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Groundwater management in the state of Piauí (Brazil) on the climate change context

Gestão das águas subterrâneas no estado do Piauí (Brasil) no contexto das mudanças climáticas

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ABSTRACT

This article aims to evaluate the current state of groundwater management in the state of Piauí, considering the scenario of climate change and its adverse effects on aquifers. The analysis is based on the socioeconomic reality of the state, the availability and demand of groundwater resources, and the level of management and the possible impacts of climate change on the state. What is noticeable is that for the projected scenarios of climate change in the state, groundwater becomes a strategic source in mitigating the effects of climate change; however, the diagnosis produced shows that the state has already been using this resource too much, but without an efficient control of the public power. This combination tends toward a pessimistic view of both the state and groundwater in relation to climate change.

Keywords: IPCC scenarios; legal and institutional framework; aquifer systems; changes in the hydrological cycle; management system.

RESUMO

O presente artigo tem o objetivo de avaliar o estado atual da gestão das águas subterrâneas no estado do Piauí considerando o cenário das mudanças climáticas e seus efeitos adversos sobre os aquíferos. A análise é feita a partir da realidade socioeconômica do estado, da disponibilidade e demanda dos recursos hídricos subterrâneos e do nível de gestão e os possíveis impactos das mudanças climáticas para o estado. O que se nota é que para os cenários projetados das mudanças climáticas no estado, as águas subterrâneas tornam-se uma fonte estratégica na amenização dos efeitos das mudanças climáticas, entretanto, o diagnóstico produzido mostra que o estado já vem utilizando esse recurso em demasia, mas sem um controle eficiente do poder público. Essa combinação tende para uma visão pessimista tanto para o estado quanto para as águas subterrâneas em relação às mudanças climáticas.

Palavras-chave: cenários do IPCC; arcabouço legal e institucional; sistemas aquíferos; alterações do ciclo hidrológico; sistema de gerenciamento.

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Introduction

The strategic character of groundwater refers to the issue of using them to know them and learn to use them more efficiently (Rebouças, 2008). It is an important function, especially if you take into account that they can mitigate the effects of climate change since they are better spatially distributed, but also because of their ability to supply water for long periods without compromising their capacity.

Notwithstanding, groundwater is not immune to climate change and can suffer its effects both directly and indirectly. However, it is still difficult to quantify these effects, mainly due to the lack of data and information on aquifer systems, especially in developing countries (Ali et al., 2022; Kanema and Gumindoga, 2022).

Nonetheless, monitoring through a network of wells requires planning, time, and financial resources (Ali et al., 2022; Ishola et al., 2022; Smida et al., 2022). Thus, many researchers have preferred the use of remote sensing and satellite images, mainly from the GRACE satellites, for predicting and diagnosing groundwater in different parts of the globe, as is the case in the research performed by Ahmed et al. (2021), Gonçalves et al. (2020), Ouatiki et al. (2022), Scanlon et al. (2012), and Seidenfaden et al. (2022).

In this way, if the impacts of climate change are known but difficult to quantify, the success of measures to prevent them falls on the governance of groundwater, specifically on the management of aquifers. What actions have the governing bodies taken? What is the management level? What is the legal framework and government infrastructure? How has the population used groundwater? Is there enough water available to meet the demands? The answers to these questions are fundamental to investigating and analyzing how public authorities have been dealing with the impacts of climate change on groundwater resources.

In this sense, this study aims to answer these questions by considering the management of groundwater in the state of Piauí. Located in the northeast region of Brazil, Piauí has a climate ranging from hot and humid to semi-arid. Its geographical position places the state in a region between the Brazilian semi-arid region and the pre-Amazon region. This characteristic causes the state to have two distinct hydrological regimes, namely, the wet border (located in the north with a rainy regime with averages that exceed 1,000 mm/year) and a dry border (located in the southeast with rainfall below 500 mm/year and evaporation greater than 2,000 mm/year).

The largest water expression in the state is underground, as 80% of its territory is based on the Parnaíba sedimentary basin (SEMAR, 2010), with large aquifers and stored volumes. Although, the state is the third with the highest number of drilled wells, whereas with a large number of irregular users and still incipient management, there are several issues to overcome.

The forecasts presented by the Intergovernmental Panel on Climate Change report (IPCC, 2021), as well as those of Brazilian research papers (Ballarin et al., 2023; Delazeri et al., 2022; Fernandes et al., 2020; Silva et al., 2020) demonstrate that the state will suffer from an increase in temperature, reaching unbearable levels, in addition to an increase in the frequency of drought events. Thus, it is not difficult to see the strategic importance that groundwater will have if these scenarios take place.

The article was organized into five sections:

- climate change and groundwater, which addresses the effects of climate change on aquifers;
- water availability in Piauí, showing the state's underground water resources;
- economic activity and water use, analyzing the socioeconomic reality of the state and the main demands on water resources;
- groundwater management, with a focus on analyzing the legal framework and the state water resources management system in the face of climate change;
- climate change in Piauí and the use of groundwater, presenting the main impacts suffered by the state concerning climate change and how they can affect the management of groundwater resources.

Methodology

The methodology for carrying out this study started with the following guiding question: how has groundwater management in the state of Piauí been preparing for climate change?

Thus, a literature review was conducted first to understand the impacts that aquifer systems are susceptible to with climate change. The Periodicals Portal of the Coordination for the Improvement of Higher Education Personnel (CAPES) was used to search for articles related to groundwater and climate change. The keywords used were "groundwater", "management", and "climate change", with preferences given to recent scientific articles published in journals by specialists in the subject of groundwater.

With the identification of the impacts, the next step of the work was based on carrying out a diagnosis of the management of Piauí. The diagnosis was divided into three parts, namely, water availability, demands, and the legal and institutional framework of the state. In the first part, the geological formations and the main aquifer systems are highlighted. They were characterized according to the reserved water volume, condition (such as confined, free, or semi-confined), thickness, production, and water quality.

The second part characterizes the demands and their implications for groundwater. The starting point was a survey carried out by the authors regarding the grants issued between 2016 and 2017. This survey revealed three major uses, namely, human consumption, irrigation, and industrial use. Based on this survey and considering the existing gaps in the granting documents, an attempt was made to complement the information by consulting a database and official documents from the federal and state governments. Thus, we collected data from the National Sanitation Information System (SNIS), the National Supply Company (CONAB), the Irrigation Atlas of the National Water and Sanitation Agency (ANA), and the State Water Resources Plan (SEMAR, 2010). In addition, due to the direct relationship that land cover has with aquifer recharge, MAPBIOMAS data were collected to show the evolution of land use and land cover in the state.

The third part of the diagnosis analyzes the legal and institutional framework of the state. Laws, decrees, and resolutions regarding the focus of the research (groundwater and climate change) and their application in the state were analyzed. As for the institutional framework, it focused on the water resources management body, addressing its organizational structure, skills, technical staff, and issues in its performance.

