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The climate and climatological water balance of Brazilian semi-arid mountainous areas and inland depression

Rebecca Luna Lucena[1], Alíbia Deysi Guedes da Silva[2], Fernanda de Cássia Neves Esteca[3], Emerson Galvani[4]

[1] Universidade Federal do Rio Grande do Norte. Professora Doutora. E-mail: rebecca.luna@ufrn.br
[2] Universidade Federal do Rio Grande do Norte. Mestranda. E-mail: alibiadeysi.prof@gmail.com
[3] Faculdade Metropolitana do Estado de São Paulo. Professora Doutora. E-mail: fernanda.esteca@usp.br
[4] Universidade de São Paulo. Professor Doutor. E-mail: egalvani@usp.br

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Abstract

This research aimed to carry out a comparative climatic analysis between high-altitude areas and those located in the inland depression according to climatic indices of aridity. This analysis chose the following municipalities: the high-altitude Guaramiranga/CE, Campos Sales/CE, Lagoa Nova/RN, Martins/RN, Monteiro/PB, Areia/PB, Triunfo/PE and Garanhuns/PE and the low-altitude Crateús/CE, Sobral/CE, Mossoró/RN, Caicó/RN, São Gonçalo/PB, Patos/PB, Petrolina/PE, and Cabrobó/PE. In order to gather both the climate analysis & its agricultural suitability, it was necessary to apply climatic indices of aridity and water availability for vegetation. The time series spanned from 1981 to 2010 and included precipitation and air temperature data and estimates of potential evapotranspiration. Data were obtained from the Brazilian National Institute of Meteorology. This study found a marked difference between the climatic conditions in elevated areas and those in lower altitudes in the Brazilian semi-arid, especially on water deficit and the prevailing high temperatures in the inland depression. Mountainous areas generally have a more humid climate than the depression due to orographic effects. However, this condition is not the rule due to the influence of other geographical factors of the climate. This study also observed that higher areas have a more climatically favorable conditions for the natural development of vegetation (and, therefore, for potential agricultural activities) than lower areas.

Keywords: High-altitude climates. Climate indices. Aridity indices. Northeastern Brazil.

Introduction

According to Brazilian Atlas of Natural Disasters data (CEPED, 2013), drought is the natural disaster that affects the largest number of people in Brazil. Meteorological and hydrological droughts constitute a common phenomenon in semi-arid areas, which cover about 55 % of the Brazilian Northeast (SÁ; SILVA, 2010). Meteorological drought results from rainfall below the expected amount, whereas hydrological drought (usually a consequence of the former), refers to the insufficiency of water available for established uses (JESUS et al., 2020).

Climatic conditions, pedological characteristics, and economic and social aspects constantly cause water crises and emergencies due to insufficient rainfall in this natural Brazilian domain (AB'SABER, 2003). The Brazilian semi-arid holds high insolation and temperature rates and interannual irregular rainfall (CORREIA et al., 2011). Thus, water deficits predominate in the region, associated with climatic conditions and water management, such as land-use associated with water control (MALVEZZI, 2007).

According to Salimon and Anderson (2018), "currently, the Brazilian Northeast is a semi-arid region prone to droughts, with high variability of rainfall and characterized by xeric shrubs (savannah) and sparse forests of deciduous thorny trees (dry forests)." However, Brazilian semi-arid areas with higher altitudes have lower temperatures and higher relative humidity than the local average due to the effect of altitude/orography (AB'SABER, 2003; SOUZA; OLIVEIRA, 2006).

Such higher areas show milder temperatures because (within the limits of the troposphere) air temperatures linearly decrease with increasing elevation (RAMASWAMY et al., 2017; LUCENA et al., 2022). Several studies have defined this rate of vertical change as the adiabatic gradient of near-surface air temperature (KATTEL et al., 2019). A value of $-0.65°C\ m^{-1}$ (vertical) is generally used to estimate air temperature at higher altitudes. This temperature drop in the troposphere has a rate that can vary based on location and season and its value strongly depends on atmospheric humidity.

Thus, the concepts of moist adiabatic lapse rate (MALR) and dry adiabatic lapse rates (DALR) were defined (SANTOS et al., 2013). For example, the gradient ranges from ~0.4°C/100 m near the surface in humid tropical regions near the equator—MALR—to much higher values (~0.8/100 m – 0.9°C/100 m) in the drier subtropics—DALR (RAMASWAMY et al., 2017). However, in addition to "altitude," attention should be paid to windward and leeward situations, important geographical facts in the capture or not of humidity in elevated semi-arid areas (VIEIRA, 2005; LUCENA et al., 2022). Windward means the slope that directly receives humid winds, whereas leeward, the opposite slope. In other words, the concepts of windward and leeward are associated with the direction of the wind flow, rather than to an exclusive characteristic of the relief (BARATTO et al., 2022).

Therefore, these high-altitude areas can be more or less humid depending on their position/orientation in relation to the winds and moister air masses from the Atlantic Ocean. They have been studied and require special attention as (due to their particularities) they are considered areas of prominence, especially for the practiced agricultural activities, such as subsistence polyculture (GOIS et al., 2019), and their tourism potential, particularly ecotourism (BARBOSA et al., 2016; NASCIMENTO et al., 2022).

