Chapter 10
Water as Capital and Its Uses in the Caatinga

Eunice Maia de Andrade, Deodato do Nascimento Aquino, Luiz Carlos Guerreiro Chaves, and Fernando Bezerra Lopes

Abstract Due to climate and local geology, the only source of water for the entire Caatinga is rainfall. Annual rainfall averages 773 mm, and 70% of this amount may precipitate in a single month. The rainfall regime in the region is more strongly affected by the great spatio-temporal variability of the rains than by the total amount of rainfall precipitated annually. This variability results in several microclimates, from a desert climate in the central region to a rainy climate along the coastal areas and mountainsides due to orographic effects, with alternating drought and flood years. The scarcity of water in the region is also linked to the physical environment, such as shallow soils, high evaporative demand, the reduction of vegetative cover, and social organization. The waterways that make up the drainage network of the Caatinga are almost entirely intermittent or ephemeral, and throughout the dry season water is available from artificial lakes and artificial perennial use of rivers. These constitute the main source of water for many uses, making the prevention and control of pollution in these sources essential to ensuring a safe water supply. This natural asset has many uses, from soil and vegetation development to climate thermoregulation. In fact, water, soil, and vegetation act in a complementary way; if the existence of vegetation is dependent on water availability, then vegetation is crucial to the infiltration of water into the soil and the maintenance of water quality.

Keywords Semiarid hydrology • Natural resources • Best management practices • Rainfall regime • Water production

---

E.M. de Andrade (✉)
Departamento de Engenharia Agrícola, Universidade Federal do Ceará, Fortaleza, CE, Brazil
e-mail: eandrade.ufc@gmail.com

D.N. Aquino
INCRA- SR(02)-Ceará, Fortaleza, CE, Brazil

L.C.G. Chaves
Faculdade Terra Nordeste, Rua Coronel Correia, Fortaleza, CE, Brazil

F.B. Lopes
Departamento de Engenharia Agrícola, Universidade Federal do Ceará, Fortaleza, CE, Brazil

J.M.C. da Silva et al. (eds.), *Caatinga*,
https://doi.org/10.1007/978-3-319-68339-3_10

10.1 Introduction

Much discussion has occurred concerning the reduction of water availability worldwide and whether it is a result of global population growth or the degradation of bodies of water through human action (Gachango et al. 2015). In addition, water availability has an important contrasting component, agriculture, which is responsible for the production of the fiber and biomass needed to meet the food and energy requirements of humans and animals (Boval and Dixon 2012). Faced with this situation, a model needs to be defined that considers the conservation and proper management of natural resources as essential components of exploiting the natural capital of a biome (Giraudeau et al. 2014) and which should consider the carrying capacity and suitability of the natural resources of each region (Lopes et al. 2009). This paradigm becomes more important in semiarid regions of the world, such as the northeast of Brazil, where natural resources (water, soil, and vegetation) are limited as a result of the climatic conditions of the region (Souza and Fernandes 2000). As a result of the prevailing crystalline geological basement of the Brazilian semiarid region, water reserves originate from rainfall that is concentrated over a few months of the year, along with intermittent surface runoff (Farrick and Branfireun 2015). This process was crucial to the formation of the deciduous forest and the caatingas, the predominant type of vegetation in the Brazilian semiarid region (Sampaio et al. 2005; Pennington et al. 2000). The classical models of man's use of natural resources have failed because they separate socio-economic issues from the environmental features inherent to a region (Nelson et al. 2009). In addition to knowledge of environmental and socio-economic dynamics, it is also necessary to identify any conflicts that may exist between development goals and the carrying capacity of the natural resources that make up the Caatinga region.

Although a new paradigm has been developed regarding the use of this natural asset, which has economic value because of the direct and indirect benefits it generates for the human population (Braat and Groot 2012), much still remains to be done. For example, low levels of social organization and joint action occur on the part of rural residents. This situation compromises the production of food for these residents, especially those of low economic status, who depend completely on the availability of natural resources in the region (Buainain and Garcia 2013). In 1980, Duque was already discussing the preference for isolated action among the people who inhabit the Caatinga.

We are living in a time in which actions and decision making must be in line with local environmental reality and consider the goods and services generated by natural assets. Therefore, this chapter discusses the production and uses of water as capital in the Caatinga.

10.2 Rainfall Regime of the Caatinga

The Caatinga is characterized by abundant solar energy, a water deficit, and low relative humidity, which contributes to the high evaporation rates of water bodies and wet surfaces. Its geographical area is bounded by the 800-mm annual isohyet. In this regard, the Caatinga is very similar to the semiarid northeastern region, which is also known as the drought polygon (Pereira Júnior 2007).

The rainfall regime is more strongly affected by the high spatio-temporal variability of the rains than the total rainfall precipitated annually (Andrade et al. 2016b). The average annual rainfall in the region is 773 mm (Table 10.1), and 70% of this amount may precipitate in a single month (Andrade et al. 2010). The rainy season does not begin or end at a fixed time.

Although 21% of the region receives annual precipitation of less than 600 mm and 0.6% of the region receives less than 400 mm (Fig. 10.1, Table 10.1), 75% of the area lies between the 600 and 1200 mm isohyets, and 1.7% of the area receives an annual total greater than 1200 mm. This spatial variability in rainfall results in distinct microclimates in the Caatinga region, ranging from a desert climate in the central region to a rainy climate along the coastal area (Fig. 10.1) and in the mountains due to the orographic effect. In these regions (*Precipitation* > 1200 mm), there are records of annual rainfall above the 1800 mm isohyet, as in the case of the city of Guaramiranga in the state of Ceará.

Due to its proximity to the equator (2°54′–16°18′ S), the Caatinga has only two distinct seasons, a wet season and a dry season, with dry years frequently alternating with years of flooding. The region is subject to the influence of subtropical high-pressure areas linked to the semi-permanent South Atlantic anticyclone (Guerreiro et al. 2013), which is in turn influenced by the Hadley (meridional) and Walker (zonal) circulations (Ferreira and Mello 2005). This produces a rainfall regime that depends on geographical position (Fig. 10.2). In the northern part of the Caatinga region, the rainy season occurs between January and May, reaching a maximum from March to April, when the Intertropical Convergence Zone (ITCZ) migrates towards the southern hemisphere and reaches latitudes up to 10° S. The upward

Table 10.1 Average annual rainfall in the Caatinga

Isopleth (mm)	Area (%)	Weighted rainfall (mm)
<400	0.6	24
400–600	21.9	109.5
600–800	38.6	270.2
800–1000	30.2	271.8
1000–1200	7.1	78.1
>1200	1.6	19.2
Total	**100.00**	**772.8**

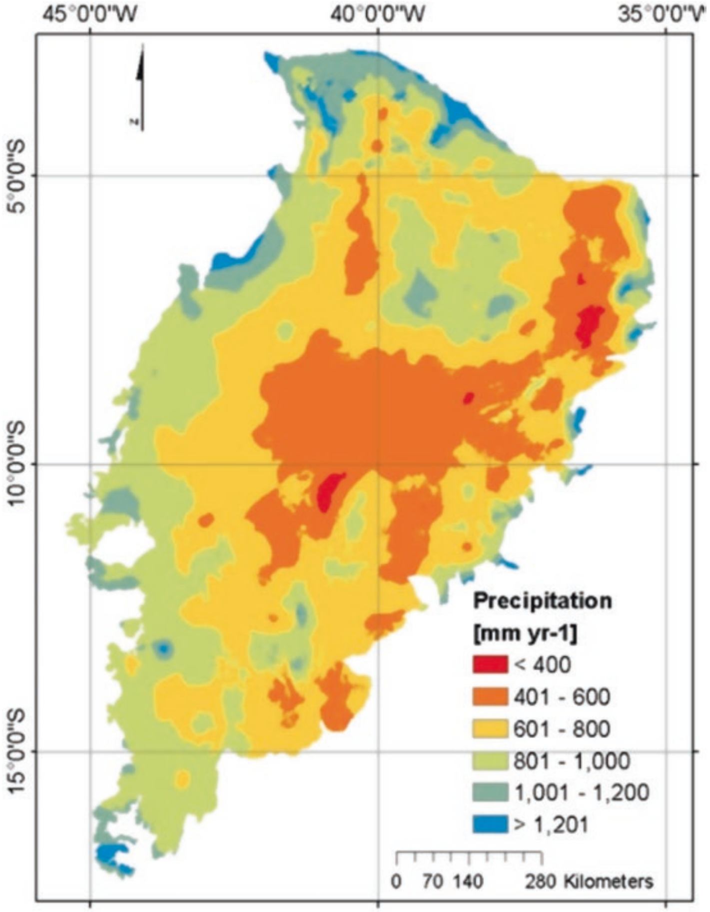


Fig. 10.1 Isohyets in the Caatinga

movement of the air associated with the ITCZ generally gives rise to intense precipitation that is convective in origin and has no definite periodicity (Sun et al. 2006; Alves et al. 2009). This behavior results in a rainfall pattern that is climatically anomalous, with highly variable spatial and temporal distributions (Bates et al. 2008).