The third stage of the research addresses the likely effects of climate change in the state, how groundwater will be affected, and the implications for management. To list the effects of climate change in the state, a search was conducted again for scientific articles using the CAPES Periodicals Portal. The keywords used initially were "Piauí" and "climate change" but, due to the scarcity of articles and the limitations of climate models, the study area was progressively expanded to "Northeast Brazil", "Brazil", and "Latin America". The sixth report of the Intergovernmental Panel on Climate Change (IPCC), the Physical Sciences Basis, and the Brazilian Panel on Climate Change (PBMC, 2016) were also consulted.

With data in hand, a discussion is promoted on the level of preparation of the managing body for climate change, the deficiencies of the information system, the main management issues, and possible solutions to circumvent the problems.

Groundwater and climate change

Identifying, qualifying, and quantifying impacts on groundwater are difficult to predict. In general, this can be explained by the residence time, which can take years before the effects are felt, and by the lack of data and monitoring. The latter seems to be the major issue in studies on groundwater, mainly to understand its relationship with climate change. Authors such as Assaoui et al. (2021), Dragoni and Sukhija (2008), Holman et al. (2012), and Kumar (2012) demonstrated how the scenario has changed little over the past two decades.

For Assaoui et al. (2021), the following factors should also be considered when considering the imprecision of the effects of climate change:

- the imprecision of climate models;
- the difficulty in estimating recharge rates;
- the difficulty in modeling the interaction between groundwater and surface water over large areas.

Holman et al. (2012) outline procedures and standards to be adopted in this type of study to maximize the value of the study as well as assess the impacts and techniques for adapting to climate change. They are using multiple scenarios of general circulation model (GCM) and regional circulation models (RCM); using multiple greenhouse gas emission scenarios; considering the implications of downscaling methods; considering the uncertainties and errors of hydrogeological models; considering indirect effects on aquifer recharge caused by climate change; evaluating, for different scenarios, the water levels in the aquifer for different climatic conditions; bearing in mind the socioeconomic impacts related to land use and occupation and water demand; and analyzing the effectiveness of adaptive techniques.

The effects of climate change on groundwater happen both directly and indirectly. In the first case, with changes in climate variables, such as precipitation and evaporation, the aquifer recharge rates, and the soil water content (SWC) will consequently change.

Amanambu et al. (2020) also warn of changes in the quality of these waters. According to the authors, the increase in rainfall in areas with high concentration of contaminants can encourage their infiltration into aquifers. The temperature increase can also alter the quality of the water since it alters the hydrogeochemical characteristics of the aquifers, which control the mobility and dissolution of contaminants (Amanambu et al., 2020).

Jannis et al. (2021) also list the following impacts due to the increase in temperature: changes in porosity and permeability of the aquifer system; changes in microbiological and chemical activity, which may favor the growth of harmful bacteria, and changes the biodegradation of contaminants; change in the dissolution of gases; changes in the geothermal functions of aquifers; also, when taking into account the discharge of these aquifers into rivers, the increase in groundwater temperature can harm river biota, especially those fish that seek refuge in colder waters because of the summer.

Secondary effects can be felt through the overexploitation of aquifers, as they tend to be more heavily employed to remedy the effects of rising temperatures and prolonged droughts. Hirata and Conicelli (2012) highlight the strategic character of groundwater in times of climate change, as aquifers can supply water for long periods and prolonged drought events; however, increased demand can affect not only aquifers but also the runoff bases of rivers and lakes, reducing biodiversity.

A very emblematic case is the state of São Paulo, whose demand for grants for groundwater increased exponentially due to the water crisis in 2014 in the main water supply systems (Governo do Estado de São Paulo, 2017).

Furthermore, overexploitation of aquifers can cause subsidence and saline intrusion. These effects are particularly important in coastal aquifers since they are vulnerable to this type of contamination when there is a lowering of the hydraulic head, allowing the inversion of the flow of salt water into the aquifer. It can cause users to drill deeper and deeper wells and encounter poor-quality water, which is common in coastal aquifers (Amanambu et al., 2020).

On subsidence, it can amplify the effect of sea level rise on coastal cities. Tokyo and Venice are examples of cities that tend to suffer from the combined effect of climate change and land subsidence. Venice in the 20th century had a relative increase in the level of the sea of 23 cm, of which 9 were due to anthropic actions (Brambati et al., 2003), whereas Tokyo had an area of 178 ha submerged (Brimblecombe et al., 2020).

In addition to the changes caused by climate change, changes in land cover can influence groundwater and accentuate the effects of climate change. Spera et al. (2016) demonstrate the change suffered in the hydrological cycle in the MATOPIBA region due to monoculture. Although evaporation rates in the dry season are lower in monoculture, they tend to be higher in the rainy season than in native vegetation. In addition, the authors point out that from 2003 to 2013, there was a water loss of 3 km³ due to the increase in cultivated areas.

In a similar proposal, Melo and Wendland (2017), when simulating the recharge volume and the water level in the outcrop zone of the Guarani Aquifer System for citrus, pasture, eucalyptus, and sugarcane areas, showed that recharge rates will be more negatively affected in the last two, especially for the sugarcane area, due to the high evapotranspiration rates of the culture.

Mahmoodi et al. (2021) and Wu et al. (2020) show that the combined action of climate change and demand for groundwater accentuate the negative effects on aquifer systems. It is noteworthy that Wu et al. (2020) demonstrate that when considering only the effects of climate change, there was an increase in aquifer storage; however, in the scenario of climate change and demand, there was storage decay.

Water availability in Piauí

Geographically, the state of Piauí is located in a transition zone, which allows rainfall heterogeneity with three very distinct types of climates, namely, semi-arid, humid tropical, and tropical (SEMAR, 2010). However, the rainfall regime is quite characteristic of the semi-arid region, with a rainy season concentrated in 3 months of the year and a dry season in the others.

In addition, its geographical position gives the state a particularity in terms of rainfall. Considering the southeast-northwest direction, precipitation in the state varies from 600 to 1,500 mm/year, with the highest rates concentrated in the north of the state and the municipalities bordering the state of Maranhão.

Evaporation follows the opposite path to precipitation, increasing from the northwest to the southeast and varying from 500 to 3,000 mm/year. The municipality of Paulistana had the highest evaporation ever recorded in the state at 4,033.30 mm/year (SEMAR, 2010).

However, 80% of the state territory is based on the Parnaíba sedimentary basin, and the remainder is divided between the crystalline basement (bordering the states of Pernambuco, Bahia, and Ceará) and the Coastal Province, on the coast (Figure 1).