In the scenario of agricultural activities, the semi-arid has historically had problems with rainfed agriculture, i.e., the one directly relying on rainfall (LEMOS; SANTIAGO, 2020). This problem mainly stems from the large interannual and intra-seasonal rainfall variability, reflected in anomalous precipitations between years and the alteration of drought cycles and seasonal rainfall (lasting from 10 to 90 days), respectively (MITTERSTEIN; SEVERO, 2008; SOUZA et al., 2017). Associated with rainfall variability, high monthly and annual values of insolation, temperature, and potential evapotranspiration often occur, generating water deficits (GOMES; ZANELLA, 2023). Thus, spatializing the climate classification based on water balance produces important information for water and agricultural management in the region.

The practical importance of this research lies in the critical need to understand the climatic variabilities across the topographic zones of the Brazilian semi-arid region since they directly impact local water and agricultural management. By identifying the climatic differences between mountainous areas and inland depression, this research can provide valuable information for the development of more effective adaptive strategies. Results can also contribute to informed decision-making to mitigate drought impacts, especially given the increasing climate variability.

In this context, this research aimed to carry out a comparative climatic analysis between high-altitude areas and inland depression areas according to climatic indices of aridity. For this, four municipalities were chosen for each of the states mentioned: Ceará, Rio Grande do Norte, Paraíba and Pernambuco—two in the mountainous and two in the depression areas. The application of climate indices of aridity aimed to evaluate the climatic disparities between these two areas (higher and lower), contributing to a deeper understanding of the challenges faced due to droughts.

Material and methods

Studied area

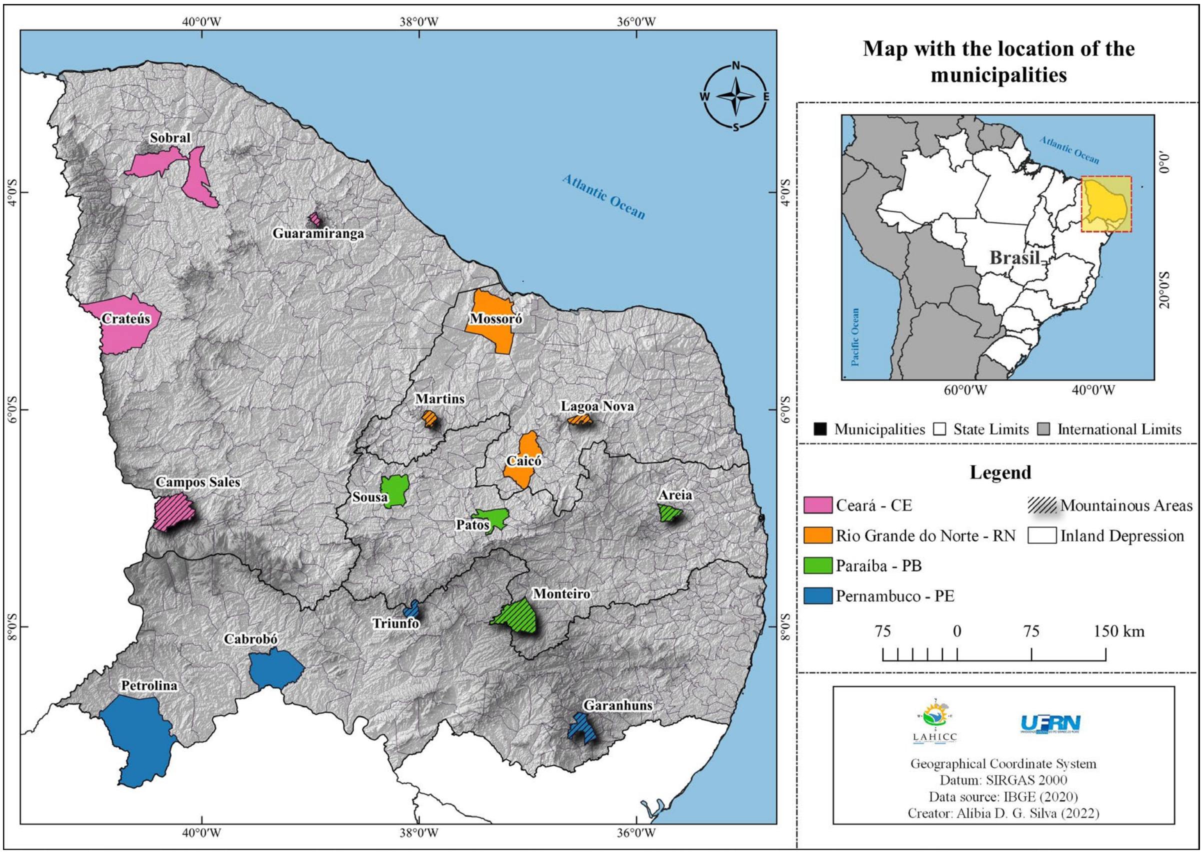
The states of Ceará, Rio Grande do Norte, Paraíba, and Pernambuco—which make up the northern section of the Brazilian Northeast—comprise a large number of municipalities within the semi-arid polygon delimited by the Superintendence for the Development of Brazilian Northeast (2017). Thus, these states constantly go through complications related to water scarcity, which has historically generated several problems for society, including the lack of sufficient good-quality water for its population and agricultural losses. In this context, 16 municipalities were chosen for this research, four for each of the aforementioned states. The map with their location (prepared on QGIS Las Palmas) is shown in Figure 1 and their altitude and geographic coordinates, in Table 1.

From each state, two municipalities with an elevation above 500 m in what is known as "mountain swamps" and two with elevations below 400 m in the lower areas of the "inland depression" were selected (AB'SABER, 2003; Table 1).

