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Groundwater resources for agricultural purposes in the Brazilian semi-arid region[1]

Recursos hídricos subterrâneos para fins agropecuários no semiárido brasileiro

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HIGHLIGHTS:

Groundwater reserves are not sufficient to meet demand and water use efficiency must be improved.
Overexploitation of groundwater prevents aquifer recovery and agricultural activities.
Groundwater quality is not limiting for agricultural use; however, water resources management strategies are required.

ABSTRACT: Exploitation of groundwater resources with no proper characterization of water reserves jeopardizes the quantity and quality of water available in the future. A major challenge is finding appropriate methods or coefficients to evaluate the carrying capacity of the aquifer. The objective of this study was to quantitatively and qualitatively characterize water reserves to provide information and management strategies for the rational use of available water resources in an alluvial aquifer in the Brazilian Northeastern semi-arid region. Shallow and medium-depth wells were analyzed. Water tables were monitored in the dry and wet seasons to calculate water reserves. Groundwater samples were collected for the determination of water quality for irrigation purposes. The increase in agricultural activities is jeopardizing the sustainability of the aquifer's water, as reserves are not sufficient to meet this demand. Groundwater quality is not limiting for agricultural use. Converting surface irrigation into localized methods will potentially increase water productivity and consequently the irrigated area. This study provides data and makes it possible to recommend appropriate strategies for the exploitation of groundwater resources for the maintenance of agricultural activities under semi-arid conditions, and to avoid overexploitation.

Key words: aquifer overexploitation, need for irrigation, water quality

RESUMO: A explotação dos recursos hídricos subterrâneos sem a caracterização adequada das reservas hídricas compromete a quantidade e a qualidade da água disponível no futuro. Um grande desafio é encontrar métodos ou coeficientes apropriados para avaliar a capacidade de recarga do aquífero. Objetivou-se caracterizar qualiquantitativamente as reservas hídricas, com vistas a disponibilizar informações e estratégias de gerenciamento para o uso racional dos recursos hídricos disponíveis em um aquífero aluvial no semiárido do Nordeste brasileiro. Foram analisados poços rasos e de média profundidade. Os níveis estáticos dos poços foram monitorados nos períodos secos e chuvosos para calcular as reservas hídricas. Foram coletadas amostras de água para a determinação da qualidade da água para fins de irrigação. A constante ampliação de áreas para atividades agropecuárias está comprometendo a sustentabilidade hídrica do aquífero, uma vez que as reservas não são suficientes para atender a essa demanda. A qualidade das águas subterrâneas não é limitante para uso agropecuário. A conversão da irrigação por superfície em métodos localizados irá proporcionar o aumento da produtividade da água e, consequentemente, a área irrigada. O estudo fornece dados e permite recomendar estratégias apropriadas para a explotação dos recursos hídricos subterrâneos, com vistas à manutenção das atividades agropecuárias em condições semiáridas, de modo a evitar a superexplotação.

Palavras-chave: superexplotação do aquífero, necessidade de irrigação, qualidade da água

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Introduction

Groundwater is an important source of water supply in the world. As water becomes scarce, reliance on agricultural groundwater is expected to increase. In periods of prolonged droughts, groundwater exploitation is the guarantee to meet demands, both for basic needs and as an input in the production system in arid regions, where groundwater is usually the main or only source available (Martínez et al., 2017; Bourque et al., 2019).

Groundwater resources are a source of supply for an increasing number of irrigation systems and a strategic resource for economic and social development in periods of water scarcity. Continuous and excess exploitation of groundwater has induced serious environmental problems, compromising natural recharges and interfering in the hydrological cycle (Changming et al., 2001; Pophare et al., 2014).

The Brazilian semi-arid region has as main characteristics the annual occurrence of irregular rains and high temperatures. However, not only the amount of water is worrying, groundwater quality should also be continuously monitored for irrigation purposes in order to prevent contamination and also enhance crop yield (Acharya et al., 2018).

Groundwater does not always have good quality, but the use of low-quality water sources in agricultural irrigation is an effective alternative for dealing with water scarcity. However, for the use of these waters, the irrigation system needs to be adequate and there must be an efficient management plan, avoiding damage to equipment and crops (Liu & Huang, 2009; Antas et al., 2018).

In recent years, groundwater depletion resulting from overexploitation has become a global concern (Famiglietti, 2014; Dalin et al., 2017). In view of the above, the objective of this study was to quantitatively and qualitatively characterize water reserves, with a view to providing information and strategies for management of the available water resources in an alluvial aquifer under semi-arid conditions.