In the southern region of the Caatinga, the rains begin in October and are concentrated in December and January. These rains are caused by cold fronts advancing toward the equator and reaching latitudes below 10° S (Ferreira and Mello 2005). To the east (Fig. 10.2), the rainy season begins in May, continues until August, and is concentrated in June and July. These rains are mainly induced by easterly waves, which consist of moist air masses moving from the coast of Africa to the east coast of Brazil (Torres and Ferreira 2011), where they join the sea breeze that advances over the continent via the process of advection. When oceanic and atmospheric

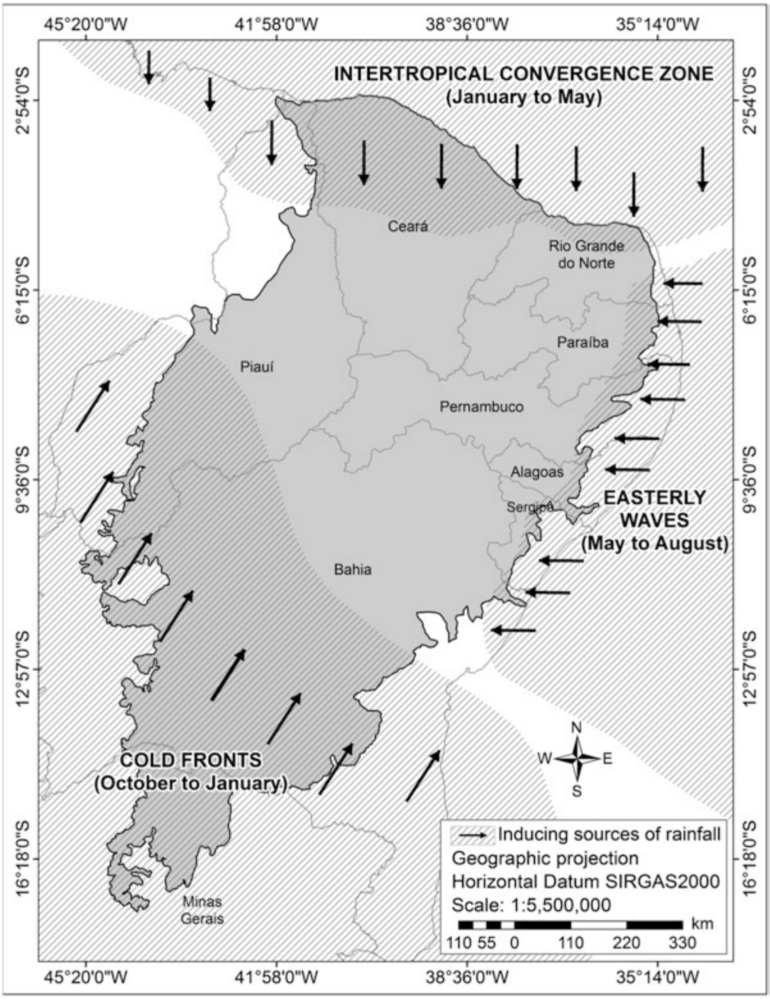


Fig. 10.2 Predominant sources of rainfall regimes in the Caatinga

conditions favor the increased displacement of the air masses, these air masses advance over the central and northern parts of the Caatinga region. In such cases, the rainy season can last until July or August (Guerreiro et al. 2013).

The rainy season has a unimodal distribution, with 60% or more of the total precipitation being recorded over 3 months (Fig. 10.3). Also, the lower the annual rainfall depth, the greater the contraction of rainfall events. At the three rainfall stations with the lowest annual rainfall depths, Petrolândia, Campos Sales, and Macau, precipitation is mainly induced by the ITCZ because the rainiest months occur between February and April. In contrast, the rainfall distribution recorded at the Bom Jesus da Lapa station shows that rainfall events there are generated by cold fronts

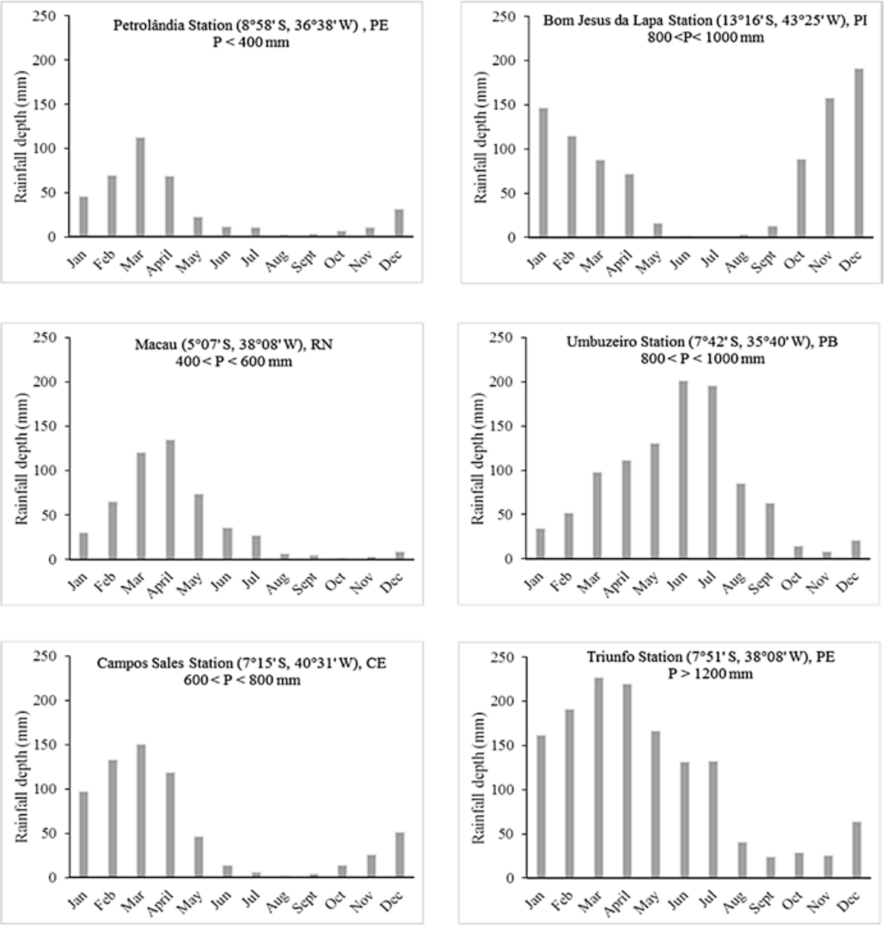


Fig. 10.3 Historical series of total monthly rainfall at six rainfall stations in the Caatinga

(Fig. 10.3), and the rains occurring at the Umbuzeiro station are mainly induced by easterly waves, with the maximum rainfall depths being recorded in June and July.