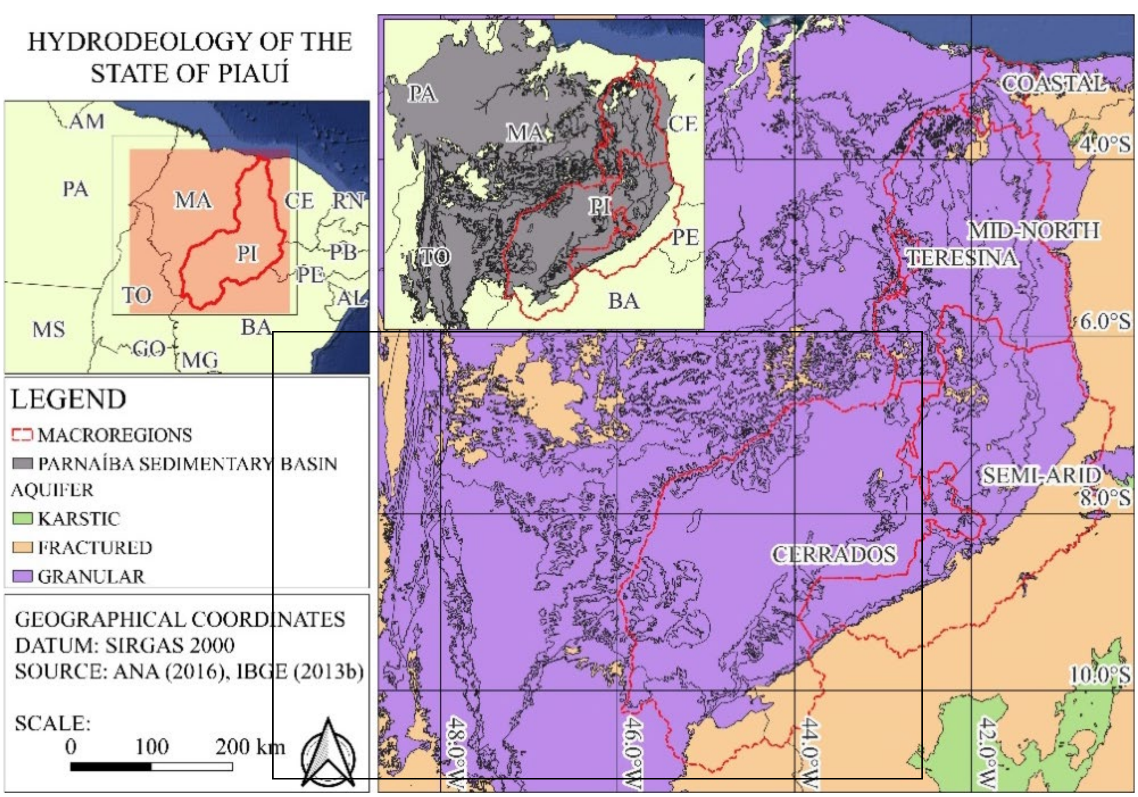

Figure 1 – Hydrogeology of the state of Piauí.
Source: ANA (2016); IBGE (2013b).

The Parnaíba sedimentary basin is the third largest in terms of water availability in Brazil (Mente, 2008) and has a rounded shape, extending from Ceará to Pará in an east-west direction and from Maranhão to Tocantins in a north-south direction. The aquifers with the greatest availability are Serra Grande, Cabeças, and the Poti/Piauí system. All of them are regional extensions and widely used in Piauí. The availability of these aquifers is 995,249, 256,443, and 541,488 hm^3/year, respectively (SEMAR, 2010). Feitosa et al. (2012) calculate that, in the area of the Gurguéia River valley, it would be possible to extract a flow of 20,000 m^3 from the Cabeças Aquifer in 300 years without compromising its reserves. The authors recommend the creation of a strategic groundwater production zone.

Both Serra Grande and Cabeças have their outcroppings in the eastern region of the state, appearing in the rest in a confined manner. The Serra Grande Aquifer has an extension of 277,750 km^2, with an average thickness of 600 m; 89% of its extension is confined, being overlapped by Aquitardo Pimenteiras. The supply of the aquifer is almost exclusively done by infiltration in its outcropping part (Feitosa, 1990).

The Cabeças Aquifer has an extension of 228,250 km^2, of which, 188,850 km^2 is confined between the Longá and Pimenteiras formations. Its thickness, in the outcropping part, can vary from 40 to 60 m and reach up to 300 m in the confined part. Its feeding takes place by direct infiltration into the aquifer, by rivers, and by the contribution of the Poti/Piauí system (SEMAR, 2010).

The Poti-Piauí system, unlike the previous ones, occurs in greater proportion as a free aquifer. Its total extension is 164,400 km^2 with an average thickness of 400 m. However, in Piauí, its thickness does not exceed 100 m. Its confined part is limited by the Areado and Pedra de Fogo formations. According to the State Plan (SEMAR, 2010), it is the main system that contributes to feeding rivers in the Parnaíba river basin.

The great water potential of the state is found at great depths. The survey carried out by the State Plan (SEMAR, 2010) shows that the average depth of the wells is greater than 100 m, with flows in the range of 8–22 m^3/s, characterizing a high to very high production. On the contrary, the free flow is characterized by a range from very low to high (CPRM, 2015).

As for water quality, the State Plan (SEMAR, 2010) points out that it is of good quality, with concentrations of total dissolved solids (TDS) below 500 mg/L. Only parts of the coast and the region of the crystalline basis have waters with higher concentrations, which can exceed 1,000 mg/L.

Economic activity and water use

To make comparison possible, the state of Piauí was divided into five areas of study, called macroregions, and illustrated in Figure 2.

