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Time series study for groundwater level evaluation in monitoring well

Rubens Oliveira da Cunha Júnior[1], João Victor Mariano da Silva[2]

[1] Universidade Federal do Cariri (UFCA), *Campus* Crato, Centro de Ciências Agrárias e da Biodiversidade (CCAB). Mestrando no Programa de Pós-graduação em Desenvolvimento Regional Sustentável. cunhajunior.rubens@gmail.com.

[2] UFCA, *Campus* Crato, CCAB. Mestrando no Programa de Pós-graduação em Desenvolvimento Regional Sustentável. joaovictormarianods@gmail.com.

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Abstract

Climate and hydrogeological conditions of the Brazilian semi-arid demand sustainable and efficient water solutions. Groundwater monitoring programs are tools to subsidize the decision-making in this sense. In Ceará state, the monitoring of Araripe sedimentary basin aquifers is important for the development of the region. In this scenario, the present work aimed to study the groundwater level through an exploratory analysis of time series. The study area covered the eastern portion of the Araripe sedimentary basin, in the municipality of Milagres, in Ceará state. As the object of this study, it was obtained the time series of monthly average groundwater levels in a monitoring well of RIMAS/CPRM and installed in the Middle Aquifer System. Graphical and numerical methods were applied for the identification and description of time series main characteristics. Precipitation data in the study area were used to evaluate the system recharge. Results were discussed according to the environmental aspects of the study area. As a result, it was possible the identification and description of time series patterns such as trend and seasonality through the applied methods. It is also highlighted the sharp drawdown of groundwater levels in long term in the time series, reflecting the quantitative state of the aquifer system, as well as the groundwater recharge during the rainy season of the region, evidenced by the study of time series seasonality together with the precipitation data.

Keywords: Araripe Sedimentary Basin. Water Resources. Semi-Arid.

Introduction

In the Brazilian semi-arid region, the water problem has been the subject of studies and interventions since the 19th century. The region is marked by high temperatures, fragile hydrography and irregular temporal and spatial precipitation distribution. These climate conditions, allied with the periodic droughts in the semi-arid, constitute a structural problem with economic and social implications. In this context, obtaining water for human supply and its usage in irrigation and industry in the region was constituted historically through the surface water impoundments in reservoirs or through wells drilling for groundwater catchment (REBOUÇAS, 1997; GARJULLI, 2003).

The semi-arid hydrogeology is characterized by two distinct contexts: the crystalline basement, in which the low permeability rocky formations give cause to efficient use of reservoirs as water solution; and the sedimentary rocks, with potential groundwater reserves (REBOUÇAS, 1997). In Ceará state, the crystalline basement predominates, corresponding to about 75 % of the territory, and is located in its large central region. However, in the south end and the state's coast, sedimentary formations with high potential in groundwater resources are found (TEIXEIRA, 2003). In particular, in the south of the state, on the border with Pernambuco and Piauí, the Araripe Sedimentary Basin is located, a relevant area of hydrogeological interest due to its qualitative and quantitative groundwater potential (CPRM, 2009).

Araripe Sedimentary Basin is the biggest groundwater reserve of Ceará state and it is geographically inserted in the Cariri (from Ceará) region. The Cariri region is supplied almost in its entirety by groundwater from wells or springs. In this scenario, the municipalities of Crato, Juazeiro do Norte and Barbalha are included, which exert strong centrality in the regional development. Population and economic growth have led to an increase in groundwater exploitation for human consumption and industry and irrigation use (VERÍSSIMO, 1999; MOURA-FÉ *et al*., 2019).

The Middle Aquifer System is the most drilled and exploited one in the Cariri region, and the aquifer recharge occurs in most part because of the rain, having yet the contribution of springs located at the Araripe plateau foot. Taking into consideration its importance for the region's development, the aquifer is exposed to a series of factors that threaten its waters. The indiscriminate well drilling, the polluting waste generation by the agricultural and industrial activities, and the contamination of surface waters are risk factors that, allied with high groundwater exploitation, highlight the importance of monitoring, diagnosis and management tools (COGERH, 2009; VERÍSSIMO, 1999).

Groundwater monitoring in Araripe Sedimentary Basin is carried out by the Brazilian Geological Service – CPRM, as part of the Groundwater Integrated Monitoring Network – RIMAS, and by the Ceará Water Resources Management Company – COGERH. The groundwater monitoring is an essential tool for the quantitative and qualitative evaluation of reserves, since, through systematic observations of dynamic processes, such as the water levels and water quality in monitoring wells, it allows the historical tracking of important hydrological variables and provide information for planning and management (FEITOSA, 2008). In face of this, formalisms such as time series are important tools in the representation, modeling and forecasting of hydrological processes (MACHIWAL; JHA, 2012; CHAN; CRYER, 2008).

