcelos Jr. et al., 2018). Various other climate systems—including the South American Monsoon System, cold fronts, upper tropospheric cyclonic vortices, quasi-linear convective systems, easterly wave disturbances, and mesoscale convective complexes—contribute to precipitation events in the region throughout the year, each with its own unique characteristics (Comin et al., 2021; Ferreira and Mello, 2005; Gomes et al., 2015; Vasconcelos Jr. et al., 2018). Understanding the interactions of these systems is essential for effective climate prediction and water resource management in Ceará.

[6] The Municipal Alert Index of Ceará (IMA) was developed in 2004 by the Permanent Interinstitutional Group for Coexistence and Sustainable Development of the Semi-Arid Region, a group created by the Institute of Research and Economic Strategy of Ceará (IPECE), with the participation of technicians from various Cearense government agencies (IPECE & SEPLAG, 2022: 5). It classifies municipalities into one of four vulnerability classes: high, medium high, medium low, and low. The IMA is primarily used by the State Secretariat of Agriculture (SDA) and the State Secretariat of Planning and Management (SEPLAG) in decisions regarding public projects to increase rural development and secure access to water, such as Projeto São José (SDA, 2023), Convivência com o Semiárido (P2MCS) (Bezerra, 2023) and multi-dimensional projects financed by the World Bank (World Bank, 2019).

3. Hydrometeorological dynamics of Ceará and the BRB

The 2012–2018 drought was one of the longest multi-year droughts experienced in Ceará since historical records began in the 19th century (Martins et al., 2017). Individually, the rainy seasons from 2012 to 2018 are ranked better than the tenth most critical year in the history of systematic records, but the persistence of drought reveals a very different drought footprint (Escada et al., 2021; Martins and Vasconcelos, 2017; Martins et al., 2017). Over these years, Ceará experienced extended periods of serious (10th percentile), extreme (5th percentile), and exceptional (2nd percentile) drought with high negative rainfall anomalies (Martins and Vasconcelos, 2017). Since 2017, rainfall levels in the BRB for the rainy season have reached or exceeded the long-term mean (calculated from 1991 to 2020) (Fig. 3). In 2019 and 2021, the deviation from the mean was close to zero.

Despite average to above-average rainfall from 2017 to 2022, long-term impacts of drought were still observed in the region through February 2023 (Fig. 4a).[7] The prolonged presence of drought impacts are related to the high spatial and temporal distribution of rainfall, as well as the intensity of rainfall events (Siqueira and Teixeira Nery, 2021). Regions coming out of drought, such as the BRB, may not experience meteorological drought (below-average precipitation and relatively dryness), while still experiencing impacts of hydrological drought (prolonged water-resource deficits) and/or agricultural drought (pastures or crops that had not completely recovered) (Monitor de Secas, 2023b; Wilhite and Glantz, 1985). After the rainfall events in March 2023, the Monitor indicated lack of drought for the entire state of Ceará for the first time since the Monitor was launched in 2014 (Fig. 4b).

[7] The February/2023 Brazil Drought Monitor map reflects the drought from November/2022 to January/2023 in a small central area of Ceará. In addition to reservoir levels, the monitor uses several products as support information on droughts, such as satellite-based products on soil moisture and vegetation health index.

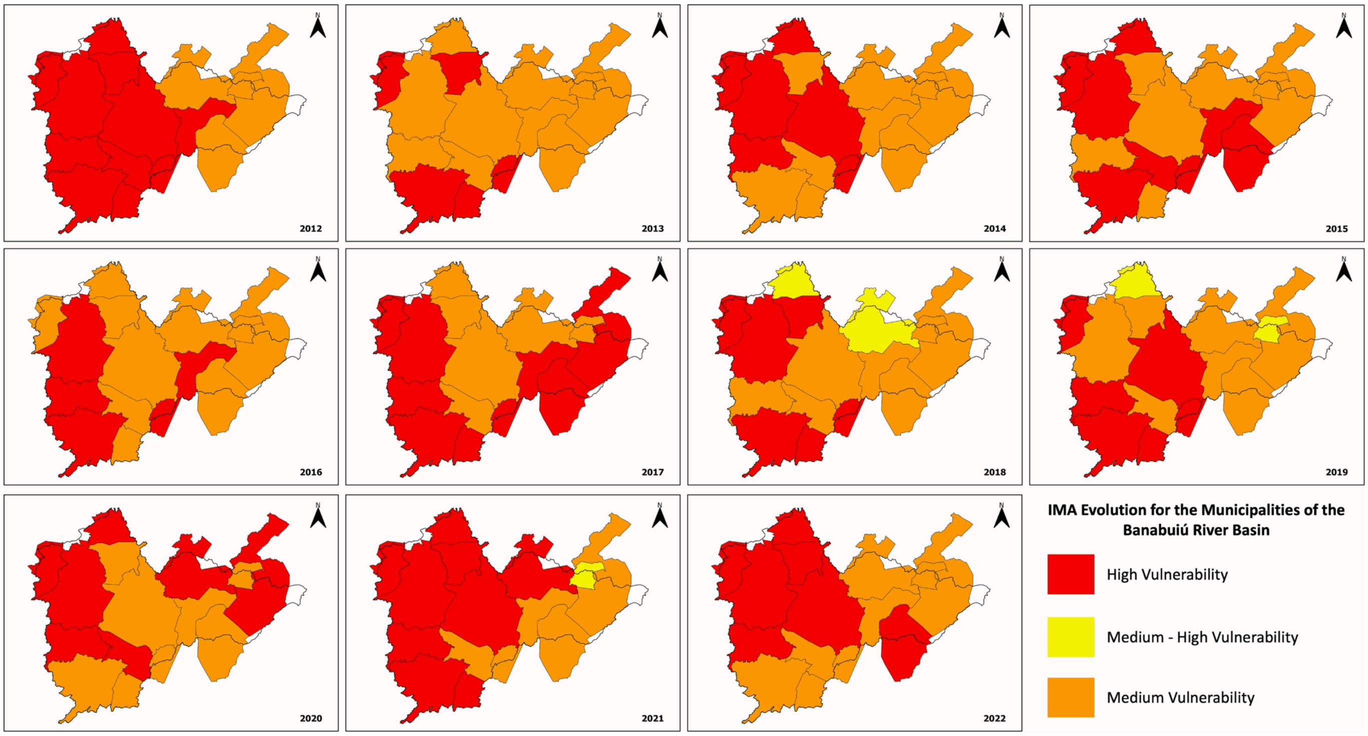

Fig. 2. The evolution of the class of vulnerability for the municipalities in the BRB according to the Municipal Alert Index (IMA) of Ceará. (Elaborated by Authors).

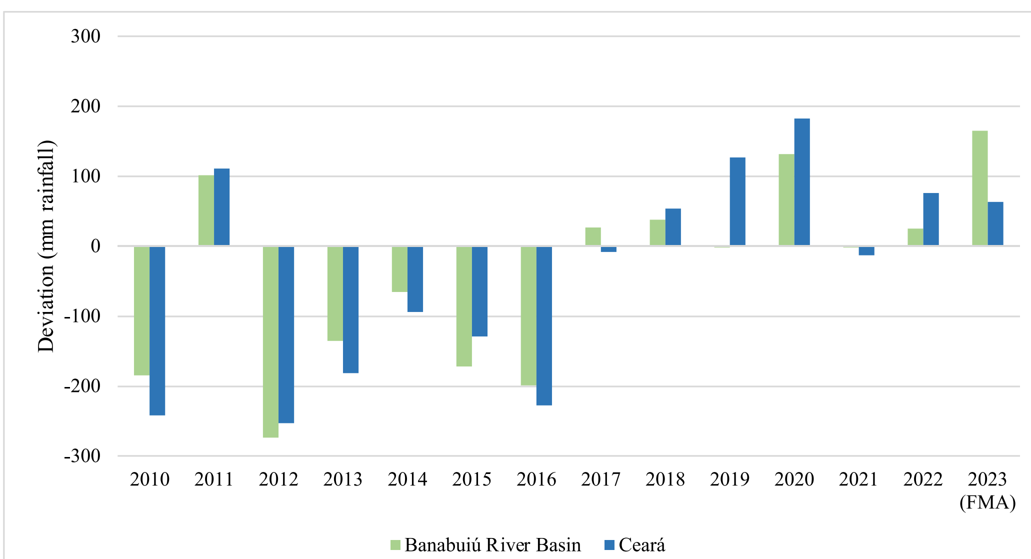

Fig. 3. Deviation from the long-term rainfall mean (1991–2020) of the rainy season (February, March, April, and May) in the BRB and the State of Ceará from 2010 to 2023. For 2023, the deviation was calculated with rainfall data for February, March, and April (FMA). The deviation from the mean was close to zero in 2019 and 2021 for the BRB. (Data source: FUNCEME).

In Section 3.1, we analyze the extreme rainfall events in the Banabuiú region using rain gauge data and historic means. Section 3.2 focuses on water levels of state-monitored reservoirs before and after the extreme rain events. Rainfall and radar data were provided by FUNCEME, the Research Institute for Meteorology and Water Resources - Ceará State. Reservoir monitoring data are available for the 157 reservoirs monitored by the State Water Resource Management Company of Ceará (COGERH) (19 of which are located in the BRB) and were obtained from the Hydrological Portal of Ceará.[8]

[8] https://www.hidro.ce.gov.br/.