Material and Methods

The study was carried out in the Morada Nova Irrigation Project (MNIP), in Morada Nova and Limoeiro do Norte, Ceará state, Brazil, located in the semi-arid region of northeastern Brazil, between latitudes 5° 06’ 07” and 5° 10’ 29” S and longitudes 38° 08’ 02” and 38° 23’ 11” W, and orthometric height of approximately 44 m. The average annual precipitation is 725 mm (average of the last 30 years), with irregularly distributed rainfall, annual average air temperature of 27.1 °C and average annual relative air humidity of 67.5%. The soils of MNIP, of alluvial origin, are classified as Fluvents.

The main water sources of the project are the systems of federal public dams. However, faced with the scenario of water scarcity, which began in 2012, groundwater exploitation became the only alternative to ensure the continuity of production activities.

The coordinates of the wells were determined with geodesic GPS receivers. Figure 1 contains information from the lithostratigraphic units of the study area and also shows the location of the wells distributed in the sectors studied in MNIP, identified by A, B, C and D, and the Banabuiú River, which has its flow in the Morada Nova-Limoeiro do Norte direction.

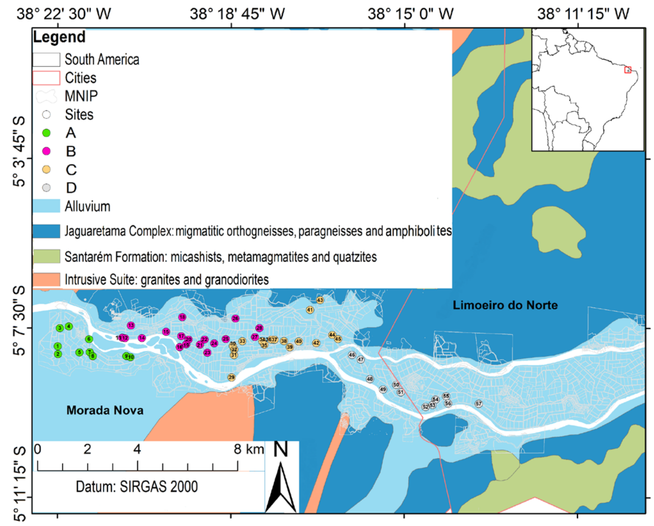


Figure 1. Location of wells and lithostratigraphic units of the Morada Nova Irrigation Project (MNIP)

The study was conducted in the years 2018 and 2019, with the monitoring of wells in the dry and rainy seasons, and the calculation was performed based on the average of the two years, which had similar annual rainfall recharges. The maps of the isobaths, or depth isolines of the static groundwater level, were constructed with the averages of static level (SL) measurements of 41 wells at the end of the rainy season and dry season.

For the flow network map, or potentiometric map, and also called isohypses or isolines of water level elevations, the survey of the SL of 50 wells at the end of the rainy season of 2019 was considered. Total soil water potential (ψ_t) was calculated with Eq. 1:

$$\psi_t = z - SL \tag{1}$$

where:

ψ_t - total soil water potential (m);

z - altitude from the point at which the well was installed (m); and,

SL - static level (m).

The measurements provided information on the behavior of groundwater based on a groundwater flow network.

The hydraulic characterization of the wells was performed through the variations of static level and determination of the current operating flow, specific capacity, hydraulic conductivity, transmissivity, effective porosity and well radius of influence. The water reserves calculations were performed for an area of 1087.75 ha (145.28 of the sector A, 460.71 of B, 364.83 of C and 116.93 ha of D). The recharge was estimated through the water table fluctuation (WTF) method, widely applied in free aquifers, and the water balance, using the methodology of Thornthwaite & Mather (1955). Eqs. 2 and 3 were used to estimate recharge by the WTF method and water balance, respectively:

$$R = \eta e \frac{dh}{dt} = \eta e \frac{\Delta h}{\Delta t} \quad (2)$$

where:

R - recharge (mm $year^{-1}$);
h - height of the groundwater level (mm);
t - time (year); and,
ηe - effective porosity (dimensionless).

$$R = P + SRn - ETA - \Delta W \quad (3)$$

where:

R - recharge (mm);
P - precipitation (mm);
SRn - surface runoff (mm);
ETA - actual evapotranspiration (mm); and,
ΔW - variation in water storage in the vadose zone (mm).

To estimate the recharge by the water balance, the average precipitation of a 30-year historical series was considered. Surface runoff was estimated through the product of precipitation by the surface runoff coefficient (C), according to the C values recommended by the Soil Conservation Service – USDA, considering the distribution of soil types, slope and use and occupation of the area under study; C = 0.36.