Data collection and climate index application

The following variables were chosen to compare the higher and lower altitude areas in the Brazilian semi-arid: precipitation, average air temperature, and potential evapotranspiration. The monthly and annual values of the Brazilian climatological normals (CLINO), available on the website of the Brazilian National Institute of Meteorology (2022), were used. For the municipalities of Lagoa Nova and Martins (both in Rio Grande do Norte State), data were collected from the atmospheric sciences department at the Universidade Federal de Campina Grande (DCA, 2022) since both lack a meteorological station.

Figure 1. Map with the location of the municipalities considered for this study



Source: prepared by the authors.

Table 1. States, altitude, and geographic coordinates of the municipalities comprising the studied area

State	Municipality	Geographical coordinates	Altitude (m)
CE	Crateús	5° 17’ S ; 40° 67’ W	296
CE	Sobral	3° 73’ S ; 40° 33’ W	109
CE	Campos Sales	7° 00’ S ; 40° 38’ W	583
CE	Guaramiranga	4° 28’ S ; 39° 00’ W	870
RN	Mossoró	5° 20’ S ; 37° 30’ W	38
RN	Caicó	6° 47’ S ; 37° 08’ W	169
RN	Martins*	6° 08’ S ; 36° 91’ W	645
RN	Lagoa Nova*	6° 09’ S ; 36° 46’ W	700
PB	São Gonçalo-Sousa	6° 75’ S ; 38° 22’ W	233
PB	Patos	7° 02’ S ; 37° 27’ W	244
PB	Monteiro	7° 88’ S ; 37° 07’ W	603
PB	Areia	6° 97’ S ; 35° 68’ W	547
PE	Petrolina	9° 38’ S ; 40° 48’ W	370
PE	Cabrobó	8° 50’ S ; 39° 31’ W	337
PE	Triunfo	7° 82’ S ; 38° 12’ W	1105
PE	Garanhuns	8° 88’ S ; 36° 52’ W	822

Source: INMET, 2023; *DCA, 2022.

Overall, three aridity indices were applied to the obtained climatic data: the climatic water balance (CWB) proposed by Thornthwaite and Matter (1955); the annual aridity index (AI), adopted by the United Nations Environment Programme – UNEP (2022); and the xerothermic index (also known as Bagnouls–Gaussen index), proposed by Gaussen and Bagnouls (1962).

CWB was adapted to a pivot table by a macro (Excel) from Rolim et al. (1998) in which water deficit, surplus, withdrawal, and replacement were calculated monthly from data on precipitation, air temperature, and potential evapotranspiration. Results were generated as water balance tables and graphs. The table model for each analyzed municipality can be accessed in studies such as Rolim et al. (1998) and Portilho et al. (2011). The graphs were generated on Excel and are included in the Results section. The adopted available water capacity totaled 100 mm, as in several studies on the Brazilian semi-arid, such as Silva et al. (2017), Costa et al. (2019), Silva et al. (2020), Silva et al. (2022a), and Silva et al. (2022b).

Then, the aridity index (AI)—adopted by the UNEP (CONTI, 2008; UNEP, 2022) (Equation 1)—was calculated and its results, arranged in different climate classes (Table 2):

$$AI = P/PET \qquad \text{(Equation 1)}$$

In which total annual precipitation values are represented by *P* and the annual potential evapotranspiration values by *PET*.

Finally, the xerothermic index, proposed by Bagnouls and Gaussen (1962) *apud* Nimer et al. (1967) was applied using Equation 2, and its results, arranged in climatic classes, as shown in Table 3.

$$Ia = P \leq 2*T \qquad \text{(Equation 2)}$$

In which *P* represents monthly precipitation values and *T*, monthly average air temperature values.

Table 2. Climate classification by aridity index

Value of AI	Climate Classes
<0.05	Hyper-arid
0.05<0.20	Arid
0.21<0.50	Semi-arid
0.51<0.65	Dry sub-humid
>0.65	Humid sub-humid

Source: UNEP, 2022

Table 3. Climate classification by the xerothermic index

Number of dry months	Climate type
12	Desert
9-11	Subdesert
7-8	Harsh dry
5-6	Medium dry
3–4	Mild dry
1-2	Transitional climate
0	Humid

Source: Torres and Machado, 2011.

The maps were generated on QGIS Las Palmas, and results were shown by inverse square distance weighting interpolation, according to Gardiman-Junior et al. (2012).