3.1. Rainfall analysis

Flooding in the BRB was the result of the heavy rainfall events in March and April and concurrent breaching of small dams. Factors such as precipitation intensity, volume, and timing, as well as the characteristics of riverbed and drainage basin (e.g., soil composition, urbanization, and the presence of dams), impact flood intensity (Seneviratne et al., 2021). In certain areas of the BRB, flooding was primarily triggered by a combination of consecutive rainy days and the extended duration of precipitation events. Rather than being predominantly caused by isolated extreme daily precipitation events, these floods typically resulted from a sequence of rainy days, with most of the daily

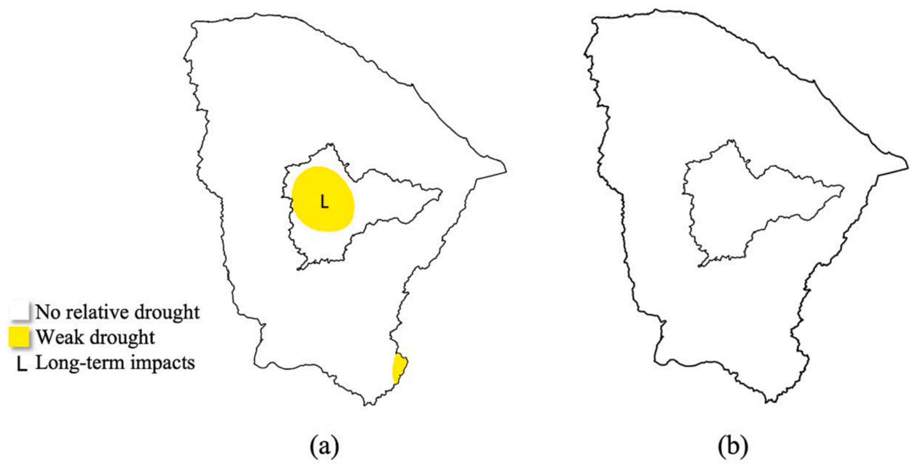

Fig. 4. Drought Monitor for Ceará for (a) February 2023 and (b) March 2023. (Source: Monitor de Secas, https://monitordesecas.ana.gov.br/).

rainfall events concentrating 80–90 % of the total precipitation within a short span of 1.5 to 3 h.

To assess rainfall intensity, daily rainfall values for the period March 1 to April 19, 2023 were obtained from the Hydrological Portal of Ceará. The range of dates was selected based on the concurrence of extreme flooding and emergency situations in the region. For municipalities with more than one rain gauge, the gauge with the maximum recorded rainfall was used.[9] While hourly (or higher frequency) precipitation data provide better information on rainfall intensity than daily totals, heavy rainfall event thresholds are normally defined based on daily rainfall records due to the lack of sub-daily rainfall data, as is the case here (de Oliveira et al., 2014). The maximum daily rainfall recorded for each municipality illustrates the high concentration of days with relatively strong to extreme rainfall events in March and April (Fig. A.2). Radar analysis also shows that the rainfall maximums in the BRB occurred in a few hours, indicating high rainfall intensity.

Following Gouvea et al. (2018), maximum daily rainfall values by municipality were categorized as weak, moderate, strong, or extreme based on the daily rainfall totals recorded at a single rain gauge. Table 1 summarizes the frequency of extreme daily rainfall (rainfall greater or equal to 50 mm) per municipality, while the full categorization is available in Table A.2. All municipalities in the BRB except Itatira experienced extreme rainfall events. Five had at least one day of rainfall between 100 and 150 mm, and two (Quixeramobim and Milhã) recorded one extreme rainfall event of more than 150 mm. The maximum rainfall value recorded was 190 mm in Milhã on March 27, 2023.

The rainfall in Milhã during March 2023 was truly exceptional. The extreme cumulative rainfall value of 190 mm in Milhã represents the highest daily precipitation recorded in the systematic record started in January 1974. When analyzed using a fitted generalized extreme distribution model, it corresponds to a 530-year return period, underlining the rarity and severity of this event. The total precipitation of 423.7 mm in Milhã for the month of March also far surpassed the climatological expected value of 182.2 mm, marking a significant deviation of 132.6 % above the mean.

The rainfall events from March 1 to April 19 led to positive anomalies compared to the long-term mean (1991 – 2020) for March and April in 14 of the 15 municipalities in the BRB (Fig. 5). Even before the end of April, all municipalities except Itatira demonstrated higher rainfall levels than the historic mean. The concentration of rainfall in the west and center of the BRB is significant, as rainfall in this area makes important contributions to water levels in state-monitored reservoirs and other reservoirs key to human water supply in urban areas and surrounding rural communities. Changes in reservoir levels in the BRB are presented in the following section, and discussion on the impacts of the heavy rainfall follows in subsequent sections.

3.2. State-monitored reservoir levels

COGERH currently monitors 19 reservoirs in the BRB, which have a total storage capacity of 2,674.59 hm^3. Table A.3 in the supplementary information indicates the municipality where each reservoir is located, the years it was constructed, its capacity, and whether it is administered by the Federal Government, the State Government of Ceará, or a private party. Daily readings are made available for all COGERH-monitored reservoirs via the Hydrological Portal of Ceará.[10] The rainfall events in March and April 2023 transformed the water-storage scenario of monitored reservoirs the BRB (Fig. 6). On February 1, 2023, the total volume of water stored in these reservoirs was 259.42 hm^3 (9.7 %), three reservoirs were completely dry, and seven reservoirs had a volume between 0 and 5 % (Fig. 6a). In comparison, on March 31, the total volume stored in monitored reservoirs was 597.16 hm^3 (22.32 %), no reservoir was completely dry, only two reservoirs had a volume between 0 and 5 %, and four had begun to spill over (Fig. 6b). By the end of the extreme rainfall events, on April 19, the total volume stored by monitored reservoirs was 1,032.25 hm^3 (38.59 %), only one reservoir had a volume of less than or equal to 5 %, and seven were overflowing (Fig. 6c). The reservoir volumes and percent capacity corresponding to Fig. 6 are available in Table A.4.

The Quixeramobim Reservoir exemplifies this transformation (Fig. 7). The reservoir was at 0 % capacity until March 17, when water from flows from non-controlled areas (i.e., areas not regulated by upstream, monitored reservoirs) began to fill the Reservoir. After much anticipation by residents, the Quixeramobim Reservoir began to overflow on April 2, 2023, in large part due to the influx of water from upstream reservoirs that had begun to overflow in the preceding days.

[9] We use the rain gauge with the maximum recorded rainfall in the analysis as a heuristic to illustrate the high frequency of heavy rainfall events in the region over the 50-day period. The data of maximum precipitation coincide with the dates when the flood impacts were felt, indicating some causal relation between the recorded precipitation and the floods that occurred in the affected regions. Additionally, a radar analysis reveals that the precipitation-inducing systems cover extensive regions throughout the duration of precipitation records at gauge stations, spanning from 7 a.m. to 7 a.m.

[10] For reservoirs in a state of collapse, measurements may not be recorded for a period of time, and volumes may not be available for all calendar dates.

Table 1
Frequency by municipality of days (7 a.m. to 7 a.m.) with extreme accumulated rainfall for March 1 to April 19, 2023 (50 days total).[a,b,c] (Data Source: Hydrological Portal of Ceará, http://www.hidro.ce.gov.br/).

Municipality	Days of Recorded Extreme Rainfall			Total days of extreme rainfall
	50 mm ≤ x < 100 mm	100 mm ≤ x < 150 mm	150 mm ≤ x	
Banabuiú	5	0	0	5
Boa Viagem	7	0	0	7
Ibicuitinga	2	0	0	2
Itatira	0	0	0	0
Jaguaretama	5	0	0	5
Madalena	8	1	0	9
Milhã	2	1	1	4
Mombaça	5	0	0	5
Monsenhor Tabosa	3	0	0	3
Morada Nova	10	0	0	10
Pedra Branca	4	0	0	4
Piquet Carneiro	3	1	0	4
Quixadá	3	0	0	3
Quixeramobim	12	3	1	16
Senador Pompeu	3	1	0	4

[a] The definition of “extreme” as cumulative rainfall of > 50 mm in 24 h is based on the work by Gouvea et al. (2018).
[b] For each municipality, the highest daily rainfall value from March 1 to April 19, 2023 was determined from rain gauge data provided by FUNCEME. Accumulated rainfall is available for 24-hour periods.
[c] The variable x represents the maximum recorded accumulated rainfall value for a given day and municipal.

4. Consequences of and responses to the extreme events

To situate the hydrological data within the sociohydrological context of the BRB, we draw on the authors’ combined experience in the region. This includes the development of research projects in the region over the past decades, as well as ethnographic fieldwork in Quixeramobim from October 2021 to September 2023. Participant observation and semi-structured interviews were conducted with civil servants at the Municipal Civil Defense, technical experts at state and municipal levels, and residents of rural communities in the BRB.

Archival data include newspaper articles, social media posts, and government reports available online. Based on in-person fieldwork and archival research, negative consequences of the extreme rainfall events in the BRB in March and April are provided in Table 2. This list is not comprehensive but rather exemplifies the vulnerabilities of the region to extreme rainfall events. Flooding occurred throughout the region due to heavy rains, reservoir overflow, and reservoir failure. Across Ceará, the government registered 2,994 people as displaced or left homeless, 29 people injured, and seven deaths due to the extreme events (Grupo de Contingência, 2023). Limited transportation access in rural areas, caused by flooding and/or strong river currents, isolated rural communities and districts and led to interruptions in schooling. Additionally, the extreme rain events negatively impacted the milk industry, particularly in the municipalities of Milhã and Senador Pompeu.

In addition to the emergency situations created, farmers noted crop losses due to the heavy rains and floods, as well as due to lack of rainfall in late April and early May 2023. In Cachoeirinha, a rural community in Quixeramobim, crops were lost due to overflow flooding of a private reservoir into areas that had been suitable for planting in past years (farmer from Cachoeirinha, personal communication, April 4, 2023). Additionally, an agronomist from the Landless Workers Movement (MST) explained that excessive rain makes sprouting difficult due to mud (personal communication, May 8, 2023). As such, many farmers waited until soil conditions improved after the rains (i.e., the soils became drier) to plant crops. However, they then expressed concern that they would lose their corn crop due to the dry period that followed the heavy rains (personal communications with farmers in Nenelândia and Cruxatú, Quixeramobim, May 7 and May 13, 2023).

Consequences of and reactions to the 2023 extreme hydrometeorological events in Ceará provide insight into the relationships among risk, vulnerabilities, and adaptation strategies to drought, extreme rainfall, and flooding. Adaptation strategies may be adaptive (i.e., decrease or avoid risk or harm) in some contexts and maladaptive (i.e., increase risk of adverse outcomes or vulnerability to hazards) in others (D’Alisa and Kallis, 2016; Glover and Granberg, 2021). Table 3 summarizes emergency and long-term adaptation strategies to hydrometeorological hazards in the BRB organized by response type (i.e., infrastructure, assessment/decision-making tool, governance, and public policy response). Observed and/or potential positive and negative outcomes for each strategy are provided. In the rest of this section, we highlight the dynamics of several of these actions across local and state levels in the context of the 2012–2018 drought and heavy rainfall events in March and April 2023.