The renewable reserve (Rr) represents the volume of water that participates annually in the hydrological cycle, which has a strong correlation with seasonal variations, and the annual recharges and exploitation of the aquifer, in general. Rr was calculated through the difference of the means of SL (Δh) of the dry and rainy seasons (seasonal variation of the static groundwater level) of 41 wells under monitoring, according to Eq. 4:

$$Rr = A \cdot \Delta h \cdot \eta e \quad (4)$$

where:

Rr - renewable reserve (m^3 per year);
A - area of surface occurrence of the aquifer studied by sector or total (m^2);
Δh - annual saturated thickness (m); and,
ηe - effective porosity (dimensionless).

The mean effective porosity (ηe) was calculated based on pumping tests performed in all sectors. The permanent reserve (Rp) is the volume of water stored in the aquifer that remains even with the periodic variation of the groundwater level. In periods of water scarcity, this reserve has great importance and should be used considering a safety factor. The Rp of the alluvial aquifer was estimated considering the hydrodynamic and dimensional characteristics of 41 wells, according to Eq. 5:

$$Rp = A \cdot h_o \cdot \eta e \quad (5)$$

where:

Rp - permanent reserve (m^3);
A - area of surface occurrence of the aquifer studied by sector or total (m^2);
h_o - average saturated thickness (m); and,
ηe - effective porosity (dimensionless).

The average thickness of the saturated layer was calculated from the difference between the depth of the wells, which are drilled up to an impermeable level, and the SL at the end of the non-rainy season.

The exploitable resources (Re), also designated as aquifer potential, are of great importance in the process of planning and integrated management of water resources, because the correct conduction of groundwater exploitation prevents overexploitation of the aquifer and, consequently, hydro-environmental damage. Therefore, to avoid risks to the aquifer, the total volume that can be safely exploited is composed of the sum of the renewable reserve and a portion of the permanent reserve. For the study, the aquifer potential was calculated as 1/3 of the total reserve, composed of the sum of renewable and permanent reserves, according to Eq. 6:

$$Re = \frac{Rr + Rp}{3} \quad (6)$$

where:

Re - exploitable resources (m^3 per year);
Rr - renewable reserve (m^3 per year); and,
Rp - permanent reserve (m^3).

In obtaining the flow in shallow wells, it is common to use the constant-rate production test, in which three consecutive measurements of flow and lowering of the groundwater are performed, starting with a low flow rate and concluding with the maximum flow rate of the pump. The maximum flow rate will correspond to 2/3 of the initial hydraulic load in the well, obtained by means of a fitted equation between flow and lowering of the water table. The calculation of the exploitable resources or aquifer potential, having as criterion 1/3 of the sum of the renewable reserve and the permanent reserve, constitutes a sustainable criterion, because it would correspond to 50% of the economic criterion used in the maximum production of wells, considering the same condition of initial hydraulic load and integrating the criterion of exploitation of a well for the scope of the basin.

The study of the radius of influence (R) makes it possible to analyze interferences between wells and helps prevent the installation of new wells in inadequate locations, being calculated by Eq. 7:

$$R = 1.5 \sqrt{\frac{T \cdot t}{\eta e}} \quad (7)$$

where:

R - radius of influence (m);
T - transmissivity ($m^2\ s^{-1}$);
t - pumping time (s); and,
ηe - effective porosity (dimensionless).

To analyze the carrying capacity of the wells it is necessary to evaluate the operating flows, reference evapotranspiration

(ETo), crop coefficients (Kc) of the main crops exploited in MNIP or water demand of the other activities. From this information, it is possible to determine the maximum area to be used for a given workday.

To evaluate the physical-chemical attributes, a total of 38 groundwater samples were considered in areas exploited with different activities. The classification of water quality for irrigation purposes was performed according to Ayers & Westcot (1994), based on electrical conductivity (ECw) and on analysis of sodium adsorption ratio (SAR) (Tables 1 and 2).

The 38 water samples were evaluated using the interpolation process by the ordinary kriging method. It is worth mentioning that the collections were carried out in the dry season, with the objective of verifying the concentrations under the most critical condition and also coinciding with the period of irrigated crops.