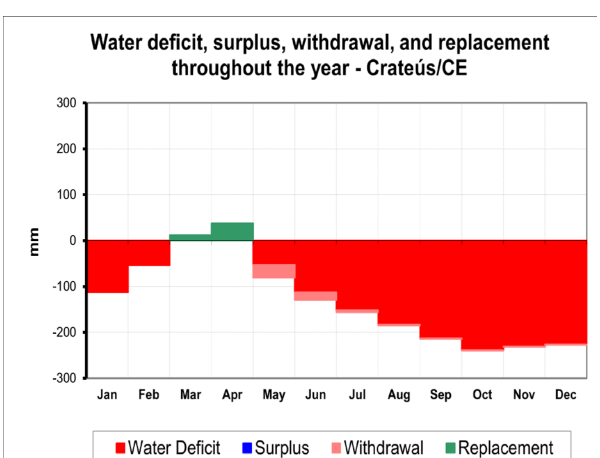
Results and discussion

Climatic water balance for the inland depression

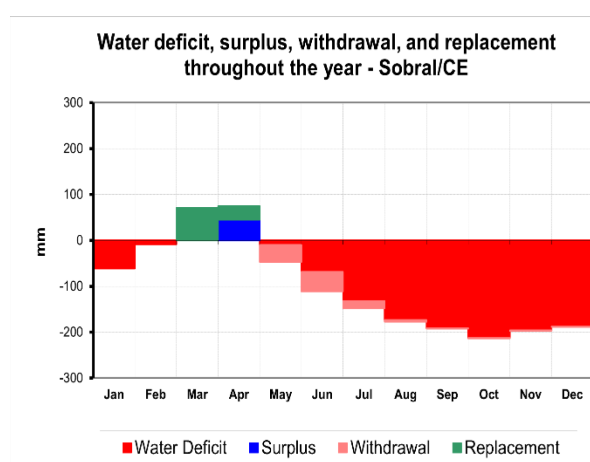
CWB analysis according to the methodology in Rolim et al. (1998) describe marked patterns in the climatic conditions of the studied municipalities. Figures 2, 3, 4, and 5 (A and B) offer a panoramic view of the results, showing that practically all months of the year and analyzed municipalities have a lower precipitation than evapotranspiration, promoting water deficit in almost the whole region, except in Sobral/CE and São Gonçalo-Sousa/PB. The annual rainfall curve is very similar between the municipalities (Figures 2 to 5), with a rainy season in the first semester of the year and a dry season in the latter semester, corroborating several studies on the semi-arid region (LUCENA et al., 2013; REBOITA et al., 2016; BRITO et al., 2017; SILVA et al., 2018). Thus, water replacement (if it occurs) always happens during the rainy season (restricted to the first months of the year), as in Figures 2 (A and B), 3 (A), and 4 (A).

Sobral/CE and São Gonçalo/PB were the only municipalities with water surplus among those selected to represent the inland depression. Crateús/CE and Mossoró/RN show water replacement in the rainiest months: March and April. According to the monthly water balance,

Figure 2. Water balance for municipalities in the inland depression (low altitude) – Ceará



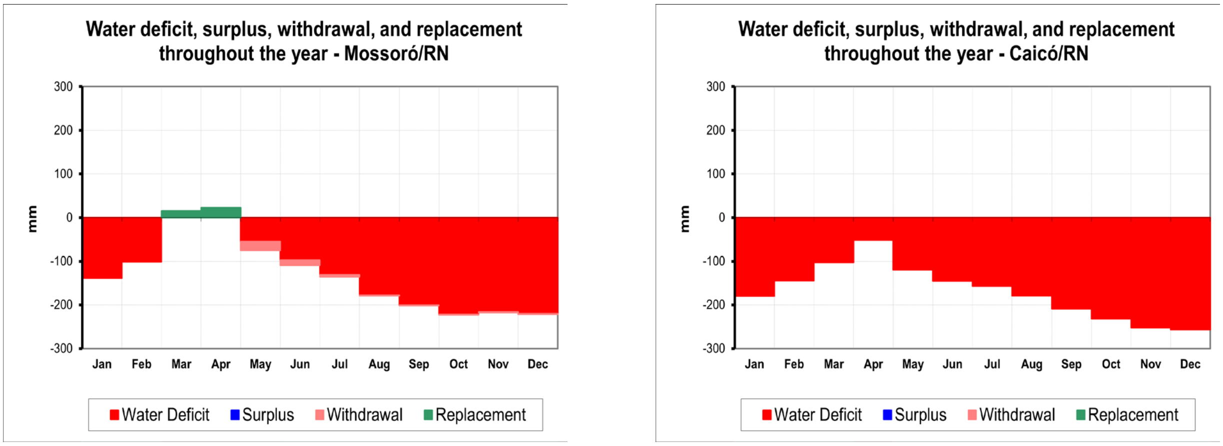
A



B

Source: prepared by the authors.

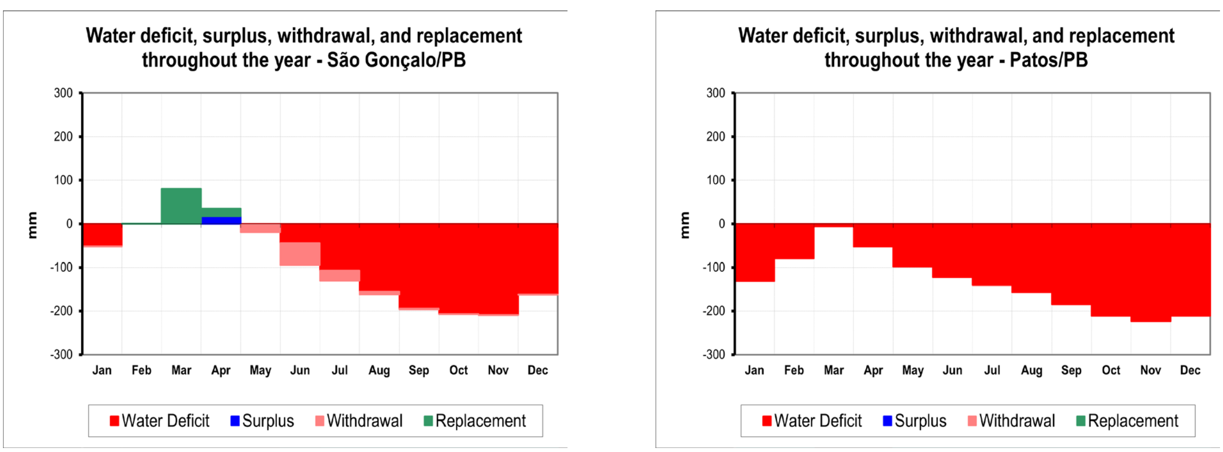
Figure 3. Water balance for municipalities in the inland depression (low altitude) – Rio Grande do Norte



A B

Source: prepared by the authors.