The greatest water shortages in the Caatinga region begin on the northern coast of Rio Grande do Norte and move toward the central area of the Caatinga. This void, located on the western side of Rio Grande do Norte and running in a north–south direction (Fig. 10.1), is determined by the leeward effect of the Borborema plateau, along with the presence of dry air masses. Between the latitudes of 8° S and 11° S, little rain falls (Fig. 10.1) because of the weak influence of the ITCZ and the polar fronts in the region, that is, the ITCZ or polar fronts do not always arrive with air masses that are humid enough to generate large amounts of rainfall.

The uncertainties of the rainfall regime are not limited to spatial variability. Rainfall is also characterized by high inter-annual variability (the existence of drought) and intra-annual variability (the existence of consecutive dry days [CDDs]

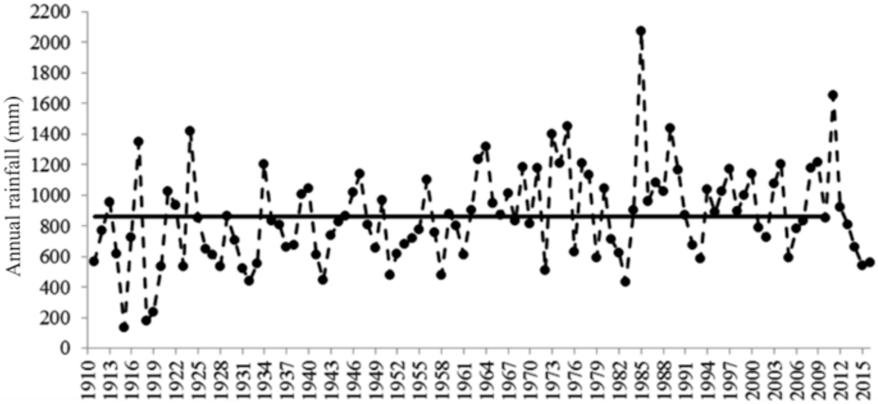


Fig. 10.4 Historical series (1910–2015) for the rainfall station at Iguatu, Ceará

during the rainy season) (Guerreiro et al. 2013; Andrade et al. 2016b; Santos et al. 2016). It is common for the total annual precipitation at any one station to vary by more than 1000% (Fig. 10.4) from one year to the next, as is the case at the Iguatu station in Ceará. For that station, the annual historical series shows records of 133 mm for 1915 and a yearly accumulation of 1348 mm 2 years later (1917). Variability of this magnitude was also seen from 1983 to 1985, when the total precipitation varied from 433 to 2075 mm. These results indicate the uncertainty of events in the Brazilian semiarid region, even on an annual scale (Guerreiro et al. 2013).

Studies of these uncertainties show that the entire Caatinga displays the vulnerabilities associated with rain-fed agricultural production or pasture (Andrade et al. 2016b). Intra-annual vulnerability is present even in regions with total annual rainfall exceeding 1200 mm, demonstrating that water vulnerability should not be limited only by annual rainfall. For a better understanding of how these events are distributed throughout the year, a monthly analysis was carried out on a historical series (1961–2015), which was part of a total series of 106 years. The complete series was not used due to the unavailability of data on a monthly scale.

Of the months that make up the rainy season, January to May, only January shows discrepant data (Fig. 10.5), and, with the exception of May, the median tends to move towards the first quartile. This pattern shows that monthly rainfall depths of less than the median have values that are close to one another and that monthly rainfall depth values greater than the median are dispersed, showing greater variability, along with a trend toward the occurrence of extreme monthly events. Lima et al. (2008) also found that for the rainiest months, no discrepant data were registered.

The precipitation that occurred in March and April also shows that 50% (median) of the total rainfall for these 2 months was higher than the annual total for years of severe drought (Fig. 10.5). In contrast, the months representing the dry season (June–December) show the existence of isolated events with high temporal

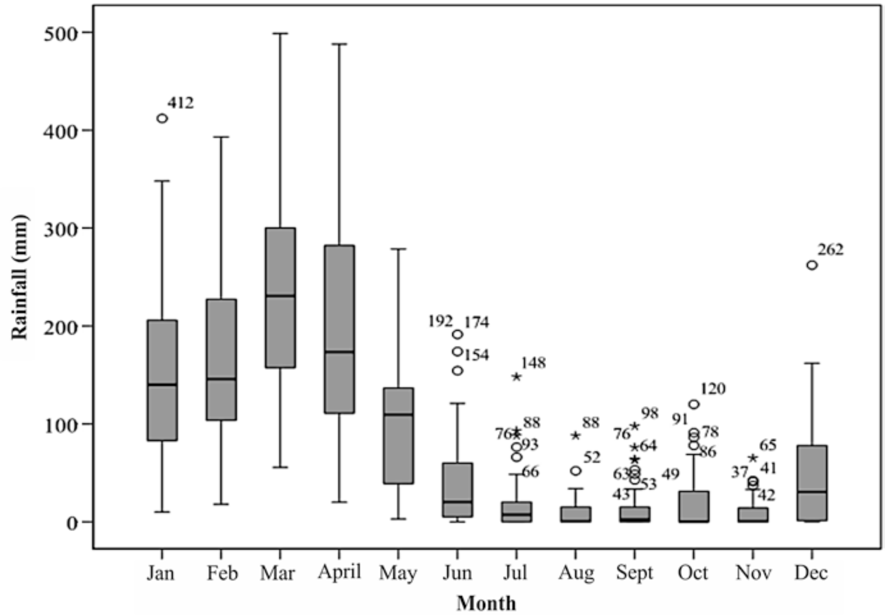


Fig. 10.5 Monthly distribution of the historical series (1961–2015) of annual rainfall for the Iguatu station

variability in that extreme events are present for every month. As seen in Fig. 10.5, no rainfall was recorded from July to November in 50% of the investigated years because the median value is zero. This demonstrates that using only average values as indicators of the rainfall regime in the Caatinga should be avoided. It is recommended that other indicators be considered, such as the monthly and annual distribution of events, the occurrence of CDDs, and extreme events. The only certainty of the local reality is the uncertainty with which rainfall events are distributed over time and space. In addition to the uncertainty of rainfall, the matrix of hydrological behavior contains shallow soils (Romero and Ferreira 2010) and a drainage system of ephemeral rivers (Campos 2011). This results in a low level of water being stored in the soil.

10.3 Geology and Soils

The Caatinga lies inclined over crystalline rocks from the Precambrian (gneisses, granites, and schists), which represent the predominant geological units in the eastern part of the northeast, with the exception of the sedimentary basins located along the coast (Saadi 1993) and the western part of the region. The evolution of the landscape in the Northeast is based on the pedimentation ramps having been subjected

Fig. 10.6 Inselbergs in the town of Quixadá, Ceará

to climatic changes in Quaternary (Maia et al. 2010), and the pediplains of the backlands are the result of a vast, slow process of erosion under very humid conditions, followed by intense aridity. In the Brazilian semiarid region, one proof of the existence of a period of high precipitation and runoff in earlier times is the presence of pebbles on the land and interfluves in the headwaters (Maia et al. 2010). This process began in Lower Tertiary, followed by phases of more recent pediplanation that were contemporary with the deposition of the Barreiras Group. Isolated traces of younger surfaces are found, which is characterized by plateaus, mountain ranges, and inselbergs (Fig. 10.6). The geological basement of the Caatinga region consists mainly of metamorphic and igneous rocks, which make up approximately 70% of the basement and are commonly described as crystalline.

Geological and climatic processes, together with the action of organisms, gave rise to the soils of the Caatinga. The result of these interactions can be seen in the high diversity of soil types, which form a true mosaic in which soil classes can vary even over short distances. Although the soils are complex and have varying characteristics (Sampaio 1995), it can be said, based on Jacomini (1996) and EMBRAPA (Empresa Brasileira de Pesquisa Agropecuária) (2013), that 70.3% of the Caatinga territory is divided into four classes of soil: latosols (24%), litholic neosols (18.2%), argisols (15.2%), and luvisols (12.9%).