4.1. Emergency responses

Over the course of the 2012–2018 drought, implemented solutions proved insufficient to withstand the continuation of below-average rainfall. Emergency measures helped assuage the more extreme consequences of drought (e.g., death, livestock losses, and migration) and included emergency credit lines, government-subsidized crop insurance for impoverished families and farmers who suffer crop loss (*Garantia Safra*), and water truck delivery services (*Operação Carro Pipa*) to supply water for human consumption (Bretan and Engle, 2017). However, these measures are often costly, provide opportunities for clientelism, and can become chronic buffers to drought emergencies (Nelson and Finan, 2009). The impacts of the 2012–2018 drought catalyzed work toward strategies to reduce the need for emergency responses, including improvements in forecasting, monitoring, and vulnerability/resilience assessments and the development of drought management plans at different governance levels and with different levels of participatory planning (Gutiérrez et al., 2014; Marengo et al., 2017).

The emergency situations that arose during the heavy rain events in March and April 2023 underscore the reactionary nature of flood management in Ceará. Emergency actions in response to flooding carried out at the state level by the State Civil Defense and Secretariat of Social Protection (SPS) included the distribution of 2,600 basic food baskets (*cestas básicas*), 1,582 kg of fresh food and pasta, and 464 mattresses across 24 municipalities, including Pedra Branca, Piquet Carneiro, Senador Pompeu, Itatira, and Milhã in the BRB (Grupo de Contingência, 2023). Additionally, the SPS distributed Social Rent (*Aluguel Social*) payments of R$400 (~80 USD) per affected family (i.e., families left homeless or forced to evacuate their homes because of high flood or landslide risk) to the mayor’s offices of impacted municipalities with declared states of emergency or public calamity recognized by the State of Ceará, according to Law No. 18.331 (Ceará, 2023). In addition to the provisioning of cash, food, and other basic needs, other emergency measures were taken to cope with flooding, including the cancelation of classes and/or public-school transportation and emergency road maintenance by municipal and state government agencies.

The Contingency Group of Ceará (*Grupo de Contigência*), an interinstitutional governance body formed in 2015 to mitigate drought impacts in Ceará, shifted its focus to the emergency flood situations during this period. The attempt to utilize the Contingency Group as a governance tool to respond to the flood emergencies was ineffective. The Contigency Group was not adequately prepared to respond to floods, because key institutions to respond to landslides, dam breaches, and floods do not form part of it, and certain institutions, such as the State Water and Sewage Company (CAGECE), were not appropriately positioned within it for flood responses. Moreover, there was a noticeable lack of coordination in responding to these hazards.

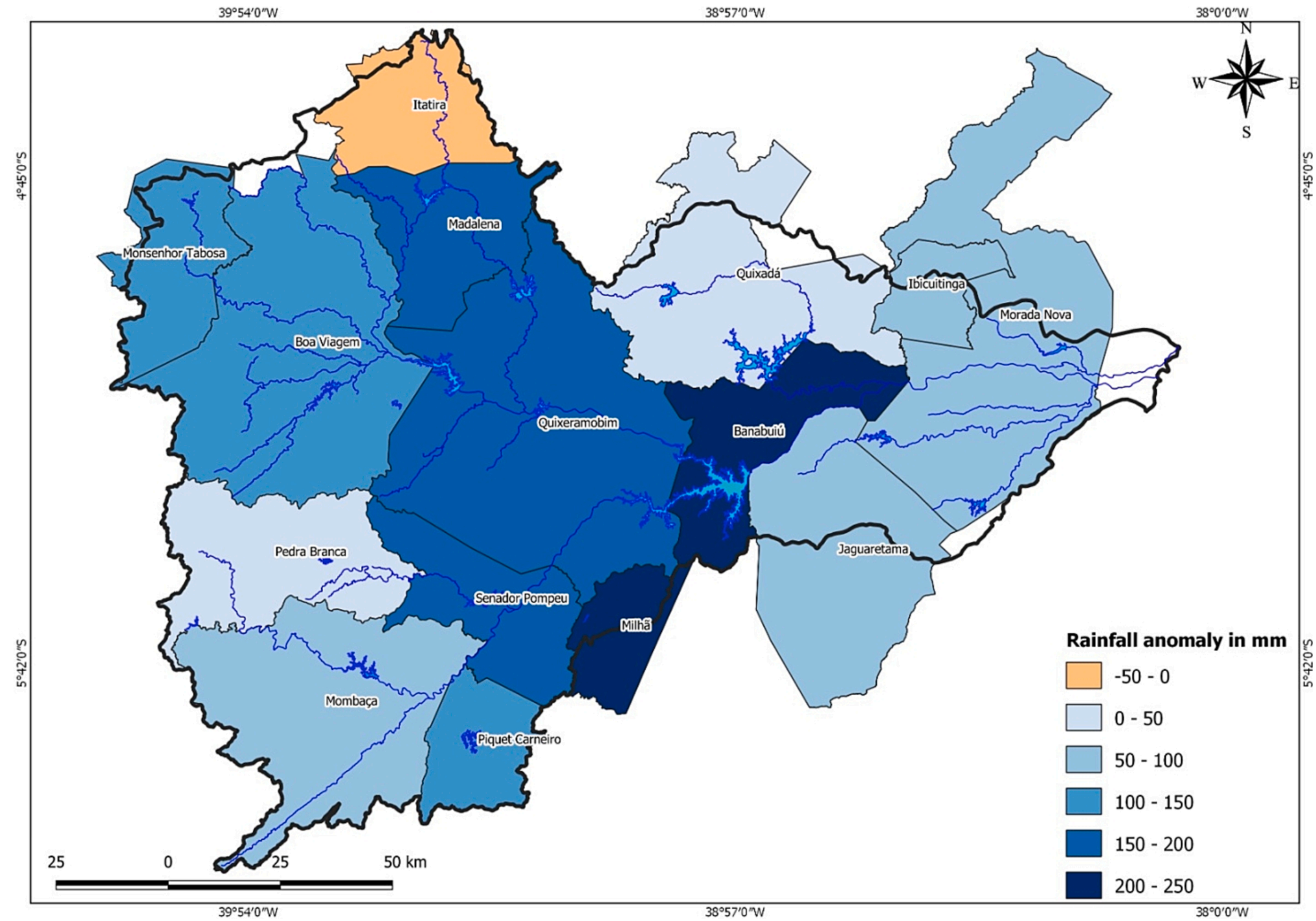

Fig. 5. Rainfall anomaly in mm calculated for March and April 2023 for the municipalities in the BRB. The rainfall anomaly was calculated by subtracting the long-term monthly mean for March and April from the reported monthly rainfall for each municipality for March 2023 and April 1–19, 2023. (Data source: Hydrological Portal of Ceará, http://www.hidro.ce.gov.br/).

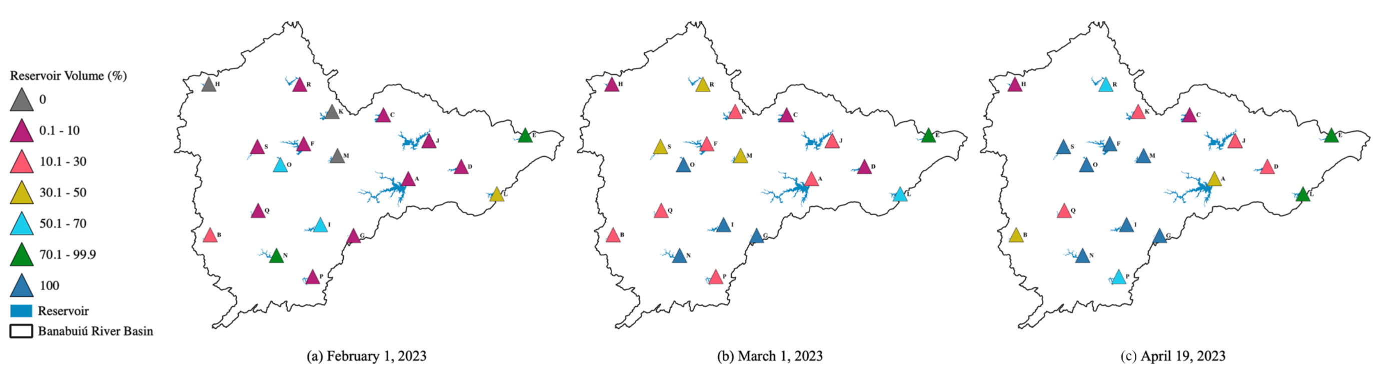

Fig. 6. Water storage volume of reservoirs in the BRB in February, March, and April 2023. For C (Cedro Reservoir), reservoir volume data from April 17 was used instead of April 19, as data were not available for April 18 or 19 for the reservoir. The reservoirs are labeled A through S in alphabetical order: A, Banabuiú; B, Capitão Mor; C, Cedro; D, Cipoada; E, Curral Velho; F, Fogareiro; G, Jatoba; H, Monsenhor Tabosa; I, Patú; J, Pedras Brancas; K, Parabibú; L, Poço do Barro; M, Quixeramobim; N, São José I; O, São José II; P, Serafim Dias; Q, Trapiá II; R, Umari; S, Vierião. (Data source: Hydrological Portal of Ceará, http://www.hidro.ce.gov.br/).

4.2. *The construction of reservoirs as an infrastructure response*

4.2.1. *Small reservoirs*

Small reservoirs have transformed the sociohydrologic dynamics of the BRB and Ceará more broadly, providing an important adaptive strategy for local communities and dairy farmers while becoming one of the most significant maladaptations during the extreme rainfall events in 2023. In Ceará, 105,843 reservoirs with walls of at least 20 m in length have been identified (FUNCEME, 2021). The BRB is the river basin with the second highest number of reservoirs (17,299), and at the municipal level, Milhã and Piquet Carneiro have two of the highest reservoir densities in the state (FUNCEME, 2021). Almost all of the reservoirs were constructed privately or by municipal governments and are unmonitored (i.e., percent volume and water quality measurements

(a) (b) (c)

Fig. 7. The Quixeramobim Reservoir's transformation during the rainy season of 2023: (a) March 12 (0 %), (b) March 17 (1.16 %), (c) April 3 (100 %). (Photos: Authors).

Table 2
Examples of negative consequences of the extreme rainfall events in March and April 2023 in the BRB, as reported in news sources and personal correspondences with the Civil Defense of Ceará.