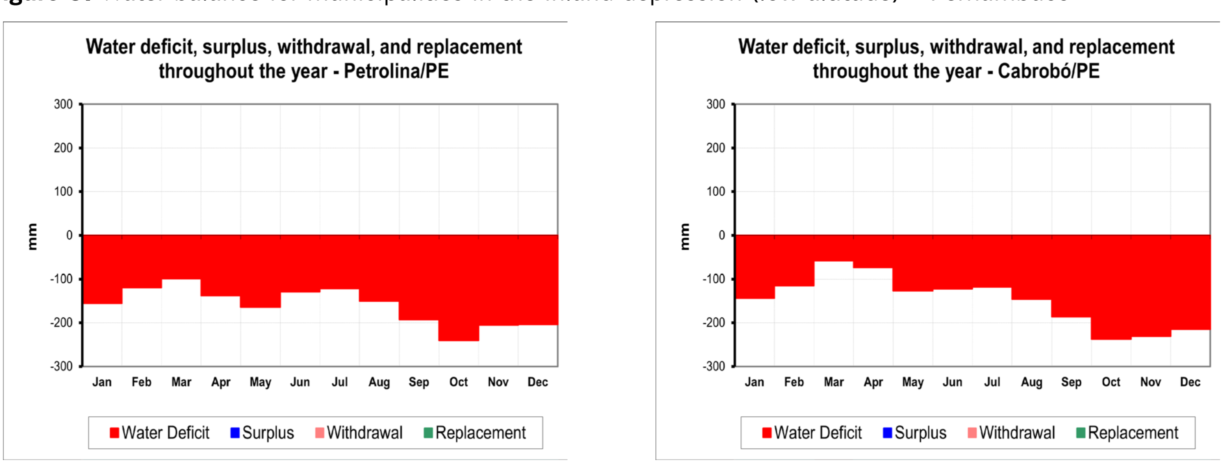
Figure 4. Water balance for municipalities in the inland depression (low altitude) – Paraíba



A B

Source: prepared by the authors.

Figure 5. Water balance for municipalities in the inland depression (low altitude) – Pernambuco



A B

Source: prepared by the authors.

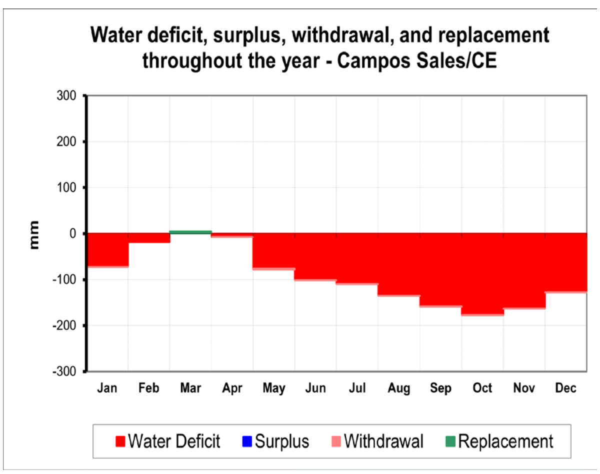
the most critical municipalities are Caicó/RN, Patos/PB, Petrolina/PE, and Cabrobó/PE due to the absence of water replacement or surplus in any month of the year in the considered period.

Climatic water balance for elevated areas

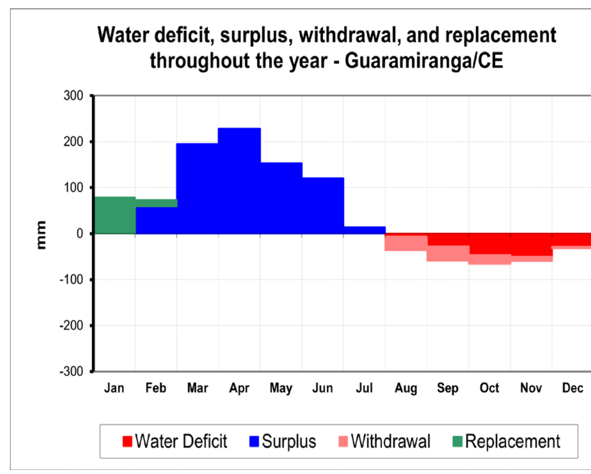
The municipalities in the Brazilian semi-arid mountains, plateaus, and *chapadas* [mesa-like formations within mountain ranges] show greater water replacement and surplus, indicating greater water availability in the soil-plant system according to the Thornthwaite-Matter climate classification (Figures 6 to 9); except for Campos Sales/CE and Monteiro/PB, which have a climatic water balance similar to that in the inland depression.