The common occurrence of latosols in the Caatinga is due to the very nature of the region, specifically the action of the climate on the bedrock. These are deep soils with low-activity clay, high aluminium content, and low levels of nutrients. The latosols are mostly located in the southern and southwestern part of the Caatinga, which corresponds to Bahia and the southern Piaui; the other three predominant classes are shallow soils with high-activity clay (2:1) that are not very deep (<50 cm) but are fertile. In general, these soils have stony surfaces or upper layers and a strong tendency toward erosion. Rocky outcroppings are common in the area and are almost always associated with litholic neosols but also occur as inclusions in other soil classes (Embrapa 2013). The greatest concentrations of argisols, litholic neosols, and luvisols are located in the northeastern region of the Caatinga, corresponding to the states of Ceará, Rio Grande do Norte, Paraiba, and Pernambuco.

The excess heat and light inherent to tropical semiarid regions results in the rapid mineralization of organic matter, with the fertility of the soil being a result of its alkalinity and base richness (Romero and Ferreira 2010). Methods of exploiting these soils should therefore cause the least possible disturbance of the biological environment and reinforce the contributions of organic matter by maintaining a live cover consisting of nitrogen-fixing plants and a mulch of crop stubble, manure, and various sources of green fertilizer (Duque 1980).

10.4 Vegetation

The combination of the predominant soils, rainfall regime, energy availability (2800–3000 h year^{-1}), and high rates of potential evaporation, which range from 1500 (coastal regions) to 3000 mm year^{-1} in the continental area (Molle 1989; IICA 2002), has resulted in various plant typologies (Neri et al. 2012.), predominantly seasonally dry tropical forest (Pennington et al. 2000). From a phytosociological point of view, the density, frequency, and dominance of the species are determined by variations in topography, soil type, and rainfall (Sampaio et al. 2005; Prado 2008; Moro et al. 2016).

As for resilience, the plant species that make up the Caatinga display physiological adaptations to their environmental conditions. Knowledge of these adaptations is indispensable in understanding the functionality of the region, which represents the largest area of seasonally dry tropical forest in South America (Miles et al. 2006; Pennington et al. 2000). Among plants of the Caatinga, closing the stomata in an attempt to maintain favorable levels of water content in their tissues for as long as possible is one of the first lines of defense against drying out (Silva et al. 2004). This mechanism of stomatal closure at the hottest times of the day constitutes a strategy used by many species that inhabit arid and semiarid regions to prevent excessive loss of water through transpiration (Chaves et al. 2016). Hence, this behavior is a form of adaptation or acclimatization by the plants to the water deficit they face, maintaining transpiration to a low level and keeping stomatal opening to the minimum necessary to assimilate a sufficient amount of CO_2 to continue with the photosynthetic process, though at a reduced capacity (Sena et al. 2007). This physiological process leads to improved water-use efficiency (WUE) (Medrano et al. 2009), and high WUE allows plants to remain alive under conditions of water stress for longer periods.

The reduction in the number of leaves seen in various species of plants in the Caatinga that are subjected to water stress is believed to be another strategy for survival under adverse conditions by virtue of the reduction of water loss through transpiration and thus a greater resistance to drought (Santiago et al. 2001). In addition to leaf senescence, there are reports in the literature of plants in the Caatinga that are subjected to severe water deficits tending to invest more in the elongation of the roots than that of shoots in order to absorb water from the deeper zones of the soil (Barbosa et al. 2000). Root architecture and roots' ability to exploit the deeper, more humid layers of the soil, together with a higher root to shoot ratio, are important characteristics among plants in the Caatinga that face water deficits (Scalon et al. 2011). Understanding these mechanisms is important because most of the global predictions concerning climate change highlight ever more frequent and extensive drought events (Magrin et al. 2014), which would lead to changes in the behaviors of some species and an increase in desertification in some regions (Santos et al. 2014).

10.5 Water Availability

The semiarid region of Brazil is characterized by a high water deficit, and it is possible for rivers to remain naturally dry for more than 18 months, which illustrates the low water availability in the region. Of the total rainfall occurring in the Caatinga, 88% is transformed into real evapotranspiration, 9% becomes runoff, and only 3% becomes groundwater flow. This demonstrates a negative water balance, and water availability is restricted to the rainy season, as can be seen in Fig. 10.7.

The semiarid region of Brazil is affected by water shortages, which are aggravated by domestic, industrial, and agricultural pollution (Rebouças 1997). Inasmuch as the global demand for water grows, the availability of fresh water decreases. Therefore, maintaining the water supply not only in terms of quantity but also in terms of quality will be a major challenge for society.

In arid and semiarid regions located at low latitudes, such as the Caatinga region, artificial lakes (Fig. 10.8) and the artificial perennial use of rivers are the main sources of water for domestic, industrial, and agricultural use, making the prevention and control of pollution in these water sources essential in ensuring the water supply. In the Caatinga, 74% of the lakes are artificial (reservoirs) and 26% are natural. This is due to the characteristics of the rainfall regime, geology, and soils, as well as the haphazard removal of natural plant cover for the construction of artificial lakes (Molle 1994).

Considering that in the basins of intermittent rivers, the natural availability of surface water is zero, storage reservoirs allow the inter-annual regulation of natural runoff and ensure the availability of a constant annual volume. In this case, flow rates, which are regulated by the reservoirs, represent the availability of surface water. For perennial rivers, the minimum natural flow rates correspond, in principle, to the availability of water (CEARÁ 2008). In terms of the territorial distribution of

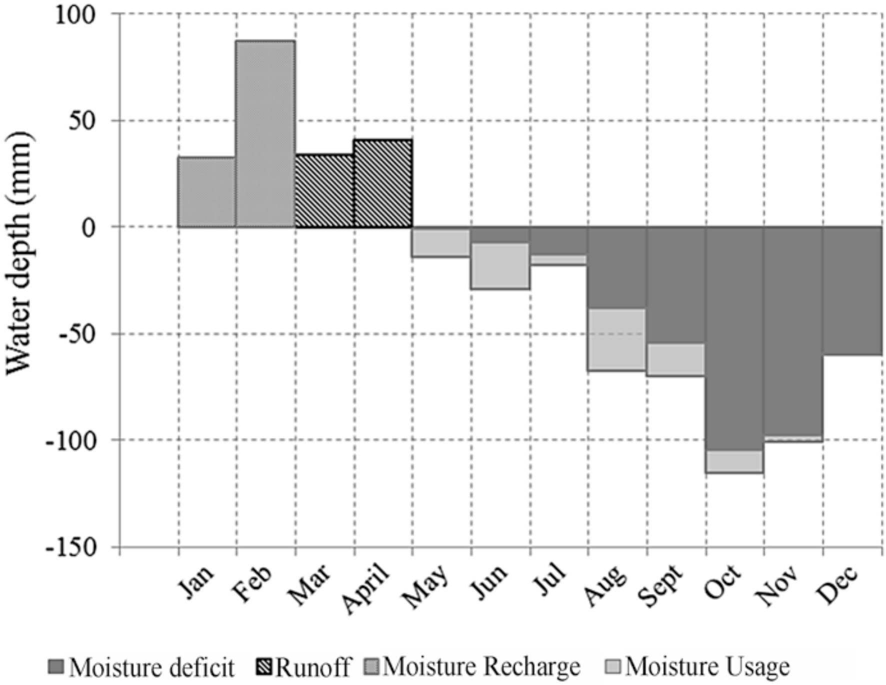


Fig. 10.7 Water balance for the town of Campos Sales, Ceará

surface water in the states of the Caatinga, Ceará stands out as having the highest concentration (1349), equivalent to 38.39% of the total, in contrast to the state of Sergipe, which has a total of only 18 reservoirs, corresponding to 0.51% of the total (Table 10.2).

The distribution of water body types in each state of the Caatinga (Table 10.2) shows the greatest number of natural bodies appearing in the state of Bahia (571), mainly due to the formation of the canyons by the São Francisco River, which are more expressive in the southwest part of the state. In the states of Ceará, Rio Grande do Norte, and Paraiba, artificial reservoirs dominate, highlighting the policy of reservoir construction in these areas to help the population of the backlands to live with the natural water scarcity that exists in the Caatinga (Bezerra et al. 2009). As seen in Fig. 10.8, in the state of Rio Grande do Norte, the reservoirs are concentrated in the central-west and much of the south of the state, where a basement of crystalline rocks predominates, while the center-north and the entire coastal area of the state are formed from sedimentary rocks and soils (Angelim et al. 2007).