Municipality	Negative Consequences
Madalena	Flooding; in-person classes for grade schools suspended
Quixadá	Flooding; falling trees and suspension of electrical power; damage to houses and stores.
Milhã	Flooding; failure of at least 40 private reservoirs; in-person classes suspended; homes and stores destroyed and residents homeless; damaged roads; milk industry negatively impacted
Senador Pompeu	Flooding; risk of large dam failure; paved and dirt road blocked, flooded or collapsed; milk industry negatively impacted
Piquet Carneiro	Flooding; paved and dirt roads blocked, flooded or collapsed; private reservoir failure; evacuation of population from the urban center
Quixeramobim	Flooding; grade-school classes suspended or made virtual in rural areas; grade-school bus transportation suspended indefinitely in rural areas; rural communities and districts isolated due to high water levels; private dam failure
Pedra Branca	Flooding; risk of dam failure; evacuation of rural communities

are not carried out in a systematic manner). Small reservoirs usually have an earth-filled embankment dam, made of compact earth, while some have more rudimentary mud structures (*barreiros*), which are characterized by low water-retention capacity during prolonged periods of drought (Molle and Cadier, 1992). Most reservoirs do not retain water from one rainy season to another, typically reaching critical levels in November or December. Sometimes used for household water consumption, these reservoirs are primarily used for livestock water supply, irrigation, and year-long fodder production in Ceará. Owning a private reservoir can lead to greater autonomy and lower socioeconomic vulnerability for producers. Farmers can also take advantage of the moisture retention on the shores of reservoirs to cultivate beans, fodder, and other crops in the dry season.

The intensification of small reservoirs in the BRB is a key strategy for the expansion of dairy production in municipalities including Quixeramobim, Senador Pompeu, and Milhã. Milk producers emphasize the importance of private small reservoirs for dairy farming: "I have to produce in my reservoir [….] the dam was our salvation for our crops [….] [It is what] creates abundance" (Dairy producer from Piquet Carneiro, personal communication, 2020).[11] In Milhã, where dairy production increased 837 % between 2012 and 2021 (IBGE, 2023), the mayor exalted the municipal program to construct small reservoirs as "a task force to strengthen our dairy farming" (Quixeramobim News, 2022).[12] As a part of the program, the municipal government supplies machinery and technical assistance to construct a small reservoir, while reservoir maintenance becomes the owner's responsibility.

The construction of private reservoirs is an adaptive practice for dairy producers and farmers, but it has maladaptive consequences for hydrologic dynamics in river basins. In semi-arid regions, the presence of small reservoirs can result in significant annual streamflow reduction during dry years, which becomes more intense during extended droughts (Rabelo et al., 2022). According to technical experts at COGERH and FUNCEME, the immense quantity and high density of these small structures in Ceará may interfere with the recharge of large, strategic reservoirs (Rodrigues, 2020). This negatively impacts urban and peri-urban water supplies, as the recharge of the strategic reservoirs that provide water to these areas is interrupted, even in years with average and above-average rainfall.

In addition to these issues, the politics of small reservoirs increase the risk of flooding due to dam failure. While most of these reservoirs would not meet volume or height characteristics of the National Reservoir Safety Policy,[13] they have high potential to cause damage. The lack of proper maintenance or other technical deficiencies led to the breaching of more than 40 dams in Milhã, in addition to failures and risk of reservoir failure in other municipalities in the BRB (Superintendent of SOHIDRA, personal communication, April 6, 2023). Vegetation growth in the spillway and near the embankment of earthen reservoirs can compromise the structural integrity and increase the risk of failure (Escolano-Sánchez and Fernández-Serrano, 2015).

The state of calamity declared in Milhã was directly related to the flooding caused by the rupture of these reservoirs. Likewise, the rupture of a private reservoir in the district of Belém in Quixeramobim isolated several rural communities, and emergency measures were carried out by the government to provide food and supplies to stranded residents and to repair roads in the flooded region to restore access (Resident of the community Pontal Alegre, personal communication, April 7, 2023). Due to the combination of lack of access and power outages, milk producers in these communities were forced to dump milk stored in community tanks. In Pontal Alegre (Quixeramobim), 7,000 liters of milk were lost (Resident of Pontal Alegre, personal communication, May 14, 2023). These losses and hardships were the result of local dams breaking and subsequent flooding, suggesting that the monitoring and maintenance outlined in the National Reservoir Safety Policy are not being carried out adequately.

[11] Original quote: "Eu tenho que produzir na minha barragem [….] o açude foi a nossa salvação para a lavoura [….] [É o que] gera fartura."

[12] Original quote: "uma grande força tarefa para fortalecer nossa pecuária leiteira".

[13] The National Reservoir Safety Policy (Law No. 14.066) applies to reservoirs with a capacity of at least three million cubic meters; wall height of at least 15 m; or medium to high potential damage in economic, social, environmental terms or in terms of loss of human life (Brazil, 2020).

Table 3
Key emergency and long-term strategies to drought and extreme rainfall/flooding (flood) employed in Ceará. Strategies are categorized by four response types: infrastructure (I), governance (G), public policy responses (P), and assessment/decision-making tools (A).

Strategy	Response Type	Response Horizon	Drought or Flood Response	Responsible Actor(s)[a]	Positive and Negative Consequences	Level of Impacts
Small reservoirs	I	Long-term	Drought	Municipalities, individuals	**Positive:** Increase in animal husbandry (cattle and milk); subsoil moisture for harvesting during summer and dry periods; water storage **Negative:** Interruption of water flow to strategic reservoirs; lack of integrity leads to failure during heavy rains	Local, river basin, regional
Large reservoirs	I	Long-term	Drought, flood	DNOCS, Brazilian Army, municipalities	**Positive:** Increase water availability for multiple uses; flood mitigation **Negative:** Perpetuation of Drought Industry and political corruption	Local, regional, state
Intrabasin water transfers through pipeline systems	I	Emergency	Drought	State Secretariat of Water Resources (SRH), COGERH	**Positive:** Water supply for household uses and production **Negative:** Conflicts between upstream and downstream communities and between communities and water authorities	Household, municipal, regional, state, federal
Projeto Malha d'Água (Water Pipeline Network Program)	I	Long-term	Drought	SRH, FUNCEME, French National Research Institute for Sustainable Development (IRD)	**Positive***: Guarantee water quality and quantity for urban areas, increase water available (e.g., by decreasing water losses due to river-aquifer interactions and evapotranspiration in open canal systems), and significantly reduce dependence on and costs associated with water truck programs (SRH, 2023) **Negative***: Management strategies unclear; potential management conflicts at the municipal level and in rural areas; does not contemplate most diffuse rural communities *These are expected outcomes, as the projects are currently being executed	Municipal, river basin
Well drilling	I	Emergency, long-term	Drought	SOHIDRA, municipalities, individuals	**Positive:** Increase water availability for household uses; desalination systems help increase water potability for human consumption **Negative:** Water table depletion; water often briny and unsuitable for human consumption	Household, community, municipal
State Contingency Group (*Grupo de Contigência*)	G	Emergency, long-term	Drought	SRH	**Positive:** Support short and long-term decision making in response to drought vulnerabilities **Negative:** Unprepared to respond adequately to extreme rainfall and flood risk	Regional, state
Drought management plans	G	Long-term	Drought	State government, universities, local institutions	**Positive***: Support short and long-term decisionmaking **Negative*:** Potential to leave out key actors and support decisions that negatively impact specific populations *The effectiveness of these plans in Ceará is unknown as they were developed but not implemented during the 2012 – 2018 drought	Local, regional, state
Social technologies (rain-harvesting cisterns, water reuse systems)	P	Long-term	Drought	Federal government, non-government organizations, individuals	**Positive:** Rainwater capture to supply potable drinking water yearlong; water storage for use when do not have other sources; reduction of distance to reliable water source; greater independence for families **Negative:** Dependence on federal government limited reach of program from 2016 to 2022	Household, community
Water trucks programs (*Operação Carro Pipa*)	P	Emergency	Drought	Brazilian Army, municipalities	**Positive:** Rural dwellers gain access to water for household consumption **Negative:** Rural dwellers become dependent on water delivery service; costly; often poor water quality	Household, community
Federal cash transfers for crop losses (*Garantia Safra*)	P	Emergency	Drought, flood	Federal government, state government, municipalities	**Positive:** Increased food security, as farmers receive money for food and other household needs **Negative:** Encourages persistent vulnerability of small farmers (Nelson and Finan, 2009)	Household
Seasonal forecasting	A	Long-term	Drought, flood	FUNCEME, CPTEC, INMET	**Positive:** Supports seasonal and long-term decision making; increased knowledge and autonomy of farmers to develop agricultural practices **Negative:** May not be used by households or large-scale agriculture due to distrust and forecasts' large spatial and temporal scales and technical presentation	Household, regional, state

(*continued on next page*)

Table 3 (*continued*)

Strategy	Response Type	Response Horizon	Drought or Flood Response	Responsible Actor(s)[a]	Positive and Negative Consequences	Level of Impacts
Sub-seasonal forecasting	A	Long-term, emergency	Drought, flood	FUNCEME, CPTEC	**Positive:** Monitoring of urban centers to anticipate the collapse of water supply systems from days to months in advance; prioritization of resource allocation (e.g., installation of pipeline system for water transfer and Civil Defense emergency responses) **Negative:** May not be used by households or large-scale agriculture due to distrust and forecasts' large spatial and temporal scales and technical presentation	Household, regional, state
Weather forecasting	A	Emergency	Flood	FUNCEME, INMET, CPTEC	**Positive:** Support short-term decision making and assess areas of higher risk; prioritization of allocation of emergency resources (food, household goods, etc.); increased knowledge and autonomy of farmers to develop agricultural practices **Negative:** May not be used by farmers given technical presentation and distrust	Household, regional, state
Drought monitor	A	Long-term	Drought	National Water and Sanitation Agency of Brazil (ANA), FUNCEME	**Positive:** Support short and long-term decision making for drought responses; assist municipalities to solicit drought policies, such as water-truck services **Negative:** Regional scale may result in overlooking critical situations at the community level	Regional, state
Flood-risk assessment	A	Long-term	Flood	CPRM, FUNCEME	**Positive:** Support short and long-term decision-making in urban areas **Negative:** Focus on urban areas leaves rural areas without adequate flood-risk information	Local

[a] Acronyms: DNOCS – National Department of Works Against Drought; CPTEC – the Center for Weather Forecasting and Climatic Studies; INMET – National Meteorological Institute of Brazil/ SRH - State Secretariat of Water Resources.