Table 1. Classification of water quality for irrigation regarding the risk of salinity

Classification	ECw (dS m^{-1})	Degree of restriction on use
C1	< 0.7	None
C2	0.7-3.0	Slight to moderate
C3	> 3.0	Severe

Source: Adapted from Ayers & Westcot (1994); ECw - Electrical conductivity of irrigation water

Table 2. Classification of water for irrigation regarding the risk of infiltration

SAR (mmolc L^{-1})$^{1/2}$	Classification - Degree of restriction on use		
	S1 None	S2 Slight to moderate	S3 Severe
	ECw (dS m^{-1})		
0-3	> 0.7	0.7-0.2	< 0.2
3-6	> 1.2	1.2-0.3	< 0.3
6-12	> 1.9	1.9-0.5	< 0.5
12-20	> 2.9	2.9-1.3	< 1.3
20-40	> 5.0	5.9-2.9	< 2.9

Source: Adapted from Ayers & Westcot (1994); SAR - Sodium adsorption ratio; ECw - Electrical conductivity of irrigation water

Results and Discussion

In the Brazilian semi-arid region, groundwater is widely exploited to meet the demand for agricultural activities. The use of groundwater in irrigation projects, where the concentration of farmers is high, requires strategies for the management of water resources with a view to sustainable use. Monitoring of water quality and the exploitable water reserves of the aquifer should be considered an integral part of the management of water resources. The characteristics of the groundwater systems are complex, both temporally and spatially.

Seasonal variation of static level (SL) and potentiometric surface

The maximum mean depth of SL in the aquifer was 12.30 m in the dry season (Figure 1, point 27, sector B) and 11.06 m in the rainy season (Figure 1, point 28, sector B). The minimum mean depth of SL was 4.25 m in the dry season and 3.64 m in the rainy season, occurring in the same well (Figure 1, point 41, sector C). In sector A, composed of the points located further West in Figure 1, the depths of SL were lower, considering the average per sector of all collection points (8.03 m in the dry season and 5.82 m in the rainy season). The variations in static level by sector were 2.21, 1.16, 1.20 and 1.49 m for the sectors A, B, C and D, respectively, considering the last months of the rainy and dry seasons. In the seasonal variation, the highest fluctuation in SL was 3.50 m (Figure 1, point 11, sector B), with overall seasonal variation of the static level (Δh) of 1.52 m. The isobath maps, or depth isolines of the SL, shown in Figure 2 are representative of the SL of the irrigation project.

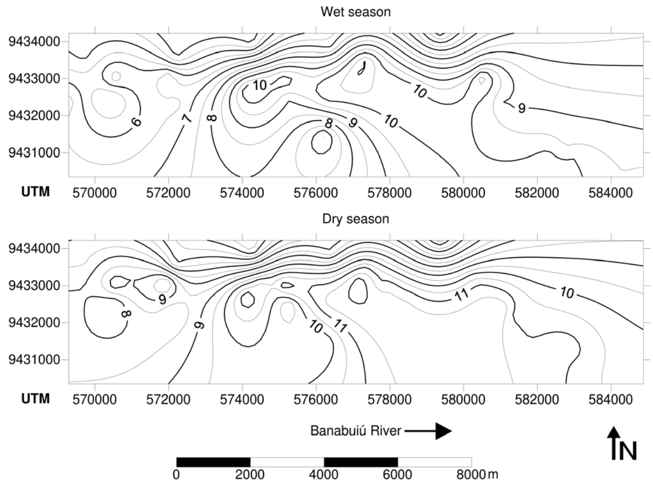


Figure 2. Static level depth isolines in the Morada Nova Irrigation Project (MNIP)

Groundwater, an important source of water supply in the world, being a source of drinking water for more than 50% of the global population, can be quantitatively affected by a combination of several natural and anthropogenic factors, such as precipitation, geology, slope and water abstraction (Chen et al., 2016; Redwan & Moneim, 2016; Sunkari et al., 2022).

Aquifers can represent complex and heterogeneous systems, which consist of challenges for modeling and systematic quantification in search of sustainable management of water resources. In an aquifer in which there is no exploitation of groundwater, the infiltration of water from rainfall is equivalent to Δh. However, in MNIP, there is exploitation for agricultural activities, especially in the second half of the year (dry season), being currently the only resource available to continue agricultural production.

In periods of prolonged droughts, groundwater exploitation ensures water to meet the demands and plays a key role for human populations, meeting basic needs and maintaining production systems in arid regions (Martínez et al., 2017). The several years of drought combined with overexploitation may be one of the biggest problems in this hydrogeological unit, which may make water sustainability impossible and lead to subsidence and depletion of groundwater (Burbey, 2008).

In this context, evaluations of the occurrence, distribution, potentiality and quality of aquifer resources have extreme relevance and are crucial for water sustainability (Redwan & Moneim, 2016), and groundwater exploitation should be limited to the recharge capacity, in order to avoid the exhaustion of the resource (Changming et al., 2001). Gomes & Frischkorn (2009) observed the occurrence of the lowering of the potentiometric surface of a different part of the same aquifer and reinforced the need for continuity of the monitoring of both surface water and groundwater levels, with a view to preserving and controlling water use. Given the current water situation, it can be inferred that the years of groundwater exploitation of the Alluvial Aquifer of the Banabuiú River and the low recharge of the last rainy seasons make it impossible to fully recover the renewable reserves and jeopardize the permanent reserve.