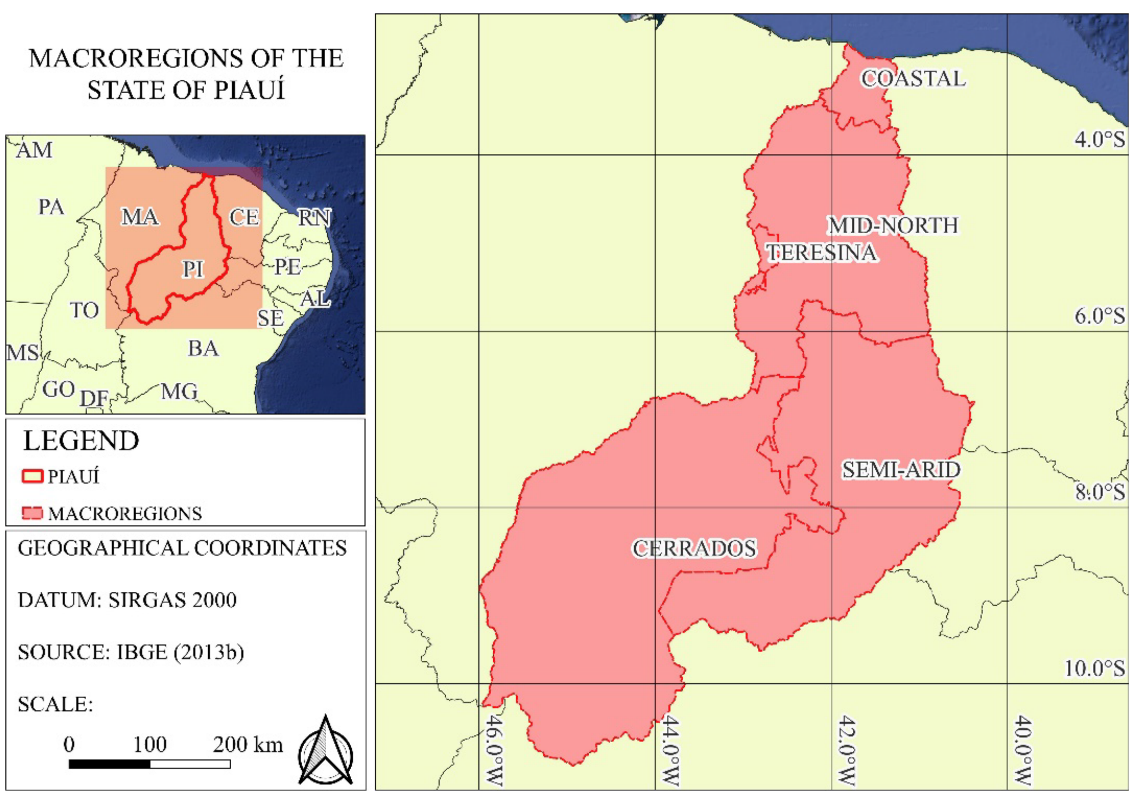

Figure 2 – Study area divided by macroregions.
Source: IBGE (2013b).

According to the 2010 Census, the population of Piauí was 3,119,015 inhabitants, divided into 224 municipalities (IBGE, 2013a), most of which are located in the capital, Teresina (26.11%). Most Piauí municipalities have a population of less than 20,000 inhabitants (89%). Only five municipalities (Teresina included) have a population of more than 50,000 inhabitants, each belonging to a macroregion of the state.

This is reflected in the volumes of water used for public supply. According to the National Sanitation Information System (SNIS, 2021), in 2020, Teresina had the largest volume of water used for this purpose, both surface and underground. It is worth noting that the volume of groundwater used is at least 10 times greater in three of the five macroregions of the state (Figure 3).

Furthermore, analyzing the evolution of water volumes (Figure 4), it is possible to notice that only in Teresina, the volume from groundwater remained constant. For the state of Piauí, in general, the demand for groundwater for public supply becomes higher from 2011 onwards. In 2020, this volume was 70% higher than that of surface water.

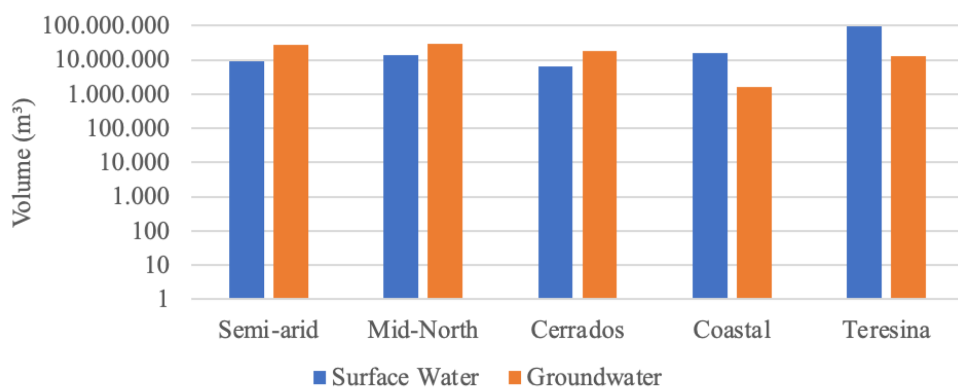

Figure 3 – Volume of water by source for human supply in 2020.
Source: based on SNIS data (2021).

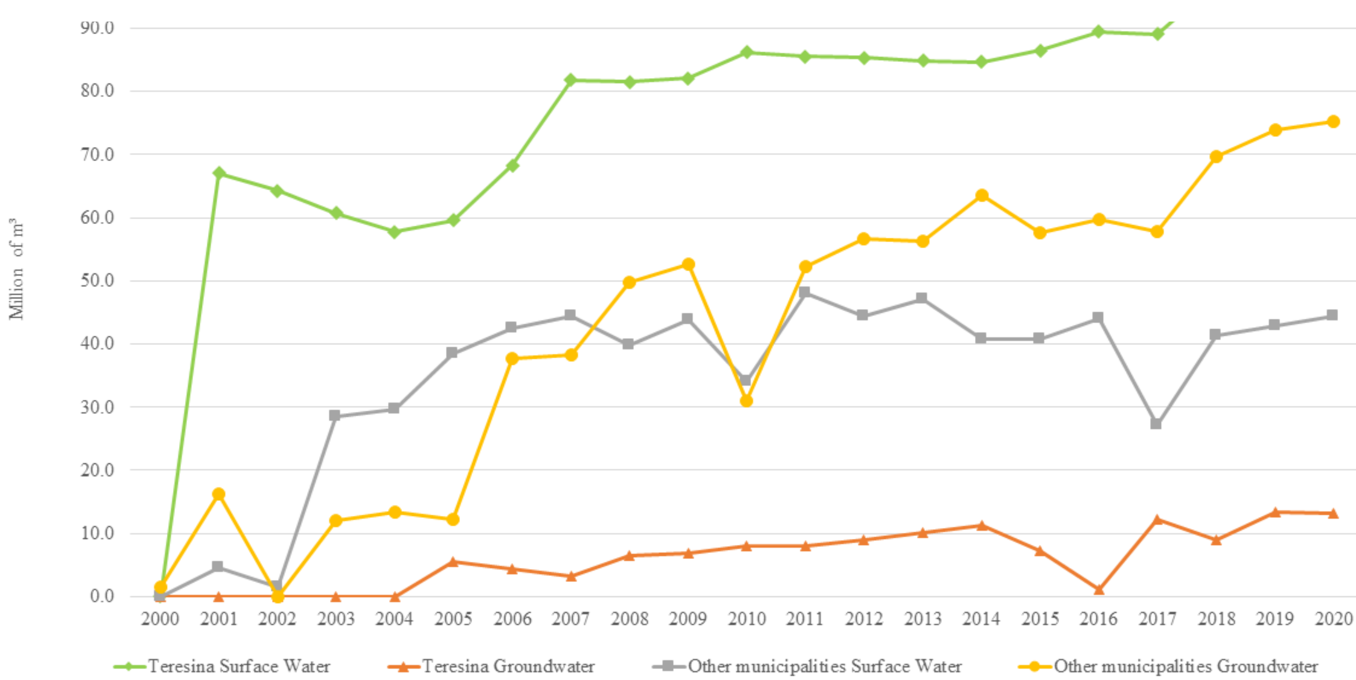

Figure 4 – Evolution of water demand for public supply by year and by source.
Source: based on SNIS data (2021).

Piauí's GDP is the lowest in the northeast region. In 2019, it reached the mark of 50 million reais, making it the seventh state of Brazil with the lowest GDP (IBGE, 2020). Of the GDP distribution by macroregion, Teresina holds 42% and the Coastal, only 6%. The other macroregions have similar percentages of participation.