Groundwater can occur naturally or artificially in a form that can be extracted and used by man. Groundwater has always been used as a water source by the populations of arid and semiarid regions since the early days of ancient civilizations (Zektser and Everett 2014). To take a simplistic view, due to its geological features,

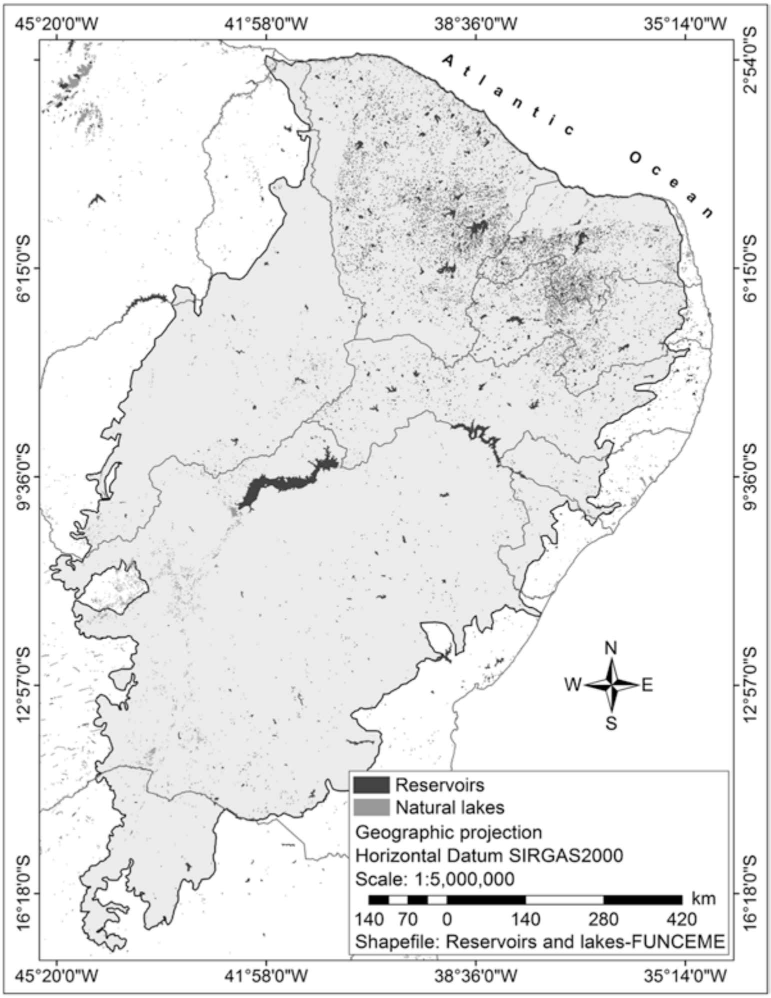


Fig. 10.8 Lakes and reservoirs with water surface of over 5 hectares along the elevation of the spillway in the Caatinga Biome

the Caatinga territory is predominantly composed of two groups of rocks that make up the hydrogeological provinces: crystalline and sedimentary.

In the region with a crystalline basement, groundwater occurs in fractures and discontinuities in the rock, which results in discrete reservoirs of limited size (Deyassa et al. 2014). The use of these sources is always associated with a high level of risk because little information exists about their exploitation and recharge flow rates. However, since the 1950s, underground reservoirs have assumed a prominent role in addressing water-related problems (Rebouças 1999). Researchers such as Feitosa and Feitosa (2011) believe that the potential volume of water to be extracted from these rocks can meet the demands of the diffuse population of the Caatinga.

Table 10.2 Lakes and reservoirs with water surface of over 5 hectares in the Caatinga

	Water reservoir/area					
State	Total	Area	Natural	Area	Artificial	Area
Alagoas	32	28	10	5	22	23
Bahia	718	3988	571	361	147	3627
Piauí	182	257	116	100	66	158
Sergipe	18	69	6	2	12	67
Ceará	1349	2036	143	160	1206	1876
Paraíba	413	495	7	3	406	492
Pernambuco	189	1073	5	2	184	1071
Rio Grande do Norte	613	720	52	83	561	637
Total	**3514**	**8666**	**910**	**716**	**2604**	**7951**

Table 10.3 Wells in the Caatinga

	Wells in the Caatinga			
State	Area (km^2)	Number of wells	Area per well (km^2)	Geology
Alagoas	28,000	1652	17	Sedimentary
Bahia	565,000	23,546	24	
Piauí	25,200	28,651	9	
Sergipe	22,000	5550	4	
Paraíba	56,000	18,953	3	Crystalline
Ceará	149,000	21,996	7	
Pernambuco	90,000	27,035	4	
Rio Grande do Norte	53,000	10,035	5	

These authors estimate that with a median flow rate of 1 m^3 h^{-1} and a pumping regime of six hours per day, 720,000 m^3 could potentially be exploited, which would allow for the consumption of 200 L day^{-1} per person for 3.6 million users. However, due to the salinity of the water (sodium chloride), the percentage of groundwater that is suitable for human consumption in the crystalline region is between 20 and 30% (BRASIL 2005). Limitations on the use of groundwater are related not only to quantity but also to quality.

Unlike the crystalline basement, the sedimentary basement shows a high potential for water storage, and the largest groundwater reservoirs are found in the sedimentary aquifers of the Caatinga territory (Ministério de Minas e Energias 2004). The aquifers of Parnaíba, Potiguar, Jatoba, Recôncavo, and Tucano-Urucuia are important among these reservoirs. The number of wells in the Caatinga is shown in Table 10.3. The state of Piauí has the largest number of wells among the Brazilian states of the Caatinga region; there are 28,651 wells, representing the greatest groundwater potential in the region as a result of being formed from the Parnaiba sedimentary basin. The remaining states of the region, such as Pernambuco, Ceará, and Paraíba, also contain large numbers of wells despite the predominance of the crystalline basement, which, in principle, has a low potential for exploitation because hydraulic conductivity is low, as are the average porosity, permeability, and opening of voids (Manoel Filho 2000).

Based on the ratio between the area of each state of the Caatinga region and the number of wells, the states of Bahia and Alagoas have the largest areas per well; that is, on average, there is a well for every 24 and 17 km^2, respectively. Paraíba has the lowest well to area ratio, with a well for every 3 km^2 on average, followed by Pernambuco and Sergipe, which both average four wells per km^2.

The Caatinga requires further hydrogeological study in order to obtain knowledge of the actual potential of the groundwater there. Only by having precise knowledge about its potential will it be possible to arrive at a plan for the use and development of the region that ensures the rational usage and sustainable availability of water.

10.6 Management of the Caatinga for Water Production

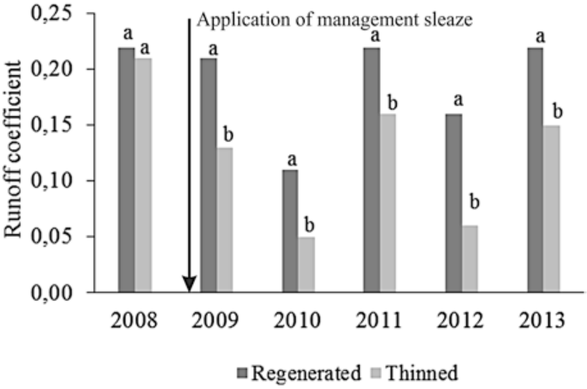
As a natural form of capital, water has various uses, from the development of the soil and vegetation (formation and conservation) to acting as a thermoregulator of the climate. In fact, water, soil, and vegetation act in a complementary and associative way, helping to sustain the environment. In the same way that the soil acts as an important reservoir of water with which to meet the consumptive demands of vegetation, the plant cover and its diversified structure are important in the process of water storage in the ground. If the existence of vegetation is dependent on water availability, the same vegetation determines water's infiltration into the soil and the maintenance of water quality.