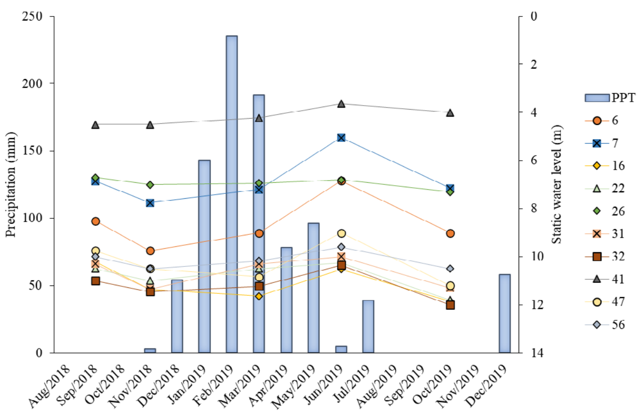
Figure 3 compares the variations in SL of ten wells to the precipitation in the monitoring years, and it is possible to observe a pattern that points to a close relationship between the potentiometric surface and aquifer recharge by rainwater.

The behavior of SL shows that in June it reaches the level closest to the soil surface. From August, without relevant contributions of precipitation, aquifer discharge occurs, and the SL reaches the maximum value in October/November. Therefore, it is possible to affirm that there is a correlation between SL and precipitation, and the aquifer recharge is related to the precipitation and hydrographic network. The prediction of groundwater level usually involves data of precipitation, in addition to the flow of water bodies, as primary sources of aquifer recharge (Tsai et al., 2016).

On the other hand, according to Malki et al. (2017), the natural recharge of groundwater in semi-arid and arid climates has no linear relationship with annual precipitation. During the dry years, the recharge can be negligible or even negative due to evapotranspiration or evaporation of SL and overexploitation of groundwater.

The flow network or potentiometric map (Figure 4) points out the total potential (ψ_t) and groundwater flow pattern of the MNIP. As in the analysis of isobaths, sector A had the highest total potential.

By observing Figure 1 and the position of the Banabuiú River, it is possible to infer that even at the end of the rainy season there is flow from the aquifer towards the river, which is due to the long period of water scarcity and, therefore, incipient flow of water in the Banabuiú River, not allowing an increasing hydraulic gradient in the aquifer-river direction. The direction of the groundwater flow follows the direction of the surface flow, with an average total potential gradient of 0.001 m m^{-1}. For wells located near the river, as in the case of wells 5-6, 12-13, 16-20, 49-50 and 55-56 (Figure 1), higher total potentials were observed in alluvium, hence with flow from the aquifer to the river.



PPT - Precipitation

Figure 3. Static water levels of the wells and precipitation in the Morada Nova Irrigation Project (MNIP)

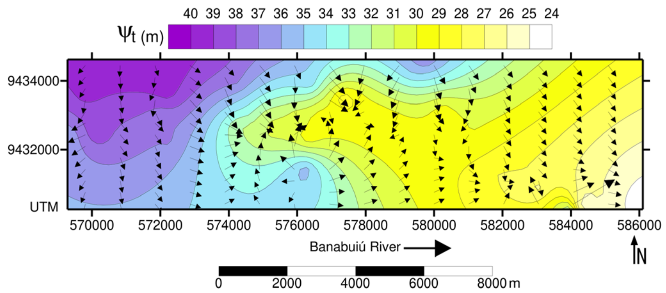


Figure 4. Potentiometric map of the studied area in the Morada Nova Irrigation Project (MNIP)

The potentiometric maps allow the identification of recharge and discharge zones, equipotential zones, in addition to the possibility of calculating hydraulic gradients and, consequently, estimating underground flow. The map shows the overall pattern of water flow in the direction of the river, a behavior similar to that observed by Vasconcelos et al. (2010), which can be attributed to the difference in the hydraulic gradient between the aquifer and the riverbed. It is worth noting that this fact is associated with the long period of drought and, consequently, of very low discharges from the river.

The difference of pattern in the flow can be justified by very permeable zones, resulting in greater underground drainage, or by overexploitation. In the study area, the overall mean hydraulic conductivity was considered high; however, in general, the aquifer does not have great differences between sectors, which reinforces that those localized changes in flow are justified by overexploitation. Surface water courses are usually sources of discharge, in the dry season, and of recharge, in the rainy season, for the groundwater aquifers. However, in MNIP, the potentiometric map at the end of the rainy season did not characterize recharge from the river to the alluvion, due to the incipient base flow in the river promoted by relatively low rainfall levels.