Despite this, much of the wealth produced in the state is due to the service sector. On average, the sector's participation in the GDP is 70%, reaching a maximum of 81% in the Meio Norte, and 47% in the Cerrados. This macroregion also has the highest added value in agriculture with 31%, while the other regions do not exceed 10%.

It is considered the last agricultural frontier in Brazil and is known as MATOPIBA, an acronym formed by the abbreviations of the states of Maranhão, Tocantins, Piauí, and Bahia to highlight a region with great soy production. Spera et al. (2016) show that, in Piauí, soybean production almost quadrupled in this area between 2003 and 2013.

According to data from the historical series made available by the National Supply Company (CONAB, 2021), soybean production in the state increased sharply from the 2001/02 harvest onwards, with only two periods of decline in production (2012/13 and 2015/16), which soon recovered in the following harvests. For example, the 2016/17 crop was more than triple the previous one. Also, if you consider the pandemic period, there was a slight drop in soybean production between the 2018/19 and 2019/20 harvests (2.71%). However, it is expected that for the 2020/21 harvest, it will be enough to recover the losses suffered and grow at the same rate (CONAB, 2021).

Regarding the total area, soybean cultivation began to increase from the year 2000 onwards, reaching a total of 758.9 ha in 2019. For the 2020/21 harvest, an increase of 10% is expected (CONAB, 2021).

The Irrigation Atlas 2019 (ANA, 2021) shows that the largest irrigated area is in the Mid-north (19.5 ha), followed by the Cerrados (12.6 ha). Sugarcane is the crop with the largest irrigated area in the state and is present in three of the five regions: Teresina, Cerrados, and Mid-north. However, there is a set of other crops and systems, not detailed in the Atlas, that have a great presence in all macroregions. According to the ANA (2021), horticulture and some grains (such as rice, beans, and soybeans) that do not use central pivots are in this group. In the semiarid region, this set represents almost all irrigated crops.

In consultation with MAPBIOMAS (Brasil, 2021), the areas of forest and non-forest natural formation have decreased in all macroregions, although this is much more noticeable in the Cerrados (Figures 5A and 5B). In this same region, there was a significant increase in the agricultural area (pastures and agriculture) from 2003 onwards (Figure 5C).

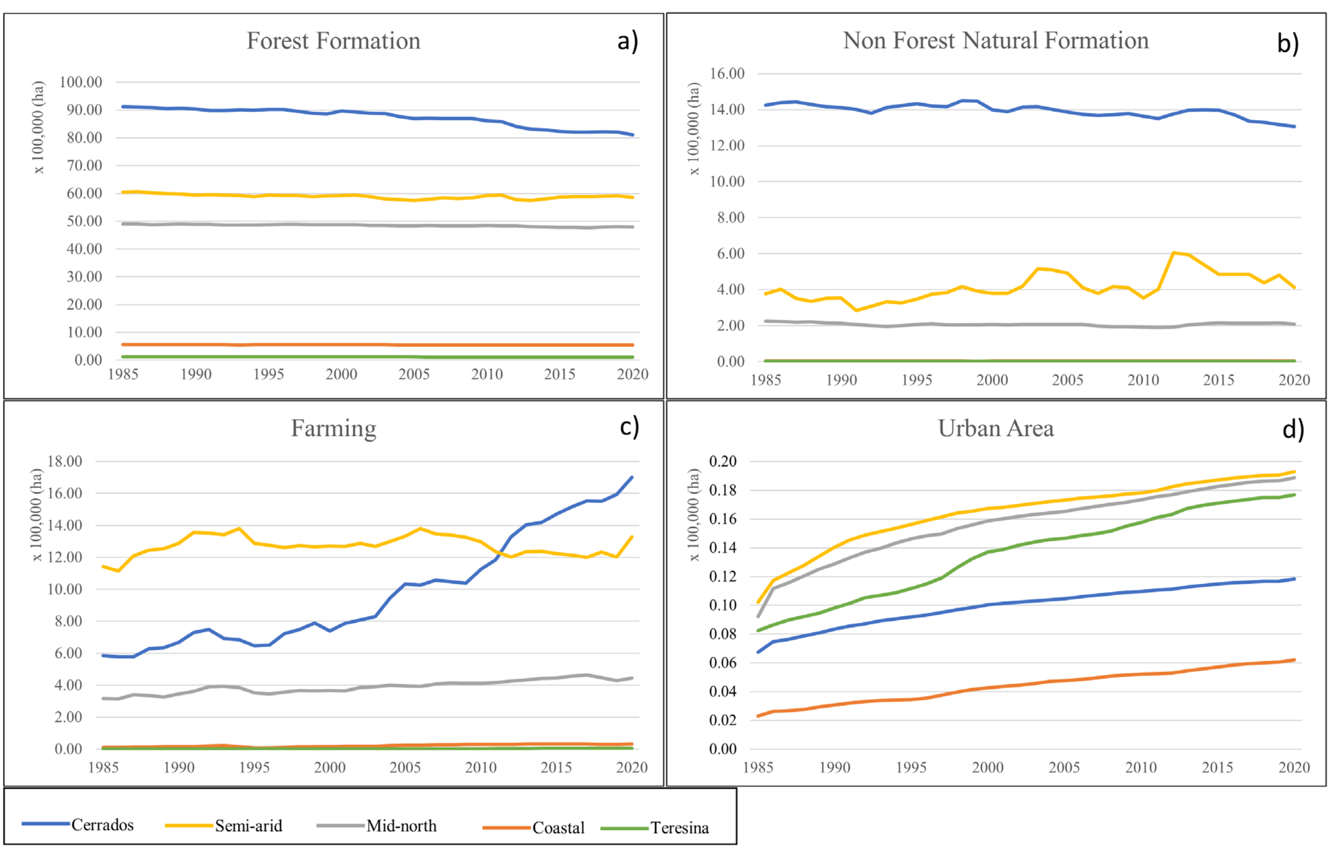

Figure 5 – Evolution of land cover in the state of Piauí: (A) forest formation, (B) non-forest natural formation, (C) agriculture, (D) urban infrastructure.

Furthermore, as per Figure 5D, there has been a constant increase in the urban area. Teresina draws attention to the fact that, despite representing a single municipality, its urban area is comparable to the macroregions of the Mid-north and Semi-arid regions.

Projections for the years 2030 and 2040 indicate an increase in the irrigated area in relation to 2019 from 30 to 67% in all macroregions, except for the Litoral, which is expected to drop from 5 to 9% (ANA, 2021). The demand for water was estimated at 10.2 m^3/s in a medium climate scenario, with a projected increase of 50% for the year 2040 (ANA, 2021). The State Plan (SEMAR, 2010) projects a total water demand for agriculture in 2030 between 39.69 and 44.80 m^3/s, depending on the adopted scenario.

Consulting the managing body, the main demands for 2016 and 2017 were for human consumption, irrigation, and industrial use. The three uses corresponded to 95 to 99% of all demand for both years analyzed (Figure 6). Of this granted volume, more than 90% had groundwater as a source. The Cerrados macroregion was the one that had the most requests approved by the managing body. Figure 7 shows that, in 2017, three of the five municipalities with the highest granted volumes are in this region.