In time series study, the use of graphic tools for data analysis is important (MORLEY; ADAMS, 1991). Many time series characteristics can be identified through the graphical analysis (HYNDMAN; ATHANASOPOULOS, 2018). Time series decomposition techniques for the identification and study of patterns such as trend and seasonality have been applied by authors like Cortes *et al*. (2018). In particular, regarding the study and evaluation of groundwater, Machiwal, Nimawat and Samar (2011) used graphic statistical techniques to evaluate groundwater monitoring networks. Also, time series approach was used by authors like Crosbie, Binning and Kalma (2005), to infer the aquifer system recharge, Carnier Neto (2006), in the assessment of monitoring networks, Hu, Zhang and Xing (2001), when analyzing the annual dynamic characteristics of groundwater level, and Gouvêa (2009), to study the influence of precipitation and soil characteristics in water level variations in recharge areas.

In light of the foregoing, the present paper aimed to analyze the evolution of groundwater level in a monitoring well in the Middle Aquifer, through time series studies. In this study, time series characteristics were graphically and numerically explored, and results were correlated with rainfall data, in order to understand the regional dynamics of the aquifer. The results obtained were discussed according to the environmental aspects of the study area.

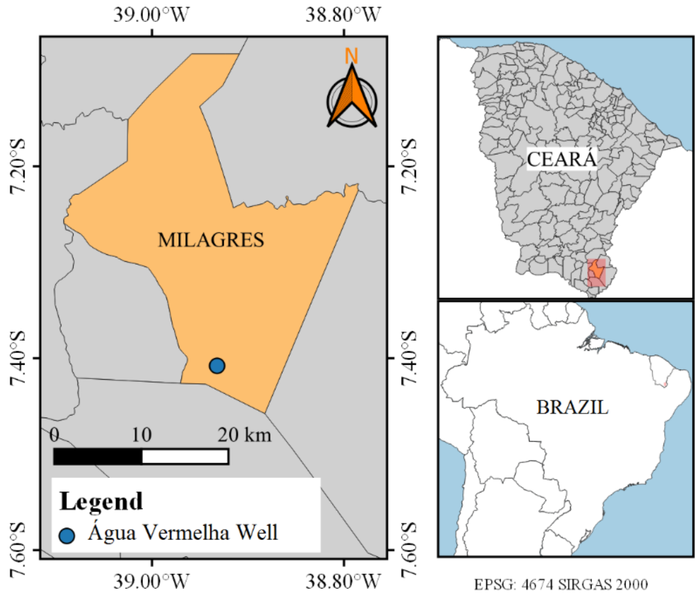
Material and methods

Study area

The study area of the present work is inserted in the municipality of Milagres, where the Água Vermelha well is situated, the object of this work. The municipality of Milagres is located at the south end of Ceará state, limited to the North by the municipalities of Barro and Aurora, to the South by Abaiara and Brejo Santo, to the East by Mauriti and Barro, and to the West by Missão Velha and Abaiara (IPECE, 2017). It has a land area of 579.097 km^2 and a population estimate of 27,462 inhabitants (IBGE, 2020).

The municipality is inserted in the context of the Salgado River sub-basin and the hydrogeological context of the Araripe sedimentary basin (COGERH, 2019a). Figure 1 shows the location of the study area.

Figure 1 – Location map of the municipality of Milagres, Ceará, highlighting the location of Água Vermelha well, 2021.



Source: Elaborated by the authors (2021).

Hydrogeology of the region is characterized by a diversified lithostratigraphy, which provides the occurrence of aquifers alternating, aquitards and aquicludes, with spatial variations and discontinuities. Thus, the following hydrogeological division of the Araripe sedimentary basin is adopted: (i) Upper Aquifer System, represented by the Exu and Arajara formations; (ii) Santana Aquiclude, characterized by the homonymous formation; (iii) Middle Aquifer System, represented by the Batateira River, Abaiara and Missão Velha formations; (iv) Brejo Santo Aquiclude, defined by the homonymous formation; and (v) Bottom Aquifer System, determined by the Mauriti formation and basal part of the Brejo Santo formation (VERÍSSIMO, 1999).

The monitoring well has a useful depth of 70.0 m and is located at an altitude of 362.34 m above sea level. Its lithographic profile involves layers of thin sandstone, claystone, clay and sandy clay (CPRM, 2021). Figure 2 shows the analyzed monitoring well.

The precipitation regime of the region is characterized by high interannual irregularity and by the rainfall temporal and spatial variability. The average annual precipitation in the Cariri region is 919.6 mm, with rainfall concentrated in the so-called rainy season, from December to May. In the months of December and January, the so-called pre-season rains occur, having the beginning of the rainy quarter in February of each year (TEIXEIRA, 2003).

The region has a warm semi-arid tropical, hot tropical and hot sub-humid tropical climate. The topography is formed by two distinct domains, plateau and depression, known respectively as Araripe plateau, which occupies 73 % of the total area of the Basin, and the Cariri Valley (COGERH, 2009).

Figure 2 – Água Vermelha well in the municipality of Milagres, Ceará, August, 2012.

Source: CPRM (2021).

Dataset

The dataset used in the present work consists of the time series of groundwater level evolution of Água Vermelha well, located in the south of Milagres municipality. The data were obtained from the Groundwater Integrated Monitoring Network - RIMAS/CPRM, station nº 2300022135 (CPRM, 2021). Water level measurements were obtained through an automatic level gauge equipped with a datalogger. The historical records of groundwater levels were obtained covering the period of August 2011 to November 2019.

For studying the aquifer recharge, it was also used precipitation data of the study area. The rainfall time series of meteorology stations located in the area of interest were obtained on the portal of the Meteorology Foundation of Ceará – FUNCEME.

Time series analysis

Time series are collections of observations sequentially realized in the time domain. Let y_t a time series, with $y_t = y_1, ..., y_n$, indexed at the times $t_1, ..., t_n$. The time series approach has applications in many fields of knowledge, such as economy, epidemiology, hydrological sciences, among others, since its study allows the understanding of the stochastic nature of the phenomena, to identify patterns and to make predictions from a known historical record. Time series analysis consists in identify its main properties, describe its behaviour and select suitable forecasting models (CHAN, CRYER; 2008).

The initial and most basic step of time series analysis is the visualization of time series values graphically disposed as a function of time. Analyzing time series plots allows identifying patterns, unusual values, changes throughout the time and relations with other variables. Besides, computing the time series descriptive statistics is also important in this step (KABACOFF, 2015; SHUMWAY; STOFFER, 2017).

Time series can exhibit different patterns, and usually is useful for the analysis to decompose the time series in components that can represent these patterns, such as trend, seasonality and random variations. The decomposition can be additive ($y_t = S_t + T_t + R_t$) or multiplicative ($y_t = S_t \times T_t \times R_t$), in which S_t, T_t and R_t represent respectively the seasonality and trend components, and a remainder component. The decomposed time series can also be expressed in the form of $y_t = S_t + A_t$, in which $A_t = T_t + R_t$ is called the seasonally adjusted component. Thus, the seasonality and the A_t component can be analyzed separately.

The trend component captures changes in the time series values throughout the time, i.e., long-term changes in positive or negative directions. The seasonality represents the seasonal effects that influence the time series values in certain periods of the year, day of the week or hour of the day. The seasonal plots are useful graphical tools in this sense, once it allows that seasonal patterns can be perceived clearly. In this plot, sub-series for each station are shown, for example, for a monthly series, the values are shown by year, and the months are disposed on the horizontal axis. Lastly, the remainder component captures influences that cannot be described by the seasonal and trend effects.

Time series that do not show trend and seasonality patterns, i.e., those whose statistical properties that describes its behaviour do not change through time, are stationary time series. However, many time series which represents real-world phenomena are not-stationary time series, since it exhibits such patterns (HYNDMAN; ATHANASOPOULOS, 2018).

There are several methods for time series decomposition, such as classical decomposition by Moving Averages, in addition to more sophisticated methods such as the Seasonal and Trend Decomposition using Loess (STL). The STL decomposition is a robust and versatile method developed by Cleveland *et al*. (1990). The method performs an additive decomposition and allows that parameters such as the trend curve smoothness and the seasonality variations can be controlled by the user. Also, the method is robust to outliers, so that the unusual values do not influence the trend and seasonality, but only the remainder component.

Through time series decomposition, the strength of the trend and seasonality components can be measured, according to the method proposed by Wang, Smith and Hyndman (2006). In time series with a strong trend pattern, the seasonally adjusted component A_t shows greater variance in comparison to the remainder component R_t. On the other hand, in cases of lower trends, the variances of both components are approximately equal. Thus, the trend and the seasonality can be calculated by Equations (1) and (2), respectively.

$$F_T = \max\left(0{,}1 - \frac{var(R_t)}{var(T_t + R_t)}\right) \quad (1)$$

$$F_S = \max\left(0{,}1 - \frac{var(R_t)}{var(S_t + R_t)}\right) \quad (2)$$

The value of $0 \leq F_T \leq 1$ is given by the relation between the variances of the remainder component and the seasonally adjusted component. Regarding the seasonality, it can have its strength measured in a similar way, but comparing the variance of a component without trend, i.e., $S_t + R_t$. The value of $0 \leq F_S \leq 1$ for time series with lower seasonality will be closer to 0, while in time series with stronger seasonal behaviour, it will be closer to 1 (HYNDMAN; ATHANASOPOULOS, 2018).

Another important characteristic of time series is the relation of dependency between its values. Autocorrelation is a measure of dependency that quantifies the form of how the observations in a time series relate to each other. To this end, lagged values of the time series are used. To lag a time series means to delay its value in a certain number k of observations. The autocorrelation, r_k, between y_t and y_{t-k} is given by Equation (3).

$$r_k = \sum_{k+1}^{n} (y_t - \bar{y})(y_{t-k} - \bar{y}) \Big/ \sum_{1}^{n} (y_t - \bar{y})^2 \quad (3)$$

At which: $\bar{y}$ is the time series average and n is the number of observations.

Once computed the correlations for many lagged values, they can be displayed graphically, through the Autocorrelation Function (ACF). The interpretation of the ACF plot can reveal the existence of trend or seasonality in time series (CHAN; CRYER, 2018).

Pluviometry

For the pluviometry study in a region, data from rainfall stations situated inside an area of interest and its surroundings are used. Then, it is adopted an average precipitation in the region, computed through methods such as arithmetic average, the Thiessen polygon method or isohyets method. This average precipitation is considered corresponding to a water depth that covers the considered area (TUCCI, 2001).

It was used 7 stations nearby to the studied well. For the selection, inactive stations, without data for the considered period or with an insufficient amount of data were not considered. For each station, the monthly accumulated precipitation time series were obtained in the period from August 2011 to November 2019. The average precipitation was computed for each month in the study period using the Thiessen polygon method, with a total influence area of 1,247 km^2. Then, the monthly precipitation time series were obtained.

In the Thiessen polygon method application, an influence area for each station inside the study area is defined, and the average precipitation is then calculated by the weighted mean of the rainfall measurements at each station so that the weights are the influence areas. Constructing the areas consists of tracing straight lines that join adjacent stations, followed by tracing the perpendicular bisectors of these areas. The generated polygons by the perpendicular bisectors are the Thiessen polygons (TUCCI, 2001).

Data processing and computational implementation

The precipitation time series, obtained from the FUNCEME website, and the groundwater level time series, available on the RIMAS website, were processed in Excel, in order to compute the monthly accumulated precipitation and average groundwater level time series, respectively. Thiessen polygon tracing and the influence areas calculation was carried out on QGIS (QGIS DEVELOPMENT TEAM, 2021), and the time series study was performed in the R statistical environment (R CORE TEAM, 2013). Gap-filling of time series was done by linear interpolation. The STL decomposition was computed by the *stl* function, using 11 observations as seasonality window (parameter *s.window* = 11) and the non-robust method (parameter *robust* = *FALSE*).

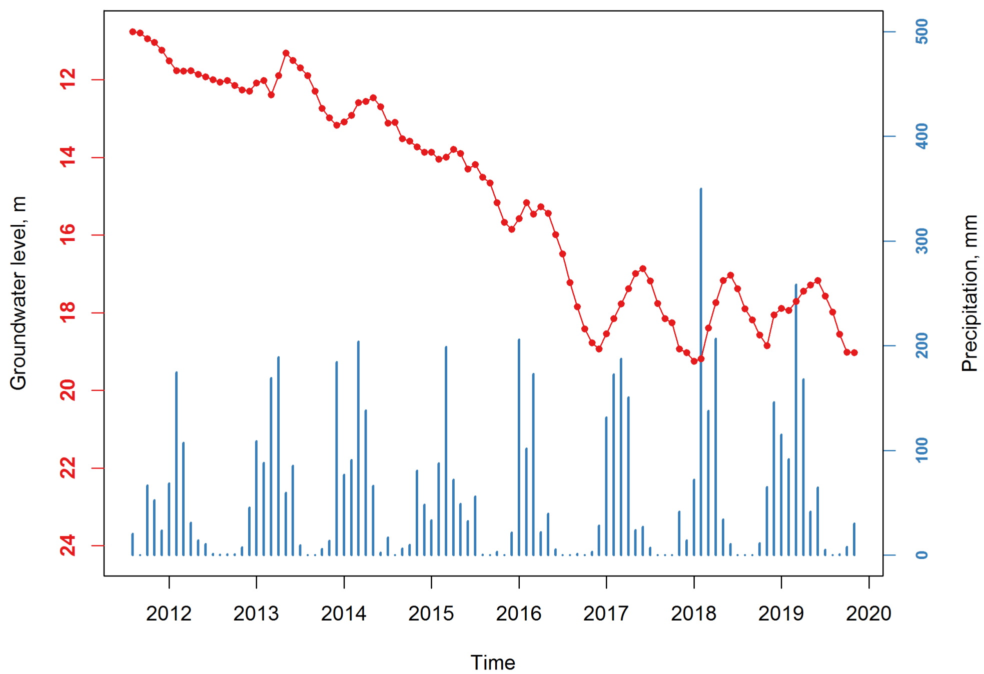
Results and discussion

Time series analysis

The monthly average groundwater level time series obtained in the Água Vermelha well showed in general a sharp drawdown. The highest water level registered was the first of the time series, of 10.76 m in August 2011, while the lowest was registered in January 2018, equivalent to 19.25 m of depth. Therefore, the time series range was 8.49 m. The groundwater lowering, from the time series start to the last record, was 8.30 m.

Monitoring groundwater levels evolution is important for water availability evaluation. Historical precipitation data are also considered in this evaluation, once it allows the measurement of the aquifer system recharge. Figure 3 shows the monthly groundwater level time series in Água Vermelha well, in comparison with the monthly accumulated precipitation time series in the study area.

Figure 3 – Evolution of monthly average groundwater level in Água Vermelha well vs. Precipitation in the study area, during the period of August/2011 to November/2019.



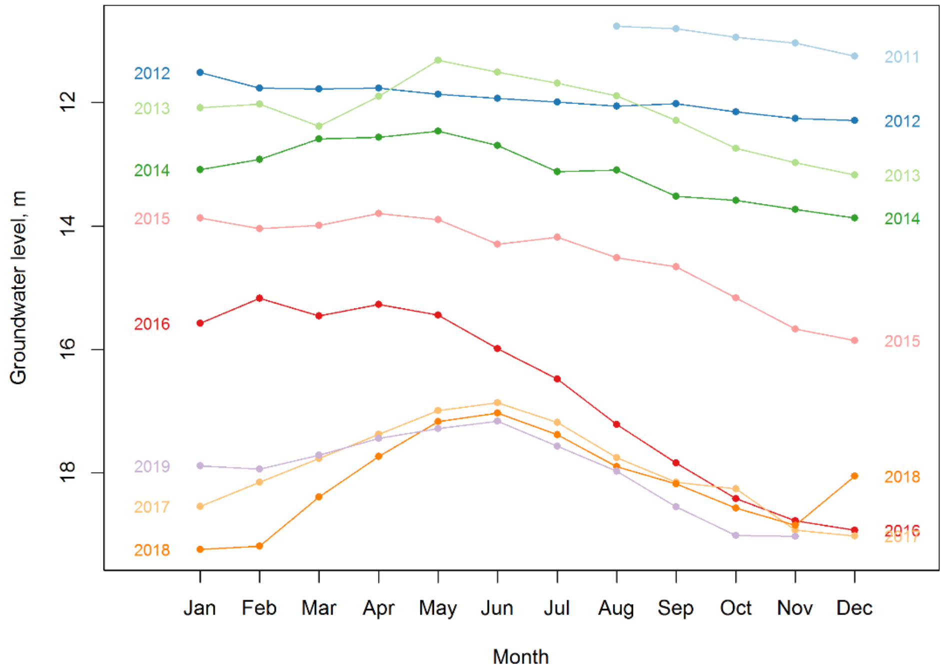
Source: Elaborated by the authors (2021).

By analyzing the groundwater level time series, it can be seen at long term a clear negative trend from 2011 to 2016, indicating the water level drawdown. Then, from 2017 to 2019, there are no trend variations, and a seasonality pattern occurs, causing a periodic increase in the time series values at the beginning of each year. This seasonal variation also occurs in the first years of the time series, but in a milder way.

Another way to clearly analyze the seasonal behaviour of time series is through the seasonal plots, shown in Figure 4. The negative trend throughout each year is evident, where 2016 was the year that showed the biggest drawdown of groundwater level. From 2017, the periodic increase of groundwater level starts in February, reaching the highest value in June. In the early years of the time series, there is also a slight increase in the level during this period. In fact, this is due to the region precipitation regime, in which the rainy season begins in February and extends to May, despite the interannual variability.

In hydrological time series, the exhibition of patterns such as trend and seasonality occurs due to climate natural variations or anthropic action (KARAMOUZ; NAZIF; FALAHI, 2012). The individual study of these components is useful to understand the time series, as well as to improve the performance of modeling techniques and prediction. The STL decomposition of the monthly groundwater level time series is shown in Figure 5. By analyzing separately each component, it can be perceived that in this method the seasonality is considered dynamic, increasing

Figure 4 – Seasonal plot of monthly average groundwater level in Água Vermelha well, during the period of August/2011 to November/2019.



Source: Elaborated by the authors (2021).

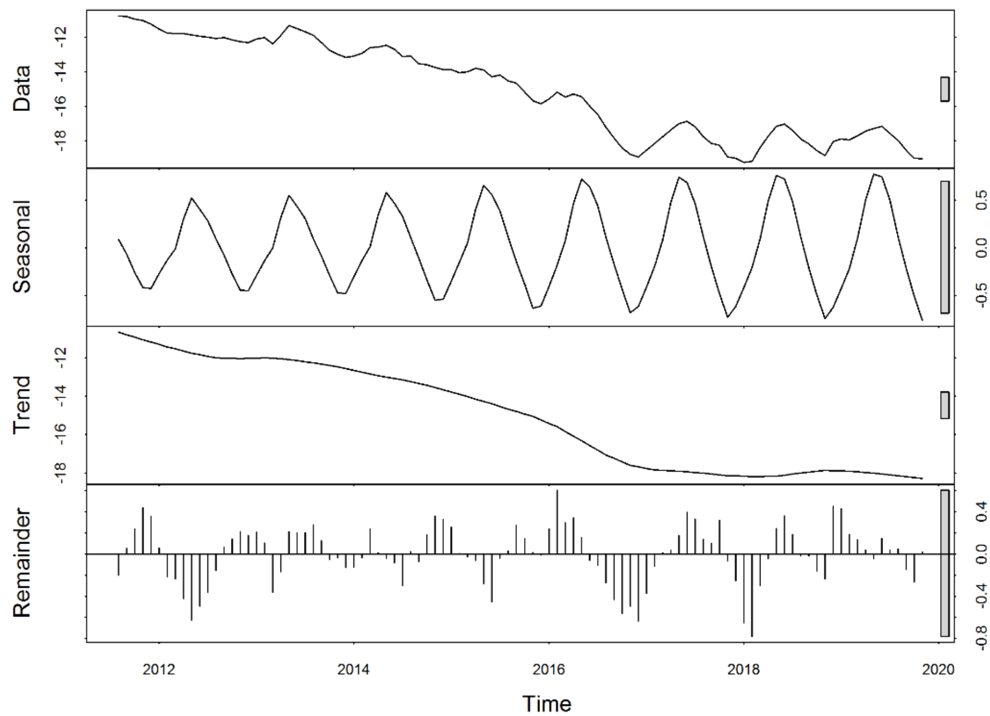
throughout the years, and the trend plot shows the drawdown of the water level, followed by a period of stability. The grey vertical bars, on the right side of each plot, have the same size, but are expressed in different scales. The difference in the bar sizes implies that the variations in the seasonality and the remainder components are small in comparison to the variations in the original time series, while in the trend, the variations are bigger in relation to the original time series. This allows to graphically infer the strength of trend and seasonality (HYNDMAN; ATHANASOPOULOS, 2018).

Another way for measuring the presence of trend and seasonality components is through the relation between its variances and the variance of the remainder component. Therefore, Equations (1) and (2) were applied and the obtained values were $F_T = 0.9897$ and $F_S = 0.7166$. The value of F_T closer to 1 is a numerical indicative of the strong trend present and allows infer that the trend is the most important component of the time series. The value of F_S indicates the existence of seasonality in the time series, although it manifests in more slightly in relation to the trend component.

The existing autocorrelation between the observations of a time series is another important factor in its study. The autocorrelation function plot for the monthly groundwater level time series up to lag 24 is shown in Figure 6. In the x-axis the lagged values of the series are disposed, i.e., the values of y_{t-k}, where k is a lag, while the y-axis is formed by the correlation values between the lags.

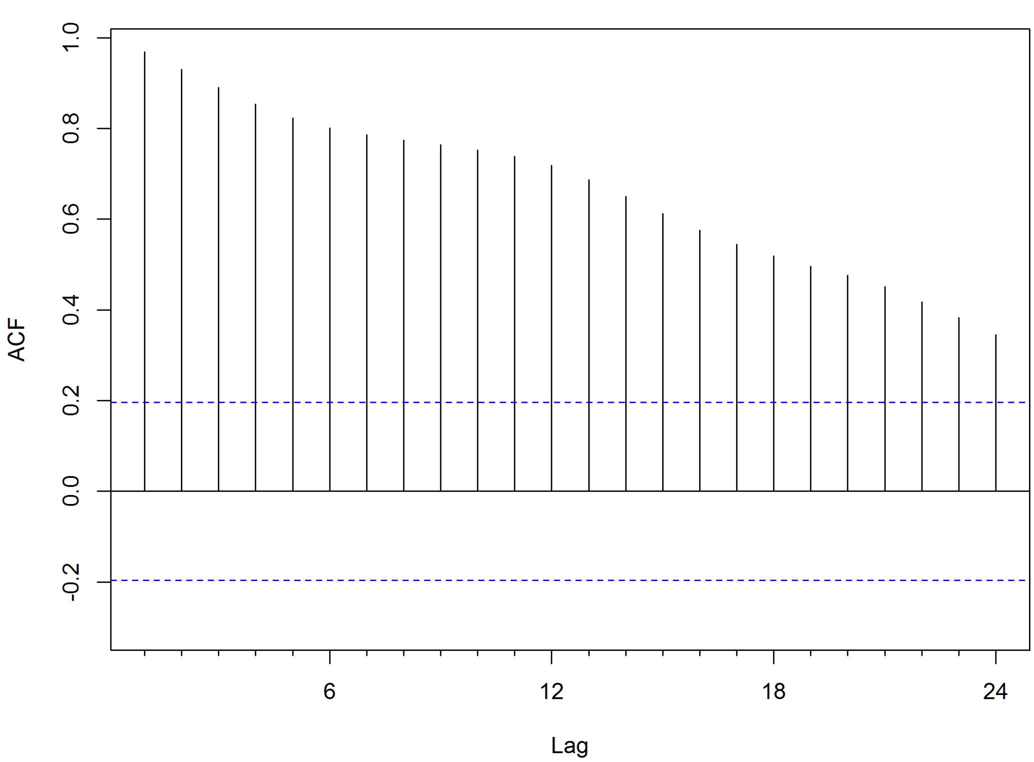
The pattern shown in the plot is characteristic of time series with the trend, since the correlation is higher and positive in the smaller lags, while smoothly decrease according to the greater the lags are. This implies that the time series observations have strong relation with the observed value at the immediately previous months. Besides, the significant correlation value at lag 12 indicates the time series annual seasonality.

Figure 5 – Monthly average groundwater level in Água Vermelha well (August/2011 to November/2019), and the 3 additive components obtained by STL decomposition.



Source: Elaborated by the authors (2021).

Figure 6 – Autocorrelation Function (ACF) plot of monthly average groundwater level time series in Água Vermelha well, during the period of August/2011 to November/2019.



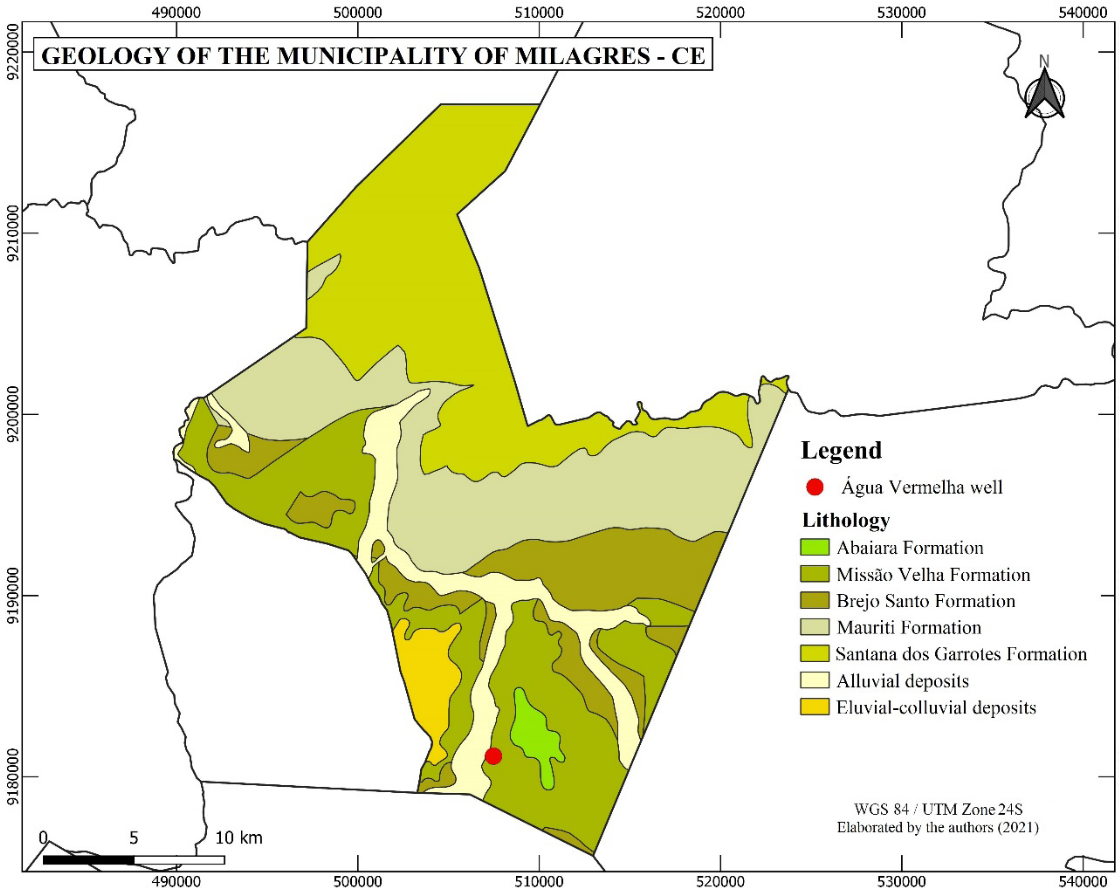
Source: Elaborated by the authors (2021).

Environmental aspects of the study area

The observed drawdown of the groundwater level in the well, according to Figure 3, reflects the situation of the quantitative state of the Middle Aquifer System. According to the Report of Monitored Wells of Cariri by COGERH (2019b), by observing the comparative of 10 years of monitoring, from 2009 to 2019, most of the monitored wells by the agency exhibits drawdown, sometimes significant, in relation to the initial values. Regarding the qualitative state of the Araripe Basin aquifers, authors like Gomes, Mendonça and Cavalcante (2019) highlight the vulnerability and the risk of pollution to which the water reserves are subjected.

Inserted in the geological context of the Araripe sedimentary basin, the municipality of Milagres has lithological characteristics that contribute to good groundwater storage capability, as can be identified by its lithologies. Figure 7 shows the geological map of the municipality.

Figure 7 – Geological map of the municipality of Milagres, Ceará, highlighting the Água Vermelha well location, 2020.



Source: CPRM (2020).

It can be seen in the municipality territory that the geological context of Milagres is characterized by the existence of sedimentary rocks derived from the Araripe sedimentary basin. According to the geological base of the Brazilian Geological Service (CPRM, 2020), its lithological heterogeneity varies among silt shales (Abaiara Formation), thick and thin sandstones, and conglomerates (Missão Velha Formation), besides the shales, argillite and silt of varied colours

(Brejo Santo Formation), overlaid by sandstones of thick granulometry (Mauriti Formation).

Based on this characterization and identification according to the map, it can be noticed that the studied well is settled on the Missão Velha Formation. In his studies, Camacho (2016) characterizes this location as an underground space where are the middle aquifer waters, situated over an aquitard derived from the Brejo Santo formation. The lithological conditions in which the Água Vermelha well is situated, marked by a rocky sedimentary substrate, provides the ideal conditions for groundwater storage. This is due to the type of rock, in which there is a porosity of interstitial or primary type, characteristic of sedimentary environment with sandy composition (REBOUÇAS, 2013).

The studied monitoring well is located relatively far from the city. Figure 8 shows the surrounding area of the studied well, from CBERS 4 satellite image obtained through the General Division of Images (INPE, 2021), referring to the period of August 2020. While it is possible to see the distancing between the well and the city space, agricultural areas can be seen in its surroundings. The Água Vermelha well is a monitoring well, therefore there is no pumping of its waters. However, the historical observations of measured groundwater level evolution exhibit a significant drawdown on the water-table level in the well. This, in turn, indicates that the aquifer systems waters of the region are subject to disturbances from climatological factors and land use.

Figure 8 – Visualization of the Água Vermelha well surroundings from a satellite image, August/2020.

Source: Elaborated by the authors (2021).

In the socio-environmental context, groundwater obtained from drilled wells are useful for the development of many functions, in the physical and biological sphere as well as in the social sphere. Groundwater is used for activities such as agricultural production, industrial activities, besides the populational supply (MANZIONE, 2015). It is important to point out that groundwater in the semi-arid environment context has greater importance, once it constitutes one of the main forms of water supply. Such fact is due to the rainfall irregularity inherent of the region, as well as by the intermittency of the watersheds, where most of them have water flow only during the rainy season (TEIXEIRA, 2003; WHEATER; MATHIAS; LI, 2010).

In general, even having immeasurable importance for the human species, the water environments are the most affected by the lack of environmental protection, population growth and land use. In surface water sources and underground environments, it can be seen the water contamination, that degrade not only the physical and biological space, but also reach the social sphere (SOARES, 2015).

Conclusion

Methods explored in this research allowed the identification and the description of the main characteristics of the analyzed time series. The Água Vermelha well showed a significant lowering of water levels, despite the recharge during the rainy season. Given the importance of the Araripe sedimentary basin aquifer systems, the study of groundwater levels evolution in monitoring wells and the evaluation of the environmental aspects in the area allow to perform the diagnosis of groundwater qualitative and quantitative states, as well as to understand the local dynamics and the aquifers systems behaviour.

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