4.2.2. *Large reservoirs*

In Ceará, the construction of large reservoirs is a historic response to drought emergency (Escada et al., 2021; Martins et al., 2017). In the BRB, these include the Cedro Reservoir—the first large reservoir constructed in Brazil and conceived by the Brazilian Empire in response to the devastating drought in 1877–1879 (Monteiro, 2020)—as well as the Banabuiú and Quixeramobim Reservoirs constructed as responses to widespread drought in the late 1950s. Currently, these reservoirs are monitored by COGERH and supply water for multiple uses to urban centers and surrounding rural regions connected via canals or pipelines. River basin committees make allocation decisions for the water stored in the state-monitored reservoirs, selecting from different rate-flow scenarios calculated by COGERH (Lemos et al., 2020). During the 2012 – 2018 drought, these reservoirs reached critical levels in part due to mismanagement of the water stored (Director of the Regional COGERH Office—Quixeramobim, personal communication, August 17, 2023). One objective of the Proactive Drought Management Plans (Section 4.4) is to avoid such situations during periods of extreme drought by establishing maximum water-release rates based on reservoir levels.

COGERH annually inspects all state-monitored reservoirs before and after the rainy season in order to identify possible faults in infrastructure integrity and to repair damage to prevent future dam failure (Superintendent of SOHIDRA, personal communication, April 6, 2023). This monitoring process follows the requirements outlined in the National Reservoir Safety Policy (Law No. 14.066, 2020), which states that the "*empreendedor*"[14] of a reservoir is responsible for the maintenance and monitoring of said reservoir (Brazil, 2020). During the extreme rainfall events in March and April 2023, none of the state-monitored reservoirs failed, a testament to the effectiveness of regular reservoir maintenance by COGERH.

[14] An empreendedor is defined as a private or governmental agent with real rights over the lands where the dam and reservoir are located or who exploit the dam for their own benefit or that of the community and may be an individual, a community association, municipal government, or state agency (e.g., COGERH), among others.

4.3. *Climate forecasting*

Seasonal climate forecasting provides useful information for decision-making processes across different sectors, including agriculture, water management, and health (Ceglar and Toreti, 2021; Escada et al., 2021). However, despite its potential utility, climate forecast information is not guaranteed to be incorporated into decision-making processes (Lemos et al., 2002). Salience, relevance, authority, and legitimacy are key factors for how different actors use or do not use forecast information when making decisions (Taddei, 2008).

Seasonal climate forecasting in Ceará has developed tremendously in recent decades (Escada et al., 2021; Marengo et al., 2022). Since 2012, FUNCEME has employed objective forecasting, producing forecasts directly from selected models. This allows the direct use of the forecast in impact assessment models (e.g., hydrological models in order to predict inflows to the main reservoirs of the state) and minimizes subjectivity inherent to consensus forecasting methods that incorporate negotiation processes into forecast development. FUNCEME's forecasts are probabilistic, providing probabilities for rainfall above, near, and below the historic mean (Martins and Vasconcelos, 2017).

Seasonal forecasts produced by FUNCEME, the Center for Weather Forecasting and Climatic Studies (CPTEC), and the National Meteorological Institute of Brazil (INMET) inform long-term policy decisions at the state level in Ceará. Seasonal forecasting was fundamental to water management decisions during the 2012–2018 drought period, supporting decisions to avoid collapse of many urban water systems and reducing the negative consequences of prolonged drought (Martins and Magalhães, 2015). While seasonal forecasting is valuable for minimizing potential drought consequences, decisions based on forecasts may not always be viable when uncertainties are high or when situational dynamics warrant alternative actions. The best option for drought preparedness is the integration of seasonal forecasts and drought-risk monitoring (Marengo et al., 2022).

Seasonal forecasting is not necessarily an effective tool for flood preparedness, as seasonal total rainfall may not be correlated to flood levels (Coughlan de Perez et al., 2017). Rather, sub-seasonal climate forecasting and weather forecasting (Moudi Pascal et al., 2023), as well as seasonal streamflow forecasts and river-basin-level hydrological models (Coughlan de Perez et al., 2017; Sahu et al., 2017), are more adept to prepare for and respond to extreme rainfall events and flooding. Weather forecasts are produced by FUNCEME, INMET, and CPTEC, while FUNCEME and CPTEC have recently advanced sub-seasonal climate forecasting for periods of 7, 14, 21, and 44 days. After the initial heavy rain events in March 2023, FUNCEME's weather and sub-seasonal climate forecasts helped guide the execution of strategic preventative actions in high-risk areas led by the Civil Defense and other state organs. The Civil Defense was particularly concerned about the possible continuation of rainfall events in areas that had already entered collapse, including Milhã. Emergency actions included evacuation of areas at risk for flooding and the inspection of small dams that could pose a risk of rupture.

4.4. Drought management plans

Drought management plans at different levels of management are fundamental to move away from crisis management approaches (Wilhite and Knutson, 2008). The recent prolonged drought catalyzed the development of different drought management plans in Ceará to mitigate drought impacts at the state, municipal, or reservoir-system level. At the state level, the Drought Coexistence Action Plan (*O Plano de Ações de Convivência com a Seca*) was developed in 2015 to evaluate drought consequences and define emergency, medium-term, and long-term actions from a multi-actor perspective by aggregating the demands of different sectors (Governo do Estado do Ceará, 2015). The Cearense Municipal Agricultural and Livestock Farming Pilot Plan to Prepare for and Respond to Droughts (*Plano Piloto Agropecuário Municipal de Preparação e Resposta às Secas do Ceará*) addressed drought vulnerabilities from a municipality perspective, and drought plans were developed for seven municipalities from 2014 to 2020, including in Piquet Carneiro (2014) and Quixeramobim (2016) (SDA, 2020). With the exception of Piquet Carneiro, plan development involved workshops with representatives from municipal and state level institutions to define solutions to drought-related problems using collective activities. While the project improved planning vision and articulation between different social and government institutions, important actors related to family agriculture were absent from the process (Farias Neto, 2019). Beginning in 2021 and currently ongoing, the Proactive Drought Management Plans Initiative (*Plano de Gestão Proativa de Secas*) uses a proactive water allocation decision-making process based on the sociotechnical methodology used in Participatory Drought Preparedness Plans to develop reservoir-system drought plans (Souza Filho et al., 2023). Led by the Federal University of Ceará (UFC) in collaboration with FUNCEME, the SRH, the Cearense Foundation for Research Support (FUNCAP), universities, and river basin committees, the Initiative collectively establishes operating policies for state-monitored reservoirs based on drought indicators and group-defined goals (See Appendix A for more details on the how plans are developed through the Initiative). The effectiveness of the three types of plans to improve drought management and minimize conflicts is still unknown but rather must be evaluated in upcoming years during and after future periods of drought.

4.5. Flood risk assessment

There are limited initiatives for flood management in Ceará. In general, flood mapping, which is essential for effective flood management, is performed periodically and limited to urban areas. Flood mapping identifies the extent and distribution of flood risks, and long-term satellite monitoring can be used as a forecasting tool (Mudashiru et al., 2021). In Brazil, flood mapping is often carried out by the Company of Mineral Resource Research (CPRM) under the auspices of the Brazilian Ministry of Mining and Energy. However, mapping is typically limited to urban areas, hindering flood risk planning in more remote, rural areas where flooding may be common. In response to the extreme rainfall events in March and April 2023, researchers at FUNCEME began emergency and long-term flood risk mapping across Ceará. For areas with high probability of heavy rainfall, flood risk was mapped as an emergency action.

4.6. Federal cash transfers for crop losses

Garantia Safra (Harvest Guarantee) is a subsidized crop insurance program established in 2002 through the Brazilian Federal Government that supports low-income small farmers in NEB who have lost crops due to drought or excess rainfall. While the program accounts for crop losses due to both drought and excess rain, in Ceará, the program is most often associated with losses due to lack of rainfall. In a speech about Garantia Safra in February 2023, Ceará Governor Elmano de Freitas observed, "Crop loss due to drought is very common for us in the Northeast [….] Garantia Safra is a very important drought policy for us [….] The forecast is for good rains, so we are preparing for future years"[15] (Falcão, 2023). Of the 184 Cearense municipalities, 181 qualify for Garantia Safra. For an individual farmer to receive the benefit, they be registered through their municipality, and there must be proof of average harvest lost at the municipal level equal to or greater than 50 % in rice, beans, corn, cassava, or cotton due to drought or excess rain in the growing season (Brazil, 2002). Initially, only farmers in municipalities with federal declarations of emergency or calamity were able to benefit from the program, but this requirement was removed in 2008 (Valadares et al., 2022). The value of the benefit increased from R$850 for the 2021/2022 season to R$1200 for the 2022/2023 season (Ministério da Agricultura, Pecuária e Abastecimento, 2023). Per registered farmer, the Federal Government is responsible for contributing at least 40 % of the benefit (R$480 in 2022/2023), while participating states must pay 12 % (R$144 in 2022/2023), municipalities 6 % (R$72), and individual families 2 % (R$24). For the 2021/2022 season, 37,710 family farmers across 47 municipalities received the benefit for crop loss (a total value of R$850,000) (Ministério da Agricultura, Pecuária e Abastecimento, 2023). For 2022/2023, about 200,000 farmers registered for the program across the state of Ceará (Falcão, 2023).

5. Discussion

Climate-related adaptive strategies have developed primarily in response to drought and drought impacts. This is understandable, given that historically, drought events have produced greater long-term impacts and challenges across local, state, and regional levels. Drought also saturates perceptions about Ceará and the Northeast (Seigerman et al., 2021). Descriptions of the hunger, economic hardship, and suffering due to drought fill accounts from throughout the occupation of present-day NEB, beginning in the 16th century (Campos, 2014). The Great Drought of 1877–1879 further engrained drought into the region's identity, as socioeconomic and political struggles in the region became a national concern and elites in the north used drought as a discursive instrument to develop regional identity (Albuquerque Jr., 2021). Drought remains at the forefront of political and popular discourse. In the 1940s, the Brazilian Government established the Drought Polygon within NEB,

[15] Original text: "A perda de safra para nós do Nordeste é muito comum com a seca. A Garantia Safra é uma política de convivência com a seca muito importante para nós [….] A previsão é de boas chuvas, portanto estamos nos preparando para anos futuros."

which continues to be the focal region of drought-related public programs supported by the Superintendency of Development in the Northeast (SUDENE) and the National Department of Works Against Drought (DNOCS). In the rural area of the BRB, family histories of the immense hardship during the 1915 and 1932 droughts mingle with the living memory of those who worked on public work projects or invaded city centers to provide food for their families during droughts through the early 1990s. The 2012–2018 drought and its socioeconomic impacts further cemented the government's investment in mitigation and adaptive drought actions.