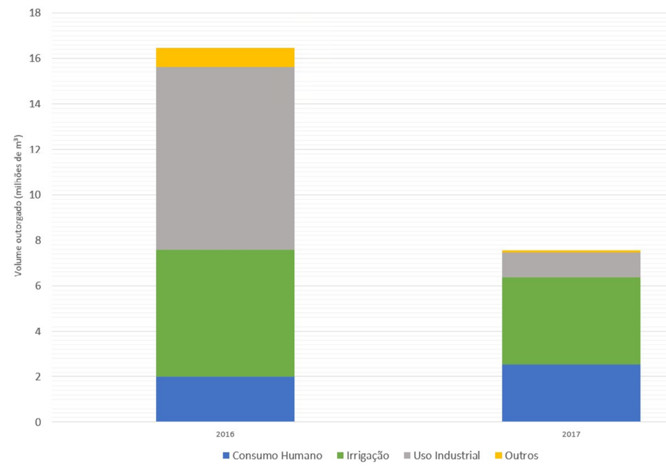

Figure 6 – Volume granted between 2016 and 2017.

The Groundwater Information System (SIAGAS) is the largest database of registered wells in Brazil. It states that in Piauí, there are more than 36,000 wells drilled. However, the managing body's database had just over 8,000 grant processes. It is not possible to know which wells registered in SIAGAS are regularized in the managing body since the platforms are not integrated and this information is not included in the SIAGAS register and vice versa (SIAGAS, 2022).

Figure 8 illustrates the density of wells by area, municipality, and by inhabitants. It is interesting to note that, in both cartograms, the region around the capital has a high density of wells. However, depending on the observed scenario, there are some differences. When looking at the population, it is noted that higher percentages are in municipalities bordering other states. For the density of wells per km², there is a certain homogeneity between municipalities with less than 0.5 wells/km². However, it is necessary to be aware of the distortions in this case since in the Cerrados macroregion, the municipalities are much larger than the other regions, therefore generating smaller percentages.

Furthermore, Figure 8 only surveys the number of wells without, however, considering the volume of water extracted from them, information not contained in the CPRM register. Thus, it is likely that there is another scenario, as shown in the previous item.

There is also the State Policy on Climate Change, enacted by Law No. 6,140/2011 (SEMAR, 2014), which lists a series of programs and subprograms targeted and specific to each sector of Piauí society aimed at reducing the emission of greenhouse gases. Among these, the Water subprogram stands out, intending to implement payments for environmental services for rural properties in up to four fiscal modules.

Despite the programs, no goals were established, nor was there a projected horizon for achieving them. The only program that is

Groundwater management

The State Water Resources Policy of Piauí was enacted by Law No. 5,165 (SEMAR, 2015). In general terms, the content of the policy is quite similar to the National Water Resources Policy, differing in a few topics, such as the chapter dedicated to groundwater, in which it establishes the protection areas for aquifers.

In general, the legal framework for water resources is small and focuses on regulating the granting of use rights. Less or no attention is directed to the other instruments of the policy. The State Plan itself (SEMAR, 2010) criticizes this fact when analyzing the organizational chart of the managing body and realizing that only the grant has a specialized department, while for the other instruments the responsible sector is not established.

That implies, for example, the monitoring of water resources. The best-monitored climate variable is rainfall. Several institutions, both state and federal, are concerned with measuring the process; however, the State Plan (SEMAR, 2010) reports the poor distribution of rainfall stations, as well as the failures and inconsistencies of the data.

Other hydrological cycle processes such as surface runoff, infiltration, and groundwater levels are poorly monitored. There are only 25 fluviometric stations, with more than half concentrated in two sub-basins (Canindé and Poti), and 4 sub-basins (Itaueira, Piranji, Difusas do Litoral, and Difusas da Barragem Boa Esperança) with none (SEMAR, 2010).

Concerning groundwater, there is only the Integrated Groundwater Monitoring Network (RIMAS), coordinated by the Geological Survey of Brazil (CPRM), but limited to some aquifers in the state, especially Serra Grande.

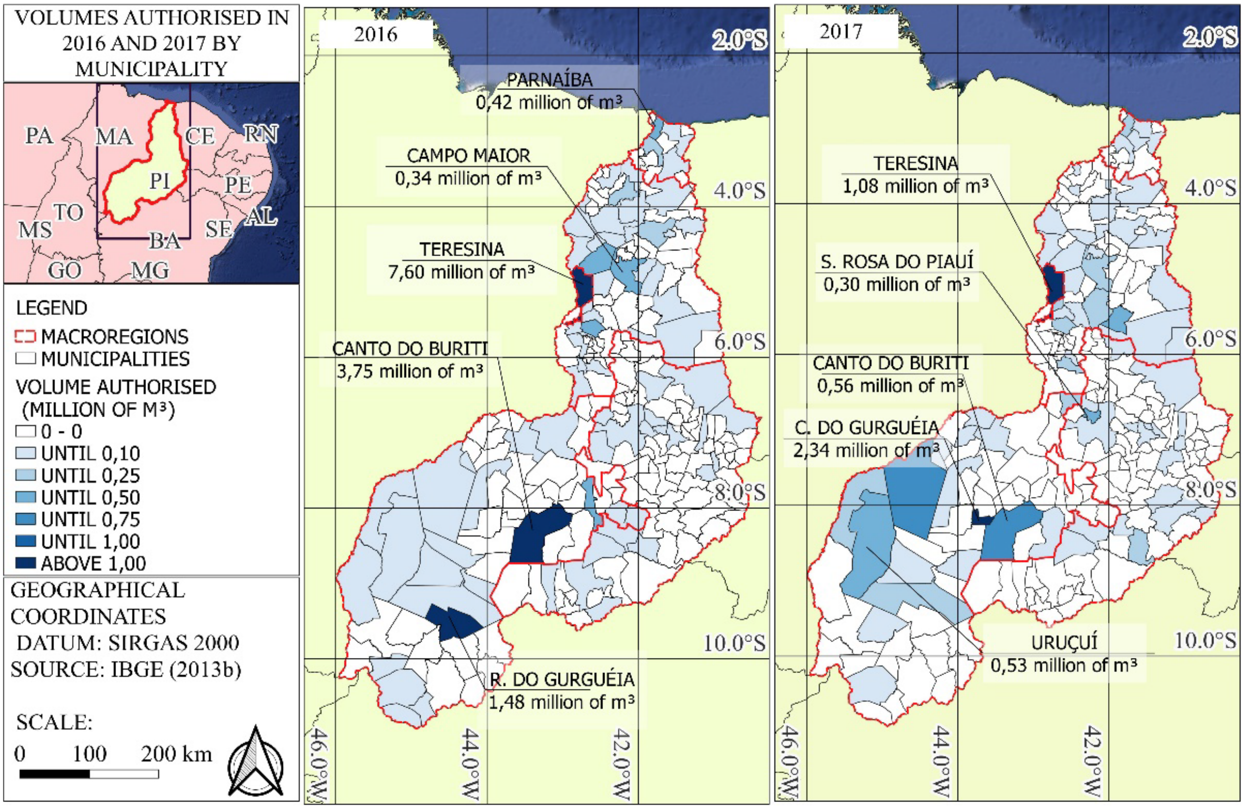

Figure 7 – Volume granted in years 2016 and 2017 by municipality.
Source: IBGE (2013b).

currently known and implemented in the state is the Ecological ICMS, whose purpose is to financially reward Piauí municipalities that promote actions for the preservation and conservation of the environment.

