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SPATIO-TEMPORAL ANALYSIS OF THE GROMBALIA AQUIFER DYNAMICS--NORTHERN EAST OF TUNISIA

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Abstract: Aquifer maps are key tools for water resources management, and allow to characterize a water table distribution and variability. The Grombalia plain in the northeast part of Tunisia was studied to identify the origin of groundwater recharge and to specify the type of recharge in the whole study area. It aims to investigate the impact of recharge schemes on the piezometric evolution of the water table. Furthermore, the purpose is to investigate the origin and dominant factor of the recharge. The methodology of this work includes two methods of analysis of the dynamics of the piezometric heads of this aquifer, namely the interpretation of piezometric maps for an evaluation of the spatial evolution and the study of piezometric sections. Both methods allow to distinguish between the different types of recharge, show which recharge sources is the most important in supplying the groundwater. In addition, they permit to analyze in detail the piezometric evolution and the impact of the various hydraulic structures on the piezometry. Without forgetting the naturel recharge coming directly from the soil surface and depending on the permeability, there is another natural recharge which comes from flooding areas. In Grombalia groundwater, this natural recharge occurs mainly at Wadi Ejjorf, Wadi Sidi Toumi and Wadi Ejdida sites. This recharge is accented for rainy years and mainly after flooding events. This study shows the picks at all the recharge sites between 1999 and 2009. However, an overexploitation of the aquifer was observed in Soliman-Fondok Jedid, Boucharray, Bou Argoub, which presented local depression zones. The used methodologies are very important tool to choose the best recharge site and allow to adjust the hydrodynamic models. In fact, there is an urgent need for assessing various aspects of ground water resources through a process of systematic data collection, analysis and synthesis.

Keywords: Grombalia plain; Groundwater; Piezometric map; Piezometric section; Recharge.

1. INTRODUCTION

All around the world and particularly in Mediterranean and MENA regions, water management has become a major concern in recent years. In, fact, this vital resource is poorly distributed in these regions (Lachaal et al., 2016). This inequality of distribution and exploitation between the different economic sectors is closely related to the constraining climatic conditions and local policies which encourage the development of irrigated agriculture, tourism and industrial sector, as is the case in the Mediterranean region, as is the case in Tunisia and more particularly in the region of the of the Cap Bon peninsula. Indeed, the Cap Bon area is known by its agricultural activities, their particular landscape, specific climate and proximity to the Mediterranean Sea.

These aspects have attracted several important economic players from both industrial and tourism sectors, which are major consumers of water. As a result, water reserves have become increasingly limited (DGRE, 2019). The management and allocation of water resources between the agricultural, industrial and tourism and domestic sectors is therefore a priority issue for sustainable development in the whole area of Cap Bon. Given the importance of this topic, several research studies have been carried out on water resource management in Cap Bon (Ennabli, 1980; Gaaloul, 2008; Gana and Fouillen, 2014). The objective is always to find the best way to management of these resources, which are becoming more and more depleted, endangering the agricultural sector, which is the main activity of Cap Bon and which is considered, according to the latest studies, to be the biggest consumer of water around 80% of total resources (DGRE, 2019).

Water demand management will therefore be a main focus of general water policy in the future, in order to control consumption in the various sectors, especially the agricultural sector. Aquifer mapping is a process that assesses the quantity, the quality, and the sustainability of groundwater using a combination of geology, geophysical, hydrologic.

The implementation of systematic aquifer mapping is anticipated to enhance our understanding of the geological composition, hydrological properties, and water level dynamics of aquifers, allowing for better insights into their behavior and fluctuations over time. Also, it shows the occurrence of both natural and anthropogenic activities that have an impact on the ground water (Lachaal et al., 2018).

The findings from these investigations will enhance the resource management tools utilized by planners, policymakers, and other stakeholders. These tools include long-term aquifer monitoring systems as well as conceptual and quantitative regional and local groundwater flow models. In Cap Bon region, the increasing pressure on water resources is leading to the degradation of groundwater (drop in piezometric levels) and environmental deterioration (degradation of the chemical quality of the water in the most vulnerable aquifers, such as the coastal aquifers). Hence, a careful consideration of the situation of aquifers and their current management is required. The reservoir of the six aquifers in Cap Bon region (Grombalia, Eastern Coast, Takelsa, Tazoghrane, El Houaria, Hammamet-Nabeul) is made up of Quaternary sediments, resting in places on Pliocene detrital formations. These aquifers are actively solicited for irrigation and during last years they have been overexploited (Gaaloul et al., 2014). The Grombalia plain, contains a multi-layer aquifer system which is the most important in the Cap Bon region. Nowadays, the phreatic system is being overexploited around (170%) in 2021, in order to meet the growing demand for water in the agricultural, industrial and tourist sectors (Kammoun et al