Groundwater reserves

The mean effective porosity (ηe) was 19.2% and the average thickness of the saturated layer was 11.16 m. For MNIP, considering the studied area (1087.75 ha), the renewable reserve (Rr) is 3.2 x 10^6 m^3 per year. In the analysis by sector, simulating the same study area for all sectors, the largest Rr was observed in sector A, being up to 68.3% higher when compared to the other sectors.

The permanent reserve (Rp) was estimated at 23 x 10^6 m^3. It is worth noting the great difference between the MNIP sectors in relation to the depth of the wells, until reaching the impermeable layer, and the static levels. Sector A, again, had the highest value (up to 39.7%) when the study area was considered the same for all sectors.

The exploitable resources (Re), or aquifer potential, considering the total volume that can be safely exploited in the area, are 8.8 x 10^6 m^3 per year.

The average annual variation of the groundwater level in the study period was 1.52 m, which led to an average annual recharge of 291.84 mm. By the methodology of water balance, considering a historical series of 30 years, the recharge was 228.27 mm. The recharge coefficient for the studied data is within the range from 0.30 to 0.40. The difference between the methods used to estimate the recharge was on the order of 21.8%.

The Rr of the study area, equal to 3.2 x 10^6 m^3 per year, represents 13.6% of the Rp, percentage of the reserves of the alluvial aquifer that is annually renewed. These values show the importance of monitoring recharges and the volume of water available for use. The Rr is the exploitable resources of the aquifer for which there is no risk of depletion of the total reserves.

The Re (8.8 x 10^6 m^3 per year of the Alluvial Aquifer, for the studied area), mainly in semi-arid region and in years of drought, should be used considering the level of safety, the dynamics of the aquifer and the policies of coexistence with drought. They can guarantee, for planning purposes under irrigation regime and without risks of overexploitation, the occupation of 75% of the area that comprised the study, considering losses of 20% in current irrigation systems and crops with the highest requirements.

It is worth pointing out that currently the deficit irrigation strategy is widely used in MNIP, which allows the expansion of the irrigated area. Hence, measures must be sought to minimize the adverse effects of water stress (Sousa et al., 2022). For the cultivation of rice, sorghum and beans, for example, considering the management adopted in MNIP, the studied area could be completely occupied with rice or beans, while for sorghum the possibility of occupation would be 70%, with no risk of overexploitation.

According to Costa et al. (2005), rice cultivation in the same irrigation project was carried out in order to use up to approximately twice as much water as the net need for irrigation, with application efficiency of only 38% in soils unsuitable for rice cultivation. Under these conditions, the exploitable resources would allow the occupation of a maximum of 3/4 of the studied area with rice, even considering only the data of areas with soils suitable for cultivation.

With regard to shrimp farming, the Re can guarantee, without risks of overexploitation, the production of 1/3 of the area that comprised the study, considering only one production cycle per year. However, in MNIP, management is carried out with a view to reaching an average of three cycles per year, which drastically reduces the aquifer's carrying capacity for such activity.

Carrying capacity/irrigated area

The radius of influence was analyzed based on the irrigation workday of 12 hours per day, resulting in an average of 46.39 m in the MNIP. The reality is that many producers use the workday of 24 hours per day, which increases the radius of influence to 65.60 m. Means of operating flows by sector ranged from 36.89 m^3 h^{-1} (B) to 45.84 m^3 h^{-1} (A). The radius of influence by sector ranged from 32.57 m (A) to 60.54 m (D). The difference observed in the flow data is justified by the spatial variability of the soil attributes in the alluvial deposits, which reflect the transmissivity of water in the soil, and by the motor-pump set installed.

The irrigated area of 3.0 ha in MNIP was obtained by the ratio between the operating flow of the well (overall mean of 43 m^3 h^{-1}) and the continuous or unitary flow of surface irrigation (2.0 L s^{-1} ha^{-1}), considering a workday of 12 hours. Table 3 shows three of the main crops of the MNIP and the maximum areas (ha) to be irrigated in a workday of 12 hours and average flow rate of 43 m^3 h^{-1}, without considering the effective precipitation and irrigation efficiency. Reference evapotranspiration (ETo) was estimated by the Penman-Monteith method (FAO) using CropWat 8.0 software (FAO).

The available resources and hydraulic characteristics found in MNIP make it possible to infer for planning purposes that, with an irrigation workday of 12 hours and average flow of 43 m^3 h^{-1}, it would be possible to perform full irrigation in the dry season of, for example, 6.02 ha of rice, or 12.12 ha of sorghum or 6.11 ha of beans (with the continuous or unitary flow rate of surface irrigation of 2.0 L s^{-1} ha^{-1}). The average area of the agricultural lot is 4.58 ha, which demonstrates the great potential of groundwater in the continuity of production.

It is worth mentioning that the operating flow is limited by the capacity of the motor-pump set and, in the case of MNIP, by the iron (Fe) inlays on the walls of suction and discharge pipes. One of the wells tested, for example, which had a flow rate of approximately 45 m^3 h^{-1} in November 2018, showed a flow rate of only 22 m^3 h^{-1} in October 2019, which is justified by the decrease in the internal diameter of the pipes due to the action of Fe. The difference observed in the flow data can also be explained by the spatial variability of the lithological attributes of alluvial deposits, which affect water transmissivity. The overall mean flow in MNIP was 43 m^3 h^{-1}, but it is worth noting that some wells had flows between 60 and 100 m^3 h^{-1}.

The number of wells in MNIP has been constantly increasing and, many times, the radius of influence calculated in this study (overall means of 46.39 and 65.60 m, for irrigation workdays of 12 and 24 hours, respectively) is not respected, which also interferes in the exploitation. Vasconcelos et al. (2010) emphasized that, despite the high potential of this aquifer, some factors, such as indiscriminate construction of wells, agricultural activities and the absence of basic sanitation, associated with natural vulnerability, threaten the integrity of their waters.

The potential for water storage of alluvium, as is the case of MNIP, is a strategic resource for the continuity of economic and social development in periods of water scarcity, since several irrigation projects of Ceará state, Brazil, are not operating or are operating on a low scale due to the low level of reservoirs. It is also worth noting that the agricultural sector in the state of Ceará is a promoter of rural economic development, especially in terms of income generation (Gomes et al., 2021).

Table 3. Maximum irrigated area according to the crop (workday of 12 hours)

Crop	Cycle (days)	ETo (mm)	ETm (mm)	Area (ha)
Rice	100	769.95	856.76	6.02
Sorghum	200	1,225.46	851.57	12.12
Bean	60	566.85	506.38	6.11

ETm - Maximum crop evapotranspiration (ETm = ETo x Kc); disregarding effective precipitation and irrigation efficiency, ETm is equivalent to the need for irrigation (NI); Full irrigation, with planting in August, and October being the month of greatest evapotranspiration; ETo - Reference evapotranspiration

However, greater attention should be paid to mechanisms for integrated management of water resources, in order to prevent overexploitation of groundwater, interference in natural recharges and the hydrological cycle, which causes serious environmental problems. According to Boretti & Rosa (2019), in general, improvements in the science and technology of water treatment, water management and clean water supply, and in the awareness of water conservation and savings may certainly alleviate future clean water scarcity.

Groundwater quality for irrigation purposes

Exploitation of groundwater for irrigation purposes has been an increasingly used resource in the Brazilian semi-arid region. In many regions, this is the only alternative that allows the continuity of food production and other agricultural activities. However, groundwater quality is not always ideal for use due to salinity and, therefore, quality monitoring is necessary (Antas et al., 2018).

The study identified points with moderate problem of salinity, as well as points without restriction on use. Among the samples evaluated, the highest water electrical conductivity (ECw) was 1.91 dS m^{-1}, with the overall mean being less than 1.0 dS m^{-1}. In general, most of the area is represented by the maximum value of SAR equivalent to 3.0 $[(mmoL_c\ L^{-1})^{1/2}]$. This value, when associated with salinity greater than 0.7 dS m^{-1} (reality of most groundwater in MNIP), does not constitute a risk of problems of water infiltration into the soil.

Figure 5 contains the results of the kriging performed from the collection points in MNIP and the classification of groundwater according to Ayers & Westcot (1994). The study identified points within three classes; however, with the kriging method, two classes were defined, C2S1 and C2S2.

The map shows that the sectors A and D were classified largely as C2S2, as well as part of B and C, which require greater attention for use. The analysis of ECw and SAR enables the determination of soil infiltration capacity and indicates the need for drainage or adoption of specific management to avoid problems of infiltration in the soil. The study of water quality in an aquifer allows verifying the existence of time/space variations, indicating the influence of different economic activities performed in the aquifer area. With this, water quality must be continuously monitored, preventing or controlling possible contamination and acting in the maintenance of crop yield (Ayers & Westcot, 1994; Acharya et al., 2018).

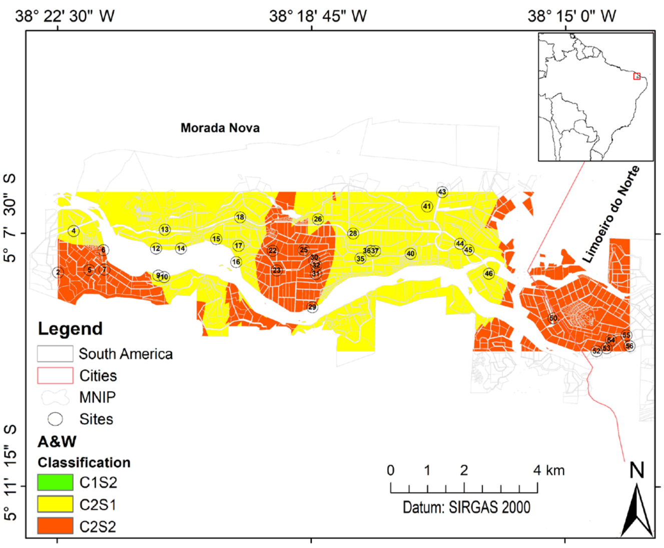


Figure 5. Classification of groundwater, according to Ayers & Westcot (1994), in the Morada Nova Irrigation Project (MNIP), with the sites indicated by circles, and the Kriging interpolation in the background

For MNIP, it was possible to observe that the waters had, at most, intermediate risk of use. The main crops of the region - rice, sorghum, maize and pasture - have salinity threshold within the intermediate range of restriction (Ayers & Westcot, 1994). The risks, however, are not limited to production. Irrigated rice cultivation, for example, is predominantly carried out by flooding, which can lead to soil salinization problems when drainage is not efficient (Singh, 2021).

For irrigation, one of the limiting factors to the use of low-quality waters is the risk of emitter clogging; however, in the MNIP, irrigating farmers do not usually use localized irrigation systems. On the other hand, water productivity, especially in arid or semi-arid regions and in periods of water scarcity, becomes the most relevant factor for the continuity of agricultural production and, to raise this indicator, localized irrigation is of fundamental importance.

According to Liu & Huang (2009), in drip irrigation all plants are expected to receive a uniform amount of water. Clogging of emitters induces poor water distribution, which can result in excess or deficit irrigation of plants. Excess irrigation causes deep percolation, which can lead to energy waste, fertilizer leaching, drainage problems and risk of groundwater contamination. It is worth noting that severe clogging of emitters can limit plant growth and hamper production or even cause plant death. Irrigation performance should be related to the technological context, real irrigation practices and decision making by the farmer (Benouniche et al., 2014). In India, the case study of Pophare et al. (2014) reveals that the adoption of participatory groundwater management practices and modern irrigation techniques, such as drip or sprinkler systems, would bring 30% saving of groundwater.

Monitoring the water quality in the aquifer enables the safe use of lower quality waters, an indispensable resource in regions prone to water scarcity. For the utilization of these waters, the adequacy of irrigation equipment and efficient management are indispensable, avoiding damage to the environment, equipment, crops and/or animals. It is worth noting that aquifer storage recovers after drought, but groundwater quality may remain jeopardized (Liu & Huang, 2009; Ferrer et al., 2019). Aquifer monitoring should be integrated with producer training and surveillance in order to ensure the rational use of water resources.

The performance of surface irrigation in MNIP is not high, even in areas with soils suitable for surface irrigation and with the techniques adopted to reduce water infiltration. However, irrigation projects are usually designed and managed for specific irrigation methods, and changing from gravity to pressurized irrigation systems can be unsuccessful and costly. Therefore, one alternative is improving the method of design in agriculture using new technologies (Araújo et al., 2019; Pazouki, 2021).

Given the above, as groundwater exploitation in the MNIP is the only water resource currently available for the maintenance of agricultural activities, which have significant importance in the economic development of the region, it is urgent to adopt practices of soil management and water monitoring, qualitatively and quantitatively, that enable the continuity of production activities and protect the environment.

Conclusions

1. The increase in agricultural activities is jeopardizing the sustainability of the aquifer's water, as reserves are not sufficient to meet this demand.

2. The exploitation of the alluvial aquifer ensures the maintenance of agricultural activities in the region, and its reserves are sufficient to meet, without risks of overexploitation, at least 75% of the agricultural demand of the studied area, depending on the management strategies adopted. For shrimp farming, the best scenario allows meeting 1/3 of the demand, considering the water management currently used and only one production cycle per year.

3. The quality of groundwater, in general, is not limiting for agricultural use. Converting surface irrigation into localized methods will potentially increase water productivity and consequently the irrigated area.

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