It is worth pointing out that both policies are coordinated by the Secretariat for the Environment and Water Resources of the State of Piauí (SEMAR). The body is also responsible for implementing and executing the Environmental, Dam Safety, and Conservation Units Policy. The State Plan (SEMAR, 2010) criticizes this concentration of attributions, as all responsibility for errors and successes falls on a single body.

SEMAR still suffers from the turnover of professionals and a small technical staff (Monteiro and Cabral, 2018). Although a public tender was held to fill 12 vacancies, the survey carried out by the State Plan (SEMAR, 2010) indicates that at least 100 effective servants would be needed.

Monteiro and Cabral (2018) also list other problems in management, such as the lack of an information system, the weak performance of the State Water Resources Management System, and the lack of integration with other policies.

Despite this, SEMAR has been trying to overcome these issues. An example of this is the recent implementation of the Integrated Environmental Management System (SIGA), the creation of a specialized department in geoprocessing, and the development of an information system on groundwater in the state. Another positive point is adherence to programs to strengthen water management coordinated by the National Water and Sanitation Agency, such as a program called *Progestão*.

Climate change in Piauí and perspectives for groundwater management

The sixth IPCC report states that since 1850, the Earth's temperature has been increasingly hot. During 2001–2020, there was an average increase of 0.99°C. In the decade 2011–2020, the global surface temperature registered an average increase of 1.09°C (IPCC, 2021). The report also states that in many parts of the world, people are already suffering from the effects of climate change as heat waves, heavy precipitation, droughts, and tropical cyclones. For northeastern Brazil, an increase in average temperature is expected (Delazeri et al., 2022; Silva et al., 2020).

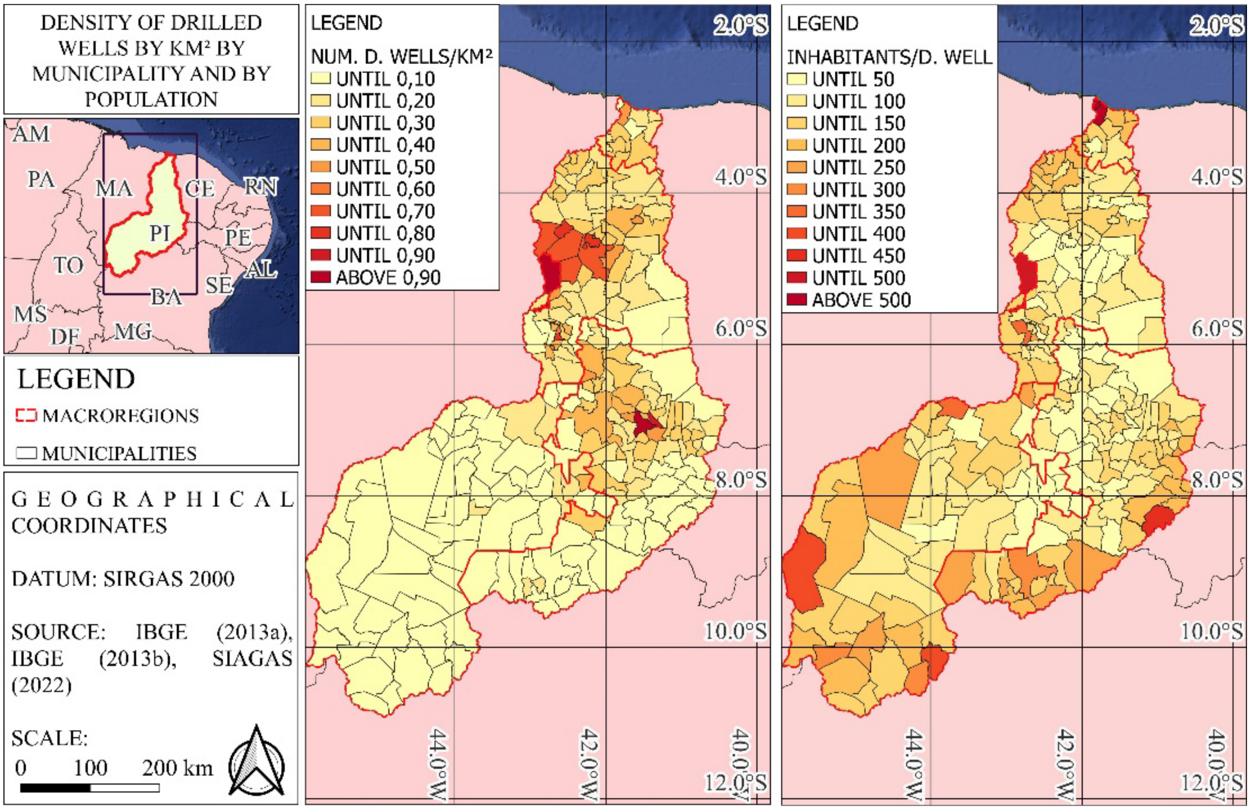

Figure 8 – Density of wells.
Source: IBGE (2013a; 2013b) and SIAGAS (2022).

Ballarin et al. (2023), based on the Couple Model Intercomparison Project Model (CMIP6) models for the SSP5-8.5 scenario, calculate that the Cerrado and Caatinga biomes, where the state is, should suffer an increase in both maximum and minimum temperature. In the Cerrado, the maximum monthly temperature variability will range from 15 to 20%, while the minimum will range from 20 to 35%. In the Caatinga, the monthly maximum temperature will increase by around 15%, while the monthly minimum will range from 15 to 25%. The authors also project a seasonal change in precipitation in the Cerrado, with the first months being the wettest and the last being the driest. However, in the Caatinga, there will be a generalized decrease in precipitation.

On the website of the National Institute of Meteorology (INMET, 2023), the climatological normals available at meteorological stations in the state of Piauí show that the period 1991–2020 has higher average temperatures than the periods 1931–1960 and 1961–1990. Fernandes et al. (2020), when analyzing data from 1961–1990 and 1981–2010, calculated an average increase of 0.8°C between the climatological normals, reaching a maximum of 1.5°C October–November–December. Meanwhile, there was a decrease in precipitation, mainly in the southern part of the state.

According to Santos and Melo (2010 *apud* PBMC, 2016), Teresina will face levels of thermal discomfort close to unbearable stress due to heat in the thermal discomfort index. For the semiarid region of the state, Brito et al. (2018) show an increase in both the frequency and severity of hydrological and agricultural droughts for the 2011–2016 5-year period when compared to previous periods.