Conversely, critical rainfall and flooding events are less frequent, more isolated, and interspersed between years with rainfall below and near average levels. These events also evoke paradoxical emotions, as the influx of water causes both relief and distress. When asked about major rainfall events, a family in the rural community Tanquinhos, Quixeramobim, recounted the 2009 rainy season with awe: although flooding caused major hardship after dividing the community into two, the rains filled drying reservoirs and provided a sense of water security into the following year (personal communication, April 4, 2022). During community meetings held in May through August 2023, several rural dwellers observed that they were grateful for the rainfall events that year. A small farmer from the community Cruxatú explained that despite his losses, with water, they can make do, but without water, suffering is much greater (personal communication, May 13, 2023). The government's attention to rain and flood hazards and related risks at the state level during and after the extreme events in March and April was a direct result of the large number of affected areas, particularly in the BRB. In this section, we highlight incoherencies between different infrastructure solutions, governance mechanisms, social programs, and assessment-based actions in response to drought and to extreme rainfall/flooding and potential synergies among these responses to address hydrometeorological extreme events into the future.

Small reservoirs can be maladaptive during both drought and extreme rainfall. The heavy rains in March and April 2023 were beneficial for small and large reservoir recharge in the BRB. However, he dams of small reservoirs throughout the region broke in 2023 due to inadequate structure or maintenance in conjunction with the rainfall intensity, resulting in flooding and critical situations. The outcomes indicate that the National Reservoir Safety Policy is insufficient and highlight the need for actions to address the construction, management, and maintenance of small reservoirs, such as those suggested by Pisaniello et al. (2015). Further research on the benefits and potential harms of small reservoir construction across levels (i.e., the individual small farm to the hydrological basin) and during drought and extreme rainfall events in semi-arid regions is also needed (Rabelo et al., 2022).

The attempt to employ the State Contingency Group as a governance mechanism to respond to extreme rainfall and flooding events exposed the lack of flood-response preparation by the State of Ceará. It became evident that a group with a different institutional composition is required created to anticipate and respond to disasters related to extreme rainfall more effectively. The alternative group would concentrate on events such as flooding, landslides, and related infrastructure disruption (e.g., road blockages, power outages, and reservoir failure). While many institutions would play fundamental roles in both groups, roles would shift during periods of heavy rainfall and flooding. For example, during periods with high risks of extreme flooding, FUNCEME would carry out monitoring and forecasts with very short (up to three hours) to short (three days) ranges. The State Civil Defense and SOP could supervise on-the-ground actions to ensure their continuation in the weeks after the initial emergency response.

The federal crop insurance program Garantia Safra and meteorological forecasting tools stand out for their ability to address both drought-related and excess-water-related situations. Globally, analyses of crop insurance most commonly focus on drought, while flood and excessive rainfall are rarely discussed (Abdi et al., 2022). Although Garantia Safra is often considered a social program focused on drought-related crop losses, it importantly also supports family farmers who have losses due to excess water. An elevated number of farmers to receive the benefit due to loss caused by flooding for the 2022/2023 season is expected. In terms of assessment tools, over the past decade, drought stimulated advances in seasonal climate forecasting, which is used in bulk water allocation decisions and has helped help government agencies prepare for rainy seasons with high probability of below-average rainfall. Weather and sub-seasonal climate forecasting are key for flood risk monitoring in areas of known high risk and have the potential to support actions by a new state-level unit focused on hazards related to excess water. Importantly, the current lack of flood risk assessments limits knowledge of flood risk and consequently the ability to use forecasting and monitoring techniques more strategically.

As hydroclimatic intensification continues in semi-arid regions, policies and actions must more adequately address the interconnections between consecutive extreme hydrometeorological events and potential compound impacts. Yet how to develop more holistic solutions remains unclear. The unpredictability of flash floods in semi-arid regions is a major challenge and needs to be incorporated into planning, mitigation, and adaptive strategies (Zhang et al., 2018). Over the past years, nature-based solutions (NBS), which incorporate green infrastructure to address socioecological challenges, have been proposed as more holistic approaches to reduce disaster risk (IUCN, 2017). In semi-arid regions, NBS can play significant roles in reducing flood risk (Abdrabo et al., 2022), while restoration of degraded drylands and development of agroforestry systems may reduce drought and flood risk (Seddon et al., 2020). However, like their built infrastructure counterparts, NBS are typically implemented for a single objective, such as drought or flood mitigation (Carvalho et al., 2022). Greater attention to the broader socioecological outcomes of NBS, particularly in the Global South, is needed to better understand the full potential of these approaches to reduce vulnerability to hydrometeorological extremes (Chausson et al., 2020).

Assessment-based responses from which lessons from drought can be carried over to extreme rainfall and flooding are the drought management plans actively being developed through participatory processes at the river-basin level in Ceará. The recent extreme rain and flood events indicate that preparation for these extreme events should also be included in proactive management plans. Flood risk assessment should include both urban and rural areas, as well as the inspection of the integrity of small reservoirs throughout the river basin. A popular empirical approach is the multi-criteria decision-making method (MCDM), a participatory method in which key actors collaborate to evaluate and select alternatives for the given problem scenario using criteria (e.g., costs, environmental impact, social impact, and effectiveness) that are subsequently measured and weighted (Mudashiru et al., 2021). The participatory structure of MCDM is similar to that of the approaches used in the development of Proactive Drought Management Plans in Ceará. Flood risk analysis should be incorporated into management plans to mitigate exposure and the severity of flood impacts.

6. Conclusions

As semi-arid areas experience increasingly extreme events on both sides of the hydroclimatic spectrum, "living with the semi-arid region" requires more integrative approaches that embrace the interrelations among these events and their impacts. Some adaptative mechanisms, including crop insurance, climatic and weather forecasting, and the restoration of degraded drylands, can successfully help mitigate the risk of disaster in semi-arid regions due to flooding and heavy rains. Yet adaptative actions typically prioritize drought. Extreme rainfall and flooding, in turn, become addressed through emergency responses. In Ceará, a focus on drought led to unpreparedness at the local and state levels to respond to the extreme events in March and April 2023. Reservoirs spilled over for the first time in over a decade, bringing relief to urban centers and rural communities in precarious water situations.

However, the historically extreme rainfall events also led to flooding and property loss, among other negative consequences, requiring emergency actions. Across semi-arid regions, there is potential to explore NBS as complementary or alternative approaches to current built-infrastructure solutions. The development of NBS together with policies that consider the intertwining dynamics of drought, extreme rainfall, and flooding may lead to more sustainable living with the semi-arid region.

CRediT authorship contribution statement

Cydney K. Seigerman: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Nicolly Santos Leite:** Writing – review & editing, Writing – original draft, Investigation, Formal analysis. **Eduardo Sávio P.R. Martins:** Formal analysis, Writing – original draft, Writing – review & editing. **Donald R. Nelson:** Writing – review & editing, Writing – original draft.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jhydrol.2024.130850.

References

Abdi, M.J., Raffar, N., Zulkafli, Z., Nurulhuda, K., Rehan, B.M., Muharam, F.M., Tangang, F., 2022. Index-based insurance and hydroclimatic risk management in agriculture: A systematic review of index selection and yield-index modelling methods. Int. J. Disaster Risk Reduct. 67, 102653 https://doi.org/10.1016/j.ijdrr.2021.102653.

Abdrabo, K.I., Kantosh, S.A., Saber, M., Sumi, T., Elleithy, D., Habiba, O.M., Alboshy, B., 2022. The Role of Urban Planning and Landscape Tools Concerning Flash flood risk reduction within arid and semiarid regions. Challenges and Advanced Approaches for Disaster Risk Reduction, Wadi Flash Floods, pp. 283–316.

Albuquerque Jr., D.M.D., 2021. A invenção do nordeste e outras artes (1st electronic ed.). Cortez Editora.

Alves da Silva, R.M., 2007. Entre o Combate à Seca e a Convivência com o Semi-Árido: políticas públicas e transição paradigmática. Retrieved from Rev. Econ. Nordeste 38 (3), 466–485. https://www.bnb.gov.br/revista/index.php/ren/article/view/539.

Bezerra, M., 2023. Titular da SDA participa de reunião da Câmara Técnica de Planos de Convivência com o Semiárido. Secretária do Desenvolvimento Agrário, Governo do Ceará https://www.sda.ce.gov.br/2023/01/27/titular-da-sda-participa-de-reuniao-da-camara-tecnica-de-planos-de-convivencia-com-o-semiarido/.

Brazil, 2002. Law No. 10.420, 11 Abril 2002. Diário Oficial da União, Brasília, DF.

Brazil, 2010. Decree No. 7.257, 4 August 2010. Diário Oficial da União, Brasília, DF.

Brazil, 2020. Law No. 14.066, 30 September 2020. Diário Oficial da União, Brasília, DF.

Bretan, E., Engle, N.L., 2017. Drought Preparedness Policies and Climate Change Adaptation and Resilience Measures in Brazil: An Institutional Change Assessment. In: Uitto, J.I., Puri, J., van den Berg, R.D. (Eds.), Evaluating Climate Change Action for Sustainable Development. Springer International Publishing, Cham, pp. 305–326.

Campos, J.N.B., 2014. Secas e políticas públicas no semiárido: ideias, pensadores e períodos. Estudos Avançados 28.

Carvalho, P.N., Finger, D.C., Masi, F., et al., 2022. Nature-based solutions addressing the water-energy-food nexus: Review of theoretical concepts and urban case studies. J. Cleaner Prod. 338, 130652. https://doi.org/10.1016/j.jclepro.2022.130652.

Ceará, 2023. Law No. 18.331. Dispõe Sobre Ações e Políticas Públicas Estaduais Para o Enfrentamento de Situação de Emergência ou de Estado de Calamidade Pública Declaradas Em Municípios do Estado, segundo o Procedimento da Lei Federal N.° 12.608, de 10 de Abril de 2012. Diário Oficial do Estado do Ceará. Série 3. No. 058.

CEDEC- Coordenadoria Geral de Defesa Civil. (2023). Registros de situações anormais (emergência ou calamidade pública) no Ceará decretadas e homologadas ou reconhecidas desde 2007. https://docs.google.com/spreadsheets/d/1eILGgKelzSfKVWeV2hSbYksGJBn_BE-U7-qvG_lluig/edit#gid=634407400. [Accessed 15 April 2023].