According to the graphs above, most high-altitude municipalities show water replacement and surplus, a climatic condition that indicates periods susceptible to agriculture that dispenses with irrigation (depending on the crop) (PEREIRA et al., 2002). Guaramiranga/CE, Areia/PB, and Triunfo/PE constitute true semi-arid "oases," with high rainfall and at least six months of

Figure 6. Water balance for municipalities in elevated areas (mountains, plateaus, *chapadas*) – Ceará



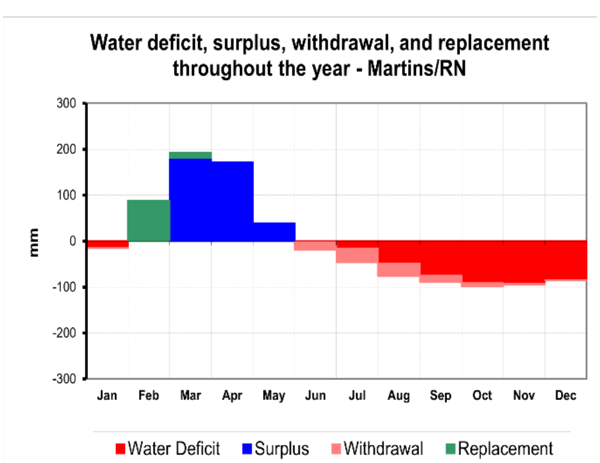
A



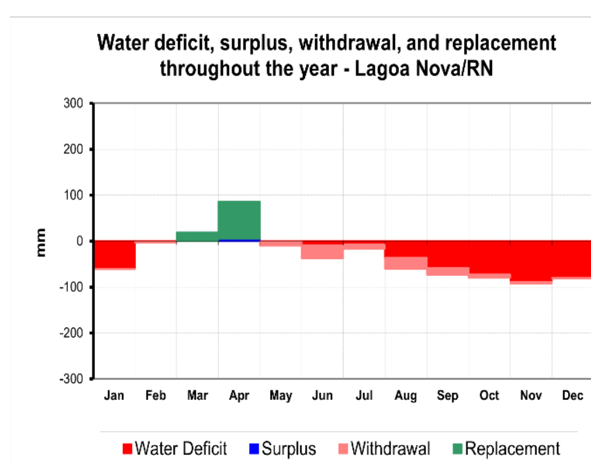
B

Source: prepared by the authors.

Figure 7. Water balance for municipalities in elevated areas (mountains, plateaus, *chapadas*) – Rio Grande do Norte



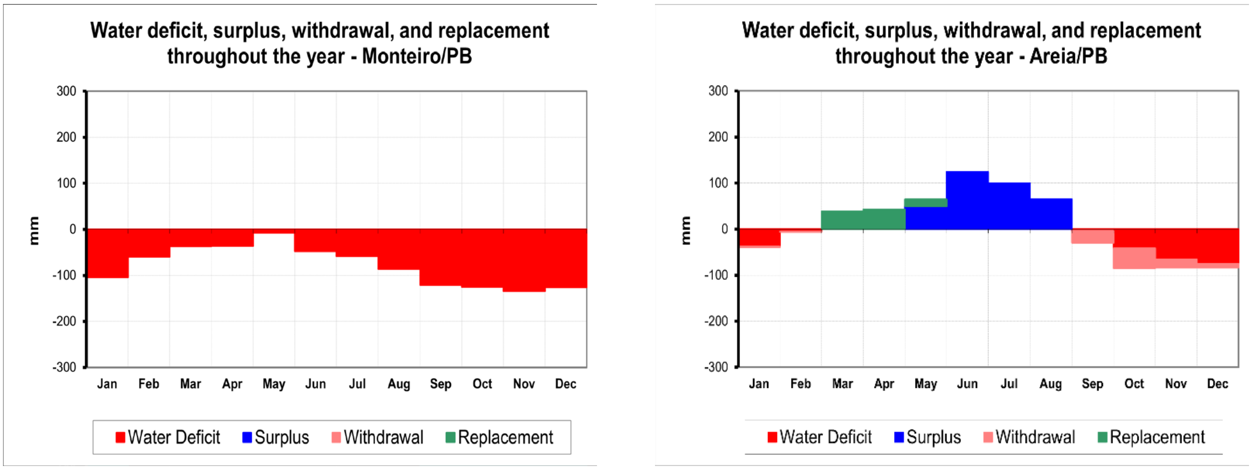
A



B

Source: prepared by the authors.

Figure 8. Water balance for municipalities in elevated areas (mountains, plateaus, *chapadas*) – Paraíba

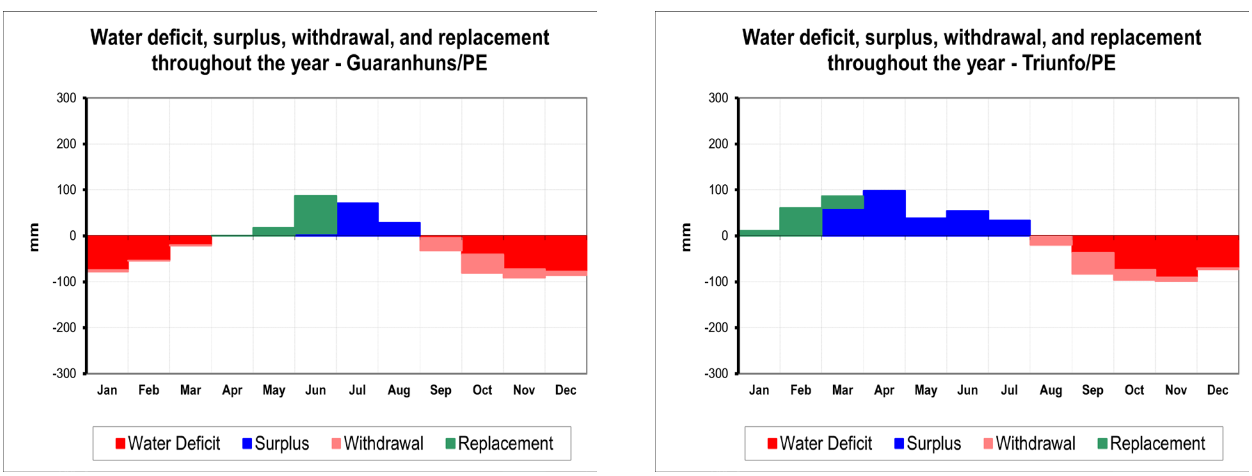


A

B

Source: prepared by the authors.