The water generated in a river basin, in addition to meeting the hydric requirements of the system, also meets the requirements of agricultural production, watering livestock, and human demand. The benefits derived from this water by maintaining the wetlands in dry tropical forests allow these ecosystems to provide very significant services in dry areas where drought is present for at least 8 months of the year (Marengo et al. 2016). The conservation of forest remnants, especially in the semiarid region, therefore contributes to the protection of surface and underground water sources, improving water availability and conservation in areas where availability is limited (Douglas et al. 2005; Farrick and Branfireun 2015). In addition to the conservation of soil, water, and plant resources, there is also the need for the production of fiber and protein needed to meet the basic food requirements of humanity.

To the extent that natural resources are managed with disregard for their ability and capacity for support human life, these resources begin to run out, and degradation sets in. In view of this, there is a need to define and test models of the exploitation of this natural asset in which the sustainability of ecosystems is maintained as close to a state of homeostasis as possible (Palácio et al. 2013). Thinning is among the management alternatives suggested to increase the production and storage of water in soils of the tropical semiarid region (Rodrigues et al. 2013; Andrade et al. 2016a). This technique consists of the selective control of woody species, in which some tree and shrub individuals are removed from the vegetation, reducing both the density of the plants and the ground cover of the woody stratum (Pimentel 2010).

Fig. 10.9 Period when thinning was being undertaken in the Caatinga

Fig. 10.10 Annual runoff coefficients in watersheds of caatingas given regeneration for 35 years and thinning for 6 years (Andrade et al. 2016a). Thinning was undertaken after the rainy season of 2008



Management via thinning, the selective removal of trees and shrubs, should be adopted to reduce competition for water, light, and nutrients, creating more room for the growth of small herbaceous species (Savadogo et al. 2008). Herbaceous ground cover is an important factor in defining the pattern of water movement in a watershed (Garcia-Ruiz et al. 2008). When carried out correctly, thinning inputs crop residues into the soil (Fig. 10.9). Together with the emergence of herbaceous undergrowth, thinning promotes the reduction of surface runoff (Fig. 10.10), an

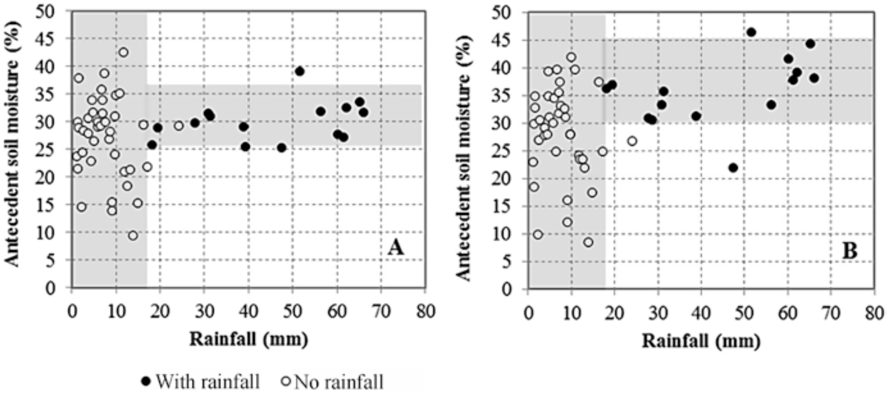


Fig. 10.11 Soil moisture during the rainy season by type of land use: caatinga under regeneration for 35 years (**a**) and caatinga under thinning for 5 years (**b**)

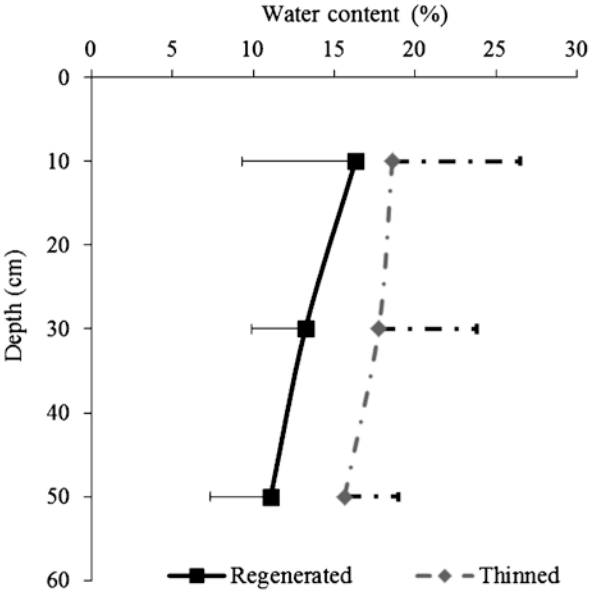


Fig. 10.12 Gravimetric moisture in the soil profile under conserved and thinned caatinga from April 2013 to March 2014 (Aquino 2015)

increase in infiltration, and, consequently, a larger percentage of water being stored in the soil (Figs. 10.11 and 10.12), as discussed by Rodrigues et al. (2013) and Andrade et al. (2016a).

The significant reduction in surface runoff after the application of thinning (Fig. 10.10) results in greater water retention and storage capacity in the soil. The production dynamics of herbaceous biomass and its relationship to changes in the humidity of an inverted neosol under two different types of land use (caatinga preserved for 35 years and caatinga thinned for a period of 6 years) showed that thinning contributes more greatly to the maintenance of moisture in the soil (Figs. 10.11 and 10.12). In the regenerating caatinga area, the runoff process begins with soil moisture content of 25% (Fig. 10.11), while in the thinned area, surface runoff begins when the soil moisture content becomes greater than 30%. The water storage capacity of the soil of the caatinga under regeneration was 10%, while for the thinned caatinga, this value reached 15%, showing that management with thinning resulted in a 5% increase in soil moisture. These results were confirmed by Aquino (2015), who identified greater soil moisture at depths of 10, 30, and 50 cm with thinning (Fig. 10.12). The reduced surface runoff and greater soil humidity result in increased biomass (Palácio 2011) and a reduction of soil and nutrient loss (Lobato et al. 2009).

Although research shows that thinning can be used to promote the sustainable use of natural resources in the Caatinga, further research is needed before thinning can be defined as an integral part of the natural system in tropical drylands. Defining the threshold of sustainability in a model for the use and exploitation of natural resources is crucial in defining the conservation or degradation of the environment.

10.7 Concluding Remarks

To understand the availability, support, and services that water can offer in environments with irregular climate regimes and a negative water balance (evaporation greater than precipitation), a holistic view, in which the territory, human beings, and natural resources of the environment are interwoven, is crucial. In seeking to meet the demand for various types of water usage, the strategies to be adopted must consider the environment and its peculiarities. It is time to change the strategy of transferring techniques that are successful in regions with sub-humid or dry-temperate climates to tropical dry regions. Decision-making must be in line with the reality of each location. In this context, any action involving water resources in the Caatinga region should consider the uncertainty of the rainy season, which is defined more by its irregularity than by actual water scarcity; population growth; the need for increased food production; and the model of natural resource exploitation used. The population that inhabits this region requires water. Therefore, future challenges must involve a better understanding of the natural system and the associative management of water as a natural asset, viewing man’s demand for water and fiber as an integral part of the natural system. This vision, together with integrated action, can widen the threshold of sustainability in dryland ecosystems.