According to the Food and Agriculture Organization of the United Nations (FAO, 2017), it is likely that the world population will exceed 11.2 billion inhabitants in 2100. If this estimate comes true, it will demand a corresponding increase in agricultural production, which imposes serious risks on the sector since it demands more natural resources, deforestation, and soil degradation. This is particularly harmful to countries like Brazil, which rely heavily on agriculture to produce jobs and wealth in addition to hampering food security and nutrition (FAO, 2017). While it is necessary to increase food production to meet the growing demand, it is essential to find sustainable ways to maintain this production without worsening the effects of climate change. However, the solution to this problem is still an issue (Leal Filho et al., 2022).

For these scenarios, it is not difficult to perceive the important role that groundwater has had and will have in mitigating the effects of climate change.

The state of Piauí is on an important water reserve. However, the state has already overexploited this resource. The sanitation (Figure 4) and agriculture (Figure 6) sectors demonstrate the pressure suffered by this source. Average monthly temperatures range from 23 to 30°C, depending on the region of the state, while maximum temperatures can reach 40°C (SEMAR, 2010). If the scenarios calculated by Ballarin et al. (2023) materialize, maximum temperatures could exceed 40°C, especially in the hottest months (September to December). This sharp temperature rise could harm not only the lives of the population of Piauí but also the fauna and flora. In addition, the temporal change in the rainfall regime in the Cerrado biome will directly impact agricultural production in the south of the state.

Soybean monoculture has expanded south of the state, which has already caused changes in the hydrological cycle, as demonstrated by Spera et al. (2016). It is also in this same region that the largest volume of groundwater granted between 2016 and 2017 was found (Figure 7), although it is not possible to make a correlation between which crops and which types of irrigation systems use the most water.

This, combined with weak management, presents a pessimistic scenario for the state. The State Plan (SEMAR, 2010) and Vidal (2003) present evidence of the lowering of the Serra Grande and Cabeças aquifers due to overexploitation in the Cerrados macroregion and the municipality of Picos (Semi-arid region). Vidal (2003) calculate the lowering of Serra Grande at 90 cm per year.

Furthermore, the state has a large number of irregular users, as can be seen from item 6. Without a robust user register, it is not possible to quantify the total volume of water used or the conditions for exploiting the aquifers.

For Lall et al. (2020), it is essential to know the volume of water extraction occuring simultaneously and on a scale of time and space appropriate for management. However, in most places, this type of information is lacking, depending on AQUASTAT, an information system on water and agriculture from the FAO. The authors criticize the system because the data come from different sources and, generally, the results are given at the continent or country level.

There is also a poor groundwater monitoring network, making it difficult to obtain safe and accurate information for the hydrological modeling process and, consequently, for decision-making. As seen in the topic "Groundwater and Climate Change", information is needed on demand, geological characteristics, climate processes, and interactions between surface and groundwater; however, the most present data are from pluviometry. Other climate data is managed exclusively by INMET, and data on aquifer systems is managed by CPRM.

Hydrological modeling becomes fundamental for management as it enables the construction of scenarios, planning, and public policies that reflect the objectives and decision-making processes (Gorelick and Zheng, 2015). Hydrological modeling can be used in different ways: to calculate safe extraction levels (safe yield) (Sayed et al., 2020), different measures of resilience against climate change (Afruzi et al., 2021; Saadatpour et al., 2022), and the sensitivity of aquifer systems to climatic and hydrological variables (Pasta Cordeiro et al., 2021; Seidenfaden et al., 2022).

An opportunity for management would be to use satellite data to monitor groundwater, even at a macro scale, and produce an updated diagnosis of the situation of aquifer systems, bearing in mind that the information that the state holds today about its underground dates from the 1980s and 1990s, in addition to isolated actions carried out by researchers. However, Amanambu et al. (2020) recommend investing in a dense and robust monitoring network, mainly for remote and underdeveloped regions, to obtain data for more detailed studies and supplement other studies whose spatial resolution is coarser. The authors stress that monitoring should focus on both quantitative and qualitative aspects.

Although there is a State Policy on Climate Change and there are predictions about the protection and importance of surface sources, few actions are noted to reduce greenhouse gases, such as the Ecological ICMS.

The State Water Resources Policy provides for the delimitation of aquifer protection areas. However, this instrument was never used, although its application could be interesting mainly in areas of recharge, vulnerability, and in the valley of the Gurguéia River. Even with the advancement of agricultural land (Figure 5C) and urban areas (Figure 5D), it is essential to protect recharge areas from both waterproofing and contamination processes. Furthermore, authors such as Afruzi et al. (2021) and Saadatpour et al. (2022) demonstrate that a reduction in the volume of water pumped or in the number of wells used brings benefits to the piezometric levels of the aquifers, even for the most pessimistic scenario (RCP8.5). Afruzi et al. (2021) also emphasize that, for irrigation, it is important to develop techniques for the efficient use of water, the reduction of the irrigation area, and the promotion of rainfed agriculture.

Although the state has promoted actions to strengthen management, they are still few and insufficient in the face of the challenges posed by climate change.

From the survey, although it is not possible to enumerate or quantify the direct effects of climate change on groundwater due to a lack of data, the diagnosis shows that the state tends to suffer from indirect effects. This situation is similar to that reported by Jayakumar and Lee (2017), who analyzed the groundwater situation of the Mekong River Basin in several Asian countries. The authors attest that the lack of information and knowledge about aquifer systems prevents a more accurate diagnosis of the effects of climate change. However, the population and economy of these countries massively depend on this water source, exerting great pressure on it.

The scenarios projected for Piauí are high temperatures, heat waves, increased frequency of droughts, decreased precipitation, and river flow. These impacts should be accentuated by the change in land cover (from natural areas to urban and agricultural infrastructure), which should put even more pressure on aquifer systems to mitigate such effects.

Conclusion

The forecast for the state of Piauí on the effects of climate change is an increase in temperature, a decrease in precipitation, and an increase in the frequency of drought events. Such impacts will affect groundwater mainly indirectly since the demand for the resource must increase to mitigate the effects of drought, projected high temperatures, and agricultural production.

Groundwater resources are already widely used by Piauí society for domestic and agricultural purposes. In addition, there is a wide range of irregular users, which does not allow the calculation of the entire volume of water extracted from aquifers nor its primary purpose.

Grain production in the state tends to increase. On the one hand, it proves advantageous from the point of view of employability and producing wealth; on the other hand, it brings challenges, as it increases the demand for water resources for arable areas, changes the use and occupation of the soil, and consequently the processes of the hydrological cycle. Thus, increased production accentuates the impacts of climate change, which in turn impacts agricultural production, generating food insecurity, malnutrition, and financial risks (FAO, 2017).

With still very incipient management, an inadequate monitoring network, a weak information system, and a weak performance by the managing body, this scenario is even more pessimistic due to the state's lack of preparation in the face of climate change. The lack of knowledge about the resource to be managed is the main issue, considering the main vulnerability of groundwater.

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