Figure 9. Water balance for municipalities in elevated areas (mountains, plateaus, *chapadas*) – Pernambuco



A

B

Source: prepared by the authors.

water replacement, generating their surplus. Novais (2023), using temperature, precipitation, and evapotranspiration data, classified these municipalities as having an equatorial mildly semi-dry climate. Altitude generates a particular thermal condition that, in turn, can provide greater humidity, except in Campos Sales/CE (Figure 6A) and Monteiro/PB (Figure 8A), in which altitude apparently was not the most important control in the CWB result. Other geographical factors of the climate should also be considered, such as underexposure to moist winds from the ocean.

Climate classifications applied to aridity

Table 4 shows the municipalities, the elevation of the meteorological station at each municipality—in which blue represents elevated areas (500–1100 m) and orange, low areas (30-400 m); the climatic type according to the Thornthwaite-Matter climatic classification; and type according to the Gaussen climatic classification. Shades of orange refer to arid climates and shades of blue, to humid climates.

The results in Table 4 highlight Campos Sales/CE, which has a semi-arid climate with

Table 4. Location, altitude, and climatic type of municipalities in the Brazilian semi-arid region

Municipality/FU	Geoenvironment	Altitude	Climate type*	Climate type**
Crateús/CE	Depression	296 m	Semi-arid	Harsh dry
Sobral/CE	Depression	109 m	Semi-arid	Harsh dry
Campos Sales/CE	Mountains/Plateaus	583 m	Semi-arid	Harsh dry
Guaramiranga/CE	Mountains/Plateaus	870 m	Humid	Mild dry
Mossoró/RN	Depression	38 m	Semi-arid	Harsh dry
Caicó/RN	Depression	169 m	Semi-arid	Harsh dry
Martins/RN	Mountains/Plateaus	645 m	Humid	Medium dry
Lagoa Nova/RN	Mountains/Plateaus	700 m	Humid	Harsh dry
São Gonçalo-Sousa/PB	Depression	233 m	Semi-arid	Medium dry
Patos/PB	Depression	244 m	Semi-arid	Harsh dry
Monteiro/PB	Mountains/Plateaus	603 m	Semi-arid	Medium dry
Areia/PB	Mountains/Plateaus	547 m	Humid	Mild dry
Petrolina/PE	Depression	370 m	Arid	Subdesert
Cabrobó/PE	Depression	337 m	Semi-arid	Harsh dry
Triunfo/PE	Mountains/Plateaus	1105 m	Humid	Mild dry
Garanhuns/PE	Mountains/Plateaus	822 m	Humid	Mild dry

*Thornthwaite aridity index; **Gaussen's xerothermic index, number of dry months.

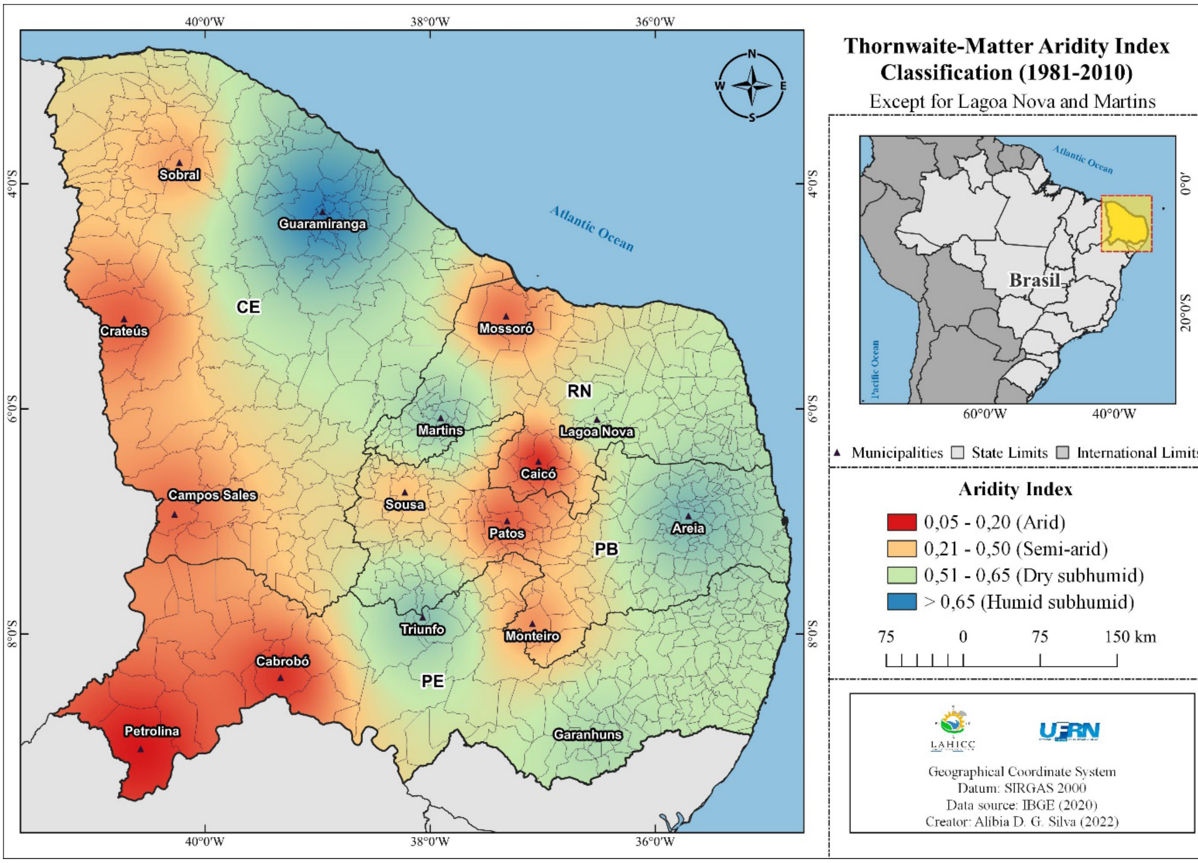
Source: prepared by the authors.

severe droughts despite its high elevation, indicating that altitude alone fails to favor the specific humidity in elevated areas and that it may be under leeward conditions. Lagoa Nova/RN showed a humid climate according to the Thornthwaite climate classification but due to its seven dry months in the year, this study classified it as under severe droughts, according to Gaussen's classification. Petrolina/PE holds the highest degree of aridity according to CWB and the aridity (arid), and the dry-month indices (subdesert). Novais' (2023) proposal for a climate classification based on the number of dry months and total annual precipitation found an "arid" climatic domain between the states of Pernambuco and Bahia and in areas to the leeward of the Borborema plateau, highlighting Petrolina (PE), Cabaceiras (PB), and Angicos (RN) as the main municipalities within this domain in the northern Northeast. Of the high-altitude municipalities, applying all indices in this study showed Guaramiranga/CE, Areia/PB, Triunfo/PE and Garanhuns/PE as the most humid. Martins/RN, Lagoa Nova/RN, Monteiro/PB, and São Gonçalo-Sousa/PB diverge somewhat according to the applied climatic classifications (Table 4).

Finally, Figure 10 shows a map with the annual aridity index (Thornthwaite), spatializing semi-aridity in the municipalities in the northern Northeast considered in this research (Figure 10). Municipalities with a humid coastal climate are not shown on the map.

Altitude offers an extremely important geographical control of climate in naturally warm environments, such as the intertropical zones of the planet (BARRY; CHORLEY, 2013). According to Ynoue et al. (2017), when solar radiation reaches Earth, about 30 % of it is directly reflected into space as shortwave radiation. The remainder enters the atmosphere and reaches the surface of the Earth. As it passes through the atmosphere, solar radiation only heats it to a mild extent, except in the stratosphere due to its

Figure 10. Aridity index applied to municipalities in the northern Northeast



Source: prepared by the authors.

absorption by ozone. The surface of continents and seas absorbing solar radiation generates heat and increases surface temperatures.

The atmosphere is practically transparent to radiation from the Sun. So, a considerable fraction of it reaches Earth's surface. Once heated, it transforms radiation into heat and re-emits it into the atmosphere as long waves, i.e., continents, waters, and objects heat up much more than the atmospheric air. Therefore, the atmosphere has basal heating, i.e., from the bottom up, within the limits of the troposphere. Thus, the more elevated municipalities in the northern Northeast will show greater thermal mildness than those in its depression. However, at least two (Campo Sales/CE and Monteiro/PB) have more pronounced aridity than those in the depression, a fact that requires further analyses. On the other hand, elevated municipalities close to the coast, such as Guaramiranga/CE and Areia/PB, benefit from orographic rain more often than those in inland high areas (despite exceptions).

The strategic relevance of elevated semi-arid areas as guardians of the main water sources that feed streams and rivers crucial to the region is highlighted. The efficient capture of water by these areas in mountains, plateaus, and *chapadas* underscores the critical importance of preserving and managing these strategic ecosystems.

Regarding the comparison between the "Thornthwaite" and "Gaussen" aridity indices, results showed a precise compatibility, except for Lagoa Nova/RN in Serra de Santana, which the Thornthwaite aridity index deems as "humid," whereas the Gaussen one, as "harsh dry." According to Galvani (2008), the Thornthwaite aridity index has more advantages than that by Gaussen, such as the "determination of the best sowing times indicating which time is less subject to water restrictions for the crop in question" (p. 4733), among other advantages, which fails to rule out the importance of Gaussen's dry-month index (which includes its easy applicability).

Conclusions

The semi-arid Northeast has intriguing nuances, among which altitude stands out as the most salient one. The substantial difference between the climatic conditions in the higher and lower areas in the Brazilian semi-arid underline a more accentuated water deficit and higher temperatures in the hinterland depression. The prevalence of a more humid climate in mountainous areas suggested the significant orographic influence on this climatic pattern, although it is imperative to recognize notable exceptions, such as Campos Sales/CE and Monteiro/PB, which lie under the marked influence of other geographical factors.

Higher areas offer more favorable conditions for the natural development of vegetation and, therefore, for potential agricultural activity than hinterland depression regions.

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