References

Alves JMB, Servain J, Campos JNB (2009) Relationship between ocean climatic variability and rain-fed agriculture in northeast Brazil. Clim Res 38:225–236. https://doi.org/10.3354/cr00786

Andrade EM, Meireles ACM, Palácio HAQ (2010) O semiárido cearense e suas águas. In: O Semiárido e o manejo dos recursos naturais. Imprensa Universitária, Fortaleza, pp 56–80

Andrade EM, Guerreiro MJS, Rodrigues JO (2016a) Change in hydrological response of catchments in a dry tropical forest subject to land use changes. In: 9th Spanish Portuguese assembly of geodesy and geophysics, Madrid

Andrade EM, Sena MGT, Silva AGR, Pereira FJS, Lopes FB (2016b) Uncertainties of the rainfall regime in a tropical semi-arid region: the case of the state of Ceará. Revista Agro@mbiente 10(2):88–95. 10.18227/1982-8470ragro.v10i2.3500

Angelim LAQ, Nesi JR, Oliveira RG, Silva RC, Jacques APR, Assunção PRS, Moraes FAB, Barros AD, Medeiros VC, Bezerril DRS, França FAB, Rêgo JM, Xavier CB, Aquino AA, Costa JL (2007) Geologia e recursos minerais do Estado do Rio Grande do Norte – Escala 1:500.000. CPRM – Serviço Geológico do Brasil, Recife

Aquino DN (2015) Ciclagem de carbono e caracterização espectral em áreas de caatinga raleada e conservada. Tese, Universidade Federal do Ceará, Fortaleza

Barbosa DC, Nogueira RJMC, Melo Filho PA (2000) Comparative studies of growth in three species of "caatinga" sumetted to water stress. Phyton 69(1):45–50

Bates BC, Kundzewicz ZW, Wu S, Palutikof JP (2008) Climate change and water. Technical paper of the intergovernmental panel on climate change, IPCC Secretariat, Geneva

Bezerra MAA, Santos JEM, Oliveira Filho IN, Correia Neto JS (2009) Gestão das Águas de Barragens do Nordeste a partir de uma Perspectiva Social e Econômica. In: Anais do 47° Congresso da Sociedade Brasileira de Economia, Administração e Sociologia Rural. UFRGS, Porto Alegre

Boval M, Dixon RM (2012) The importance of grasslands for animal production and other functions: a review on management and methodological progress in the tropics. Journal of animal. Bioscience 6:748–762. https://doi.org/10.1017/S1751731112000304

Braat LC, Groot R (2012) The ecosystem services agenda: bridging the worlds of natural science and economics, conservation and development, and public and private policy. Ecosyst Serv 1:4–15. https://doi.org/10.1016/j.ecoser. 2012.07.011

BRASIL (2005) Programa de Cadastramento de Fontes Hídricas Subterrâneas. Projeto de Integração do Rio São Francisco com Bacias Hidrográficas do Nordeste Setentrional – Projeto Básico Ambiental – PBA. Documento: 2255–00-PBA-RL-0001-00

Buainain AM, Garcia JR (2013) Développement rural dans la région semi-aride du Brésil: transformations récentes, défis et perspectives. Revue Franco-Brésilienne de Geographe (on line) 19:1. https://doi.org/10.4000/confins.8633

Campos JNB (2011) Águas superficiais no semiárido brasileiro: Desafios ao atendimento aos usos múltiplos. In: Medeiros SS, Gheyi HR, Galvão CO, Paz VPS (eds) Recursos Hídricos em regiões áridas e semiáridas, 1.Ed edn. Instituto Nacional do Semiárido, Campina Grande, pp 250–268

CEARÁ. Assembleia Legislativa do Estado do (2008) Cenário Atual dos recursos hídricos do Ceará/Conselho de Altos Estudos e Assuntos Estratégicos. Eudoro WS (Coord), INESP, Fortaleza

Chaves MM, Costa JM, Zarrouk O, Pinheiro C, Lopes CM, Pereira JS (2016) Controlling estomatal aperture in semi-arid regions – the dilemma of saving water or being cool? Plant Sci 225:54–64. https://doi.org/10.1016/j.plantsci.2016.06.015

Deyassa G, Kebede S, Ayenew T, Kidane T (2014) Crystalline basement aquifers of Ethiopia: their genesis, classification and aquifer properties. J Afr Earth Sci 100:191–202. https://doi.org/10.1016/j.jafrearsci.2014.06.002

Douglas EM, Sebastian KV, Wood S (2005) The role of tropical forests in supporting biodiversity and hydrological integraty: a synoptic overview. World Bank Working Paper, Washington, DC

Duque G (1980) Solo e água no polígono das secas. 5.ed. ESAM (Coleção Mossoroense 142), Mossoró

EMBRAPA – Empresa Brasileira de Pesquisa Agropecuária (2013) Sistema Brasileiro de Classificação de Solos, 3rd edn. Embrapa Solos, Rio de Janeiro

Farrick KK, Branfireun BA (2015) Flowpaths, source water contributions and water residence times in a Mexican tropical dry forest catchment. J Hydrol 529:854–865. https://doi.org/10.1016/j.jhydrol.2015.08.059

Feitosa FAC, Feitosa EC (2011) Realidade e perspectivas do uso racional de águas subterrâneas na região semiárida do Brasil. In: Medeiros SS, Gheyi HR, Galvão CO, Paz VPS (eds) Recursos Hídricos em regiões áridas e semiáridas, 1st edn. Instituto Nacional do Semiárido, Campina Grande, pp 269–306

Ferreira AG, Mello NGS (2005) Principais sistemas atmosféricos atuantes sobre a região nordeste do Brasil e a influência dos oceanos pacífico e atlântico no clima da região. Revista Brasileira de Climatologia 1(1):15–28

Gachango FG, Andersen LM, Pedersen SM (2015) Adoption of voluntary water-pollution reduction technologies and water quality perception among Danish farmers. Agric Water Manag 158:235–244. https://doi.org/10.1016/j.agwat.2015.04.014

Garcia-Ruiz JM, Regüés D, Alvera B, Lana-Renault N, Serrano-Muela P, Nadal-Romero E, Navas A, Latron J, Martí-Bono C, Arnáez J (2008) Flood generation and sediment transport in experimental catchments affected by land use changes in the central Pyrenees. J Hydrol 274:30–46. https://doi.org/10.1016/j.jhydrol.2008.04.013

Giraudeau M, Nolan PM, Black CE, Earl SR, Hasegawa M, McGraw KJ (2014) Song characteristics track bill morphology along a gradient of urbanization in house finches (*Haemorhous mexicanus*). Front Zool 11:83. https://doi.org/10.1186/s12983-014-0083-8

Guerreiro MJS, Andrade EM, Lajinha IAT (2013) Long-term variation of rainfall indices in Ceará State, Northeast Brazil. Int J Climatol 33:2929–2939. https://doi.org/10.1002/joc.3645

IICA - Instituto Interamericano de Cooperação para Agricultura (2002) Projeto Áridas. http://www.iica.org.br/2001/projaridas. Accessed 2 Aug 2016

Jacomini PKT (1996) Solos sob caatingas: características e uso agrícola. In: Alvarez VH, Fontes LEF, Fontes MPF (eds) O solo nos grandes domínios morfoclimáticos do Brasil e o desenvolvimento sustentável. SBCS-UFV, Viçosa, pp 95–111

Lima JSS, Silva SA, Oliveira RB, Cecílio RA, Xavier AC (2008) Variabilidade temporal da precipitação mensal em Alegre – ES. Rev Ciênc Agron 39:327–332

Lobato FAO, Andrade EM, Meireles ACM, Santos JCN, Lopes JFB (2009) Perdas de solo e nutrientes em área de Caatinga decorrente de diferentes alturas pluviométricas. Revista Agro@mbiente On-line 3:65–71. 10.18227/1982-8470ragro.v3i2.247

Lopes FB, Andrade EM, Aquino DN, Lopes JFB (2009) Proposta de um índice de sustentabilidade do Perímetro Irrigado Baixo Acaraú, Ceará, Brasil. Rev Ciênc Agron 40:185–193

Magrin GO, Marengo JA, Boulanger JP, Buckeridge MS, Castellanos E, Poveda G, Scarano FR, Vicuña S (2014) Central and South America. In: Climate change 2014: impacts, adaptation, and vulnerability. Part B: regional aspects. Contribution of working group II to the fifth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge/New York, pp 1499–1566

Maia RP, Bezerra FHR, Sales VC (2010) Geomorfologia do Nordeste: concepções clássicas e atuais acerca das superfícies de aplainamento nordestinas. Rev Geogr 1:6–19. (V. especial, VIII SINAGEO)

Manoel Filho J (2000) Ocorrência das águas subterrâneas. In: Feitosa FAC, Manoel Filho J (eds) Hidrogeologia: conceitos e aplicações. CPRM, Fortaleza, pp 13–33

Marengo JA, Torres RR, Alves LM (2016) Drought in Northeast Brazil – past, present, and future. Theor Appl Climatol 124:1–12. https://doi.org/10.1007/s00704-016-1840-8

Medrano H, Flexas J, Galmés JM (2009) Variability in water use efficiency at the leaf level among Mediterranean plants with different growth forms. Plant Soil 317:17–19. https://doi.org/10.1007/s11104-008-9785-z

Miles L, Newton AC, DeFries RS, Ravilious C, May I, Blyth S, Kapos V, Gordon JE (2006) A global overview of the conservation status of tropical dry forests. J Biogeogr 33(3):491–505. https://doi.org/10.1111/j.1365-2699.2005.01424.x

Ministério de Minas e Energias (2004) Estudos hidrogeológicos de bacias sedimentares da região semi-árida do nordeste brasileiro. MME/CPRM, Brasília

Molle F (1989) Perdas por evaporação e infiltração em pequenos açudes. Série Hidrologia 25. SUDENE, DPG. PRN. HME, Recife

Molle F (1994) Marcos históricos e reflexões sobre a açudagem e seu aproveitamento, Série Hidrologia 30. SUDENE/DPG/PRN/HME, Recife

Moro MF, Nic LE, Filer DL, Araújo FS, Martins FR (2016) A phytogeographical metaanalysis of the semiarid Caatinga Domain in Brazil. Bot Rev 82(2):91–148. https://doi.org/10.1007/s12229-016-9164-z

Nelson DR, West CT, Finan TJ (2009) Introduction to "in focus: global change and adaptation in local places". Am Anthopol 111:271–274. https://doi.org/10.1111/j.1548-1433.2009.01131.x

Neri AV, Silva AF, Souza AL, Ferreira-Junior WG, Meira-Neto JAA (2012) The influence of soils on the floristic composition and community structure of an area of Brazilian Cerrado vegetation. Edinb J Bot 69:1–27. https://doi.org/10.1017/ S0960428611000382

Palácio HAQ (2011) Avaliação emergética de microbacias hidrográficas do semiárido submetidas a diferentes manejos. Tese/Universidade Federal do Ceará, Fortaleza

Palácio HAQ, Andrade EM, Santos JCN, Araújo Neto JR, Brasil PP (2013) Emergy evaluation of semi-arid watersheds under different management strategies. Am Soc Agric Biol Eng J 56(6):1357–1363. 10.13031/trans.56.9951

Pennington RT, Prado DE, Pendry CA (2000) Neotropical seasonally dry forests and quaternary vegetation changes. J Biogeogr 27:261–273

Pereira Júnior JS (2007) Nova delimitação do semi-árido brasileiro. Câmara dos Deputados, Brasília

Pimentel JVF (2010) Caatinga e manejo agrossilvipastoril. In: Andrade EM, Pereira OJ, FER D (eds) Semiárido e o manejo dos recursos naturais: uma proposta de uso adequado do capital natural. Imprensa Universitária UFC, Fortaleza, pp 106–132

Prado DE (2008) As caatingas da América do Sul. In: Leal IR, Tabarelli M, Silva JMC (eds) Ecologia e Conservação da Caatinga, 3rd edn. Universitária da UFPE, Recife, pp 3–73

Rebouças AC (1997) Água na região Nordeste: desperdício e escassez. Estudos Avançados 11:127–154. https://doi.org/10.1590/S0103-4014199700 0100007

Rebouças AC (1999) Águas subterrâneas. In: Rebouças AC, Braga B, Tundisi JG (eds) Águas doces do Brasil: capital ecológico, uso e conservação. Escrituras, São Paulo, pp 117–151

Rodrigues JO, Andrade EM, Mendonça LAR, Plácio HAQ, Araújo EM (2013) Respostas hidrológicas em pequenas bacias na região semiárida em função do uso do solo. Rev Bras Eng Agríc Ambient 17(3):312–318. https://doi.org/10.1590/S1415-43662013000300010

Romero RE, Ferreira, TO (2010) Morfologia e classificação dos solos predominantes no semiárido cearense. In: Andrade EM, Pereira OPJ, Dantas FER (eds) Semiárido e o manejo dos recursos naturais. Imprensa Universitária, Fortaleza, pp 23–55

Saadi A (1993) Neotectônica da plataforma Brasileira: Esboço e interpretações preliminares. Geonomos 1(1):1–15. 10.18285/geonomos.v1i1e2.233

Sampaio EV (1995) Overview of the Brasilian Caatinga. In: Bullock SH, Mooney HA, Medina E (eds) Seasonaly dry tropical forests. Cambridge University Press, Cambridge, pp 35–58

Sampaio EVSB, Pareyn FGC, Figuerôa JM, Santos Junior AG (2005) Espécies da Flora Nordestina de importância econômica Potencial. Editora Universitária, Recife

Santiago AMP, Nogueira RJMC, Lopes EC (2001) Crescimento em plantas jovens de *Mimosa Caesalpiniifolia* Benth., cultivadas sob estresse hídrico. Revista Ecossistema 26(1):23–30

Santos MG, Oliveira MT, Figueiredo KV, Falcão HM, Arruda ECP, Almeida-Cortez J, Sampaio EVSB, Ometto JPHB, Menezes RSC, Oliveira AFM, Pompelli MF, Antonino ACD (2014) Caatinga, the Brazilian dry tropical forest: can it tolerate climate changes? Theor Exp Plant Physiol 26:83–99. https://doi.org/10.1007/s40626-014-0008-0

Santos JCN, Andrade EM, Guerreiro MJS, Medeiros PHA, Palácio HAQ, Araújo Neto JR (2016) Effect of dry spells and soil cracking on runoff generation in a semiarid micro watershed under land use change. J Hydrol 541:1057–1066. https://doi.org/10.1016/j.jhydrol.2016.08.016

Savadogo P, Tiveau D, Sawadogo L, Tigabu M (2008) Herbaceous species responses to long-term effects of prescribe fire, grazing and selective cutting tree in the savanna-woodland of west Africa. Perspect Plant Ecol Evol Syst 10:179–195. https://doi.org/10.1016/j.ppees.2008.03.02

Scalon SPQ, Mussury RM, Euzébio VLM, Kodama FM, Kissman C (2011) Estresse hídrico no metabolismo e crescimento inicial de mudas de mutambo (Guazuma ulmifolia Lam.) Revista Ciência Florestal 21(4):655–662. https://doi.org/10.5902/ 198050984510

Sena JOA, Zaidan HA, Castro PRC (2007) Transpiration and stomatal resistance variations of perennial tropical crops under soil water availability conditions and water deficit. Braz Arch Biol Technol 50:225–230. https://doi.org/10.1590/S1516-89132007000200007

Silva EC, Nogueira RJMC, Azevedo Neto AD, Brito JZ, Cabral EL (2004) Aspectos ecofisiológicos de dez espécies em uma área de caatinga no município de Cabaceiras, Paraíba, Brasil. Iheringia, Série Botânica 59(2):201–205

Souza ER, Fernandes MR (2000) Sub-bacias hidrográficas: unidades básicas para o planejamento e a gestão sustentáveis das atividades rurais. Informe Agropecuário 207:15–20

Sun L, Li H, Ward MN (2006) Climate variability and corn yields in semiarid Ceará, Brazil. J Appl Meteorol Climatol 46:226–239. https://doi.org/10.1175/JAM2458.1

Torres RR, Ferreira NJ (2011) Case studies of easterly wave disturbances over northeast Brazil using the eta model. Weather Forecast 26:225–234. https://doi.org/10.1175/2010WAF2222425.1

Zektser IS, Everett LG (2014) Groundwater resources of the world and their use. UNESCO, Paris