Ceglar, A., Toreti, A., 2021. Seasonal climate forecast can inform the European agricultural sector well in advance of harvesting. Npj Clim. Atmos. Sci. 4 (1), 42. https://doi.org/10.1038/s41612-021-00198-3.

Chausson, A., Turner, B., Seddon, D., Chabaneix, N., Girardin, C.A.J., Kapos, V., Seddon, N., 2020. Mapping the effectiveness of nature-based solutions for climate change adaptation. Glob. Chang. Biol. 26 (11), 6134–6155. https://doi.org/10.1111/gcb.15310.

Comin, A.N., Justino, F., Pezzi, L., et al., 2021. Extreme rainfall event in the Northeast coast of Brazil: a numerical sensitivity study. Meteorol Atmos Phys 133, 141–162. https://doi.org/10.1007/s00703-020-00747-0.

Coughlan de Perez, E., Stephens, E., Bischiniotis, K., van Aalst, M., van den Hurk, B., Mason, S., Pappenberger, F., 2017. Should seasonal rainfall forecasts be used for flood preparedness? Hydrol. Earth Syst. Sci. 21 (9), 4517–4524. https://doi.org/10.5194/hess-21-4517-2017.

Cuny, F.C., 1991. Living with floods: Alternatives for riverine flood mitigation. Land Use Policy 8 (4), 331–342. https://doi.org/10.1016/0264-8377(91)90023-C.

D'Alisa, G., Kallis, G., 2016. A political ecology of maladaptation: Insights from a Gramscian theory of the State. Glob. Environ. Change 38, 230–242. https://doi.org/10.1016/j.gloenvcha.2016.03.006.

de Oliveira, P.T., Silva, C.M.S.E., Lima, L.C., 2014. Linear trend of occurrence and intensity of heavy rainfall events on Northeast Brazil. Atmos. Sci. Lett. 15 (3), 172–177. https://doi.org/10.1002/asl2.484.

Escada, P., Coelho, C.A.S., Taddei, R., Dessai, S., Cavalcanti, I.F.A., Donato, R., Moscati, M.C.L., 2021. Climate services in Brazil: Past, present, and future perspectives. Clim. Serv. 24, 100276 https://doi.org/10.1016/j.cliser.2021.100276.

Escolano-Sánchez, F., Fernández-Serrano, R., 2015. Hazards caused by uncontrolled vegetation and inadequate maintenance practice in earth dams. Tecnología y Ciencias Del Agua 6 (6), 137–144.

Falcão, L., 2023. 200 mil agricultores familiares no Ceará serão apoiados com o Garantia Safra 2022/2023. Ematerce. https://www.ematerce.ce.gov.br/2023/02/10/200-mil-agricultores-familiares-no-ceara-serao-apoiados-com-o-garantia-safra-2022-2023/.

Farias Neto, J., 2019. Avaliação da governança participativa desenvolvida nos municípios de Piquet Carneiro e Quixeramobim, na implementação do plano piloto agropecuário municipal de preparação e resposta as secas do Ceará (Masters Dissertation). Universidade Federal do Ceará (UFC). Fortaleza. 220 pp. https://siduece.uece.br/siduece/trabalhoAcademicoPublico.jsf?id=94053.

Ferreira, A.G., Mello, N.G.D.S., 2005. Principais Sistemas Atmosféricos Atuantes Sobre a Região Nordeste do Brasil e a Influência dos Oceanos Pacífico e Atlântico no Clima da Região. Rev. Bras. Climatol. 1, 15–28. https://doi.org/10.5380/abclima.v1i1.25215.

Ferreira, C.S., Mourato, S., Kasanin-Grubin, M., Ferreira, J.D.A., Destouni, G., Kalantari, Z., 2020. Effectiveness of nature-based solutions in mitigating flood hazard in a mediterranean peri-urban catchment. Water 12 (10). https://doi.org/10.3390/w12102893.

FUNCEME – Fundação Cearense de Meteorologia e Recursos Hídricos. (2021). Mapeamento das barragens dos pequenos reservatórios d'água situados no Estado do Ceará.

Geris, J., Comte, J.-C., Franchi, F., Petros, A.K., Tirivarombo, S., Selepeng, A.T., Villholth, K.G., 2022. Surface water-groundwater interactions and local land use control water quality impacts of extreme rainfall and flooding in a vulnerable semi-arid region of Sub-Saharan Africa. J. Hydrol. 609, 127834 https://doi.org/10.1016/j.jhydrol.2022.127834.

Glover, L., Granberg, M., 2021. The Politics of Maladaptation. Climate 9 (5). https://doi.org/10.3390/cli9050069.

Gomes, H.B., Ambrizzi, T., Herdies, D.L., Hodges, K., Pontes da Silva, B.F., 2015. Easterly wave disturbances over Northeast Brazil: an observational analysis. Adv. Meteorol. 2015, 176238 https://doi.org/10.1155/2015/176238.

Gouvea, R., Campos, C., Menezes, J., Moreira, G., 2018. Análise de frequência de precipitaÇão e caracterizaÇão de anos secos e chuvosos para a Bacia do Rio Itajaí. Revista Brasileira de Climatologia 22, 309–323. https://doi.org/10.5380/abclima.v22i0.55276.

Governo do Estado do Ceará, 2015. Plano Estadual de Convivência com a Seca: Ações Emergenciais e Estruturantes [State Plan for Coping with Drought: Emergency and Structural Actions]. Fortaleza. 96 pp. https://www.ipece.ce.gov.br/wp-content/uploads/sites/45/2015/02/Plano_Convivencia_com_a_Seca_02_03_2015.pdf.

Grupo de Contingência, 2023. Boletim Integrado de Ações de Apoio aos Cearenses Afetados pelas Chuvas. Governo do Ceará. https://www.ceara.gov.br/2023/04/24/boletim-integrado-de-acoes-de-apoio-aos-cearenses-afetados-pelas-chuvas/ [Accessed 15 May 2023].

Gutiérrez, A.P.A., Engle, N.L., De Nys, E., Molejón, C., Martins, E.S., 2014. Drought preparedness in Brazil. Weather Clim. Extremes 3, 95–106. https://doi.org/10.1016/j.wace.2013.12.001.

Hastenrath, S., Greischar, L., 1993. Further Work on the Prediction of Northeast Brazil Rainfall Anomalies. J. Clim. 6 (4), 743–758. https://doi.org/10.1175/1520-0442(1993)006<0743:FWOTPO>2.0.CO;2.

Hastenrath, S., Heller, L., 1977. Dynamics of climatic hazards in northeast Brazil. Q. J. r. Meterol. Soc. 103 (435), 77–92. https://doi.org/10.1002/qj.49710343505.

Hooke, J.M., 2019. Extreme sediment fluxes in a dryland flash flood. Sci Rep 9, 1686. https://doi.org/10.1038/s41598-019-38537-3.

IBGE - Instituto Brasileiro de Geografia e Estatística, 2023. Portal Cidades. https://cidades.ibge.gov.br/.

IPECE - Instituto de Pesquisa e Estratégia Econômica do Ceará & SEPLAG - Secretaria do Planejamento e Gestão. (2022). Índice Municipal de Alerta (IMA): Um Instrumento para Orientações Preventivas Sobre as Adversidades Climáticas. Fortaleza: Estado do Ceará. https://www.ipece.ce.gov.br/wp-content/uploads/sites/45/2022/10/IMA_2022.pdf.

IUCN - International Union for Conservation of Nature. (2017). *Nature-based solutions to disasters*. IUCN Issue Briefs. https://www.iucn.org/resources/issues-brief/nature-based-solutions-disasters [Accessed 20 April 2023].

Kayano, M.T., Capistrano, V.B., 2014. How the Atlantic multidecadal oscillation (AMO) modifies the ENSO influence on the South American rainfall. Int. J. Climatol. 34 (1), 162–178. https://doi.org/10.1002/joc.3674.

Lemos, M.C., Finan, T.J., Fox, R.W., Nelson, D.R., Tucker, J., 2002. The use of seasonal climate forecasting in policymaking: lessons from Northeast Brazil. Clim. Chang. 55 (4), 479–507. https://doi.org/10.1023/A:1020785826029.

Lemos, M.C., Puga, B.P., Formiga-Johnsson, R.M., Seigerman, C.K., 2020. Building on adaptive capacity to extreme events in Brazil: water reform, participation, and climate information across four river basins. Reg. Environ. Chang. 20 (2), 53. https://doi.org/10.1007/s10113-020-01636-3.

Lindoso, D.P., Eiró, F., Bursztyn, M., Rodrigues-Filho, S., Nasuti, S., 2018. Harvesting water for living with drought: insights from the brazilian human coexistence with semi-aridity approach towards achieving the sustainable development goals. Sustainability 10 (3). https://doi.org/10.3390/su10030622.

Liu, H., Lei, T.W., Zhao, J., Yuan, C.P., Fan, Y.T., Qu, L.Q., 2011. Effects of rainfall intensity and antecedent soil water content on soil infiltrability under rainfall conditions using the run off-on-out method. J. Hydrol. 396, 24–32. https://doi.org/10.1016/j.jhydrol.2010.10.028.

Marengo, J.A., Torres, R.R., Alves, L.M., 2017. Drought in Northeast Brazil—past, present, and future. Theor. Appl. Climatol. 129 (3), 1189–1200. https://doi.org/10.1007/s00704-016-1840-8.

Marengo, J.A., Galdos, M.V., Challinor, A., Cunha, A.P., Marin, F.R., Vianna, M.D.S., Bender, F., 2022. Drought in Northeast Brazil: A review of agricultural and policy adaptation options for food security. Clim. Resil. Sustain. 1 (1), e17.

Martins, E.S.P.R., Coelho, C.A.S., Haarsma, R., Otto, F.E.L., King, A.D., Jan van Oldenborgh, G., Cullen, H., 2018. A multimethod attribution analysis of the prolonged northeast brazil hydrometeorological drought (2012–16). Bull. Am. Meteorol. Soc. 99 (1), S65–S69. https://doi.org/10.1175/BAMS-D-17-0102.1.

Martins, E.S.P.R., Magalhães, A.R., 2015. A seca de 2012–2015 no Nordeste e seus impactos. Rev. Parcerias Estratégicas 20 (41), 107–128.

Martins, E.S.P.R., Vasconcelos Jr, F.D.C., 2017. O clima da Região Nordeste entre 2009 e 2017: monitoramento e previsão. Rev. Parcerias Estratégicas 22, 17–40.

Martins, E.S.P.R., Magalhães, A.R., Fontenele, D., 2017a. A seca plurianual de 2010–2017 no Nordeste e seus impactos. Rev. Parcerias Estratégicas 22, 17–40.

McGreevy, J.R., Adrien, E., 2023. Second impact syndrome: The influence of climate change and increased disaster frequency on livelihoods and adaptive capacity in rural Haiti. Int. J. Disaster Risk Reduct. 85, 103509 https://doi.org/10.1016/j.ijdrr.2022.103509.

Medeiros, F.J.D., Prestrelo de Oliveira, C., Avila-Diaz, A., 2022. Evaluation of extreme precipitation climate indices and their projected changes for Brazil: From CMIP3 to CMIP6. Weather Clim. Extremes 38, 100511. https://doi.org/10.1016/j.wace.2022.100511.

Ministério da Agricultura, Pecuária e Abastecimento, 2023. Resolution 94, 30 June 2023. Diário Oficial da União, Brasília, DF.

Molle, F., Cadier, E., 1992. Manual do pequeno açude. SUDENE-DPG-PRN-DPP-APR, Recife, 528 pp.

Monitor de Secas, 2023a. Mapas. https://monitordesecas.ana.gov.br/mapa.

Monitor de Secas, 2023b. Tabela de classificação de severidade da seca. https://monitordesecas.ana.gov.br/tabela-de-classificacao.

Monteiro, R.F., 2020. Um monumento ao sertão? Expectativas diversas em torno da construção do açude Cedro, em Quixadá-CE (1884–1906). Rev. Mundos Trabalho 12, 1–15. https://doi.org/10.5007/1984-9222.2020.e75108.

Moudi Pascal, I., Kammalac Jores, T., Talib, J., Appolinaire, V.D., Hirons, L., Christian, N., Ngaryamgaye, S., 2023. Strengthening weather forecast and dissemination capabilities in Central Africa: Case assessment of intense flooding in January 2020. Clim. Serv. 32, 100411 https://doi.org/10.1016/j.cliser.2023.100411.

Mudashiru, R.B., Sabtu, N., Abustan, I., Balogun, W., 2021. Flood hazard mapping methods: A review. J. Hydrol. 603, 126846 https://doi.org/10.1016/j.jhydrol.2021.126846.

Nelson, D.R., Finan, T.J., 2009. Praying for drought: persistent vulnerability and the politics of Patronage in Ceará, Northeast Brazil. *Am. Anthropol.* 111 (3), 302–316. https://doi.org/10.1111/j.1548-1433.2009.01134.x.

Panthou, G., Lebel, T., Vischel, T., Quantin, G., Sane, Y., Ba, A., Diopkane, M., 2018. Rainfall intensification in tropical semi-arid regions: the Sahelian case. Environ. Res. Lett. 13 (6), 064013 https://doi.org/10.1088/1748-9326/aac334.

Pisaniello, J.D., Dam, T.T., Tingey-Holyoak, J.L., 2015. International small dam safety assurance policy benchmarks to avoid dam failure flood disasters in developing countries. J. Hydrol. 531, 1141–1153. https://doi.org/10.1016/j.jhydrol.2015.09.077.

Pontes Filho, J.D., Souza Filho, F.D., Martins, E.S., Studart, T.M., 2020. Copula-based multivariate frequency analysis of the 2012–2018 drought in Northeast Brazil. Water 12 (3). https://doi.org/10.3390/w12030834.

Quixeramobim News, 2022. Prefeito de Milhã cria maior programa de açudagem da região [Accessed 15 April 2023] Quixeramobim News. https://quixeramobimnews.com.br/prefeito-de-milha-cria-maior-programa-de-acudagem-da-regiao/.

Rabelo, U.P., Costa, A.C., Dietrich, J., Fallah-Mehdipour, E., Van Oel, P., Lima Neto, I.E., 2022. Impact of dense networks of reservoirs on streamflows at dryland catchments. Sustainability 14 (21). https://doi.org/10.3390/su142114117.

Rahman, M.T., Aldosary, A.S., Nahiduzzaman, K.M., Reza, I., 2016. Vulnerability of flash flooding in Riyadh, Saudi Arabia. *Natural Hazards* 84 (3), 1807–1830. https://doi.org/10.1007/s11069-016-2521-8.

Rodrigues, R., 2020. Estudo inédito estima a existência de quase 90 mil barragens no Ceará. Diário Do Nordeste. https://diariodonordeste.verdesmares.com.br/regiao/estudo-inedito-estima-a-existencia-de-quase-90-mil-barragens-no-ce-1.2969982.

Sahu, N., Robertson, A.W., Boer, R., Behera, S., DeWitt, D.G., Takara, K., Singh, R.B., 2017. Probabilistic seasonal streamflow forecasts of the Citarum River, Indonesia, based on general circulation models. Stoch. Environ Res. Risk Assess. 31 (7), 1747–1758. https://doi.org/10.1007/s00477-016-1297-4.

SDA - Secretaria de Desenvolvimento Agrário, 2020. Plano Agropecuário Municipal de Preparação e Resposta às Secas (2016–2020): Município Quixeramobim. Fortaleza.

SDA, 2023. O Projeto. https://www.sda.ce.gov.br/projeto-sao-jose-iv/area-abrangencia/.

Seddon, N., Chausson, A., Berry, P., Girardin, C.A.J., Smith, A., Turner, B., 2020. Understanding the value and limits of nature-based solutions to climate change and other global challenges. Philos. Trans. R. Soc., B 375 (1794), 20190120. https://doi.org/10.1098/rstb.2019.0120.

Seigerman, C. K., Basílio, R., Nelson, D. R. Secas entrelaçadas: Uma abordagem integrativa para explorar a sobreposição parcial e as divisões volúveis entre definições, experiências e memórias da seca em Ceará, Brasil. In Memória ambiental e o tempo vivido: Etnografia da duração e coleções de imagens. Porto Alegre: Editora UFRGS, Associação Brasileira de Antropologia.

Seneviratne, S. I., Zhang, X., Adnan, M., Badi, W., Dereczynski, C., Luca, A. D., . . . Zhou, B. (2021). Weather and Climate Extreme Events in a Changing Climate. In V. Masson-Delmotte, P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, & B. Zhou (Eds.), Clim. Chang. 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (pp. 1513-1766). Cambridge, United Kingdom and New York, NY USA: Cambridge University Press.

Silva, T.A., Ferreira, J., Calijuri, M.L., dos Santos, V.J., Alves, S.d.C., Castro, J.D.S., 2021. Efficiency of technologies to live with drought in agricultural development in Brazil's semi-arid regions. J. Arid Environ. 192, 104538 https://doi.org/10.1016/j.jaridenv.2021.104538.

Siqueira, B., Teixeira Nery, J., 2021. Spatial and temporal variability of precipitation concentration in northeastern Brazil. Investigaciones Geográficas 104, e60091. https://doi.org/10.14350/rig.60091.

Souza Filho, F.A., de Carvalho Studart, T.M., Filho, J.D.P., Martins, E.S.P.R., Ayrimoraes, S.R., Pessoa, C.A.P., de Aquino, S.H.S., 2023. Integrated proactive drought management in hydrosystems and cities: building a nine-step participatory planning methodology. Nat. Hazards 115 (3), 2179–2204. https://doi.org/10.1007/s11069-022-05633-z.

Sumi, T., Kantoush, S. A., Saber, M. (Eds.), 2022. Wadi Flash Floods: Challenges and Advanced Approaches for Distaster Risk Reduction. Springer. https://doi.org/10.1007/978-981-16-2904-4.

Taddei, R., 2008. A comunicação social de informações sobre tempo e clima: o ponto de vista do usuário. Boletim SBMET 76–86.

Valadão, C.E.A., Carvalho, L.M.V., Lucio, P.S., Chaves, R.R., 2017. Impacts of the Madden-Julian oscillation on intraseasonal precipitation over Northeast Brazil. Int. J. Climatol. 37 (4), 1859–1884. https://doi.org/10.1002/joc.4818.

Valadares, A., Alves, F., Pereira Silva, S., 2022. O programa Garantia-Safra: Gênese normativa e trajetória de implementaÇão (2002-2021). mercado de trabalho 74, 97–111. https://doi.org/10.38116/bmt74/pf2.

Vasconcelos Jr, F.d.C., Jones, C., Gandu, A.W., 2018. Interannual and Intraseasonal Variations of the Onset and Demise of the Pre-Wet Season and the Wet Season in the Northern Northeast Brazil. Rev. Bras. Meteor. 33, 472–484.

Ward, P.J., de Ruiter, M.C., Mård, J., Schröter, K., Van Loon, A., Veldkamp, T., Wens, M., 2020. The need to integrate flood and drought disaster risk reduction strategies. Water Secur. 11, 100070 https://doi.org/10.1016/j.wasec.2020.100070.

Werren, G., Reynard, E., Lane, S.N., et al., 2016. Flood hazard assessment and mapping in semi-arid piedmont areas: a case study in Beni Mellal. Morocco. Nat Hazards 81, 481–511. https://doi.org/10.1007/s11069-015-2092-0.

Wilhite, D.A., Glantz, M.H., 1985. Understanding the drought phenomenon: the role of definitions. Water Int. 10 (3), 111–120. https://doi.org/10.1080/02508068508686328.

Wilhite, D.A., Knutson, C.L., 2008. Drought management planning: conditions for success. In: López Francos, A. (Ed.), Drought Management: Scientific and Technological Innovations. Zaragoza, CIHEAM, pp. 141–148.

World Bank, 2019. Project Appraisal Document on a Proposed Loan in the Amount of US $ 100 Million to the State of Ceará with the Guarantee of the Federative Republic of

Brazil for the Ceará Rural Sustainable Development and Competitiveness Project Phase II. (Report No. PAD3167). World Bank Group.
Yang, L., Smith, J., 2018. Sensitivity of extreme rainfall to atmospheric moisture content in the arid/semiarid Southwestern United States: implications for probable maximum precipitation estimates. J. Geophys. Res. Atmos. 123 (3), 1638–1656. https://doi.org/10.1002/2017JD027850.
Zhang, J., Yu, Z., Yu, T., Si, J., Feng, Q., Cao, S., 2018. Transforming flash floods into resources in arid China. Land Use Policy 76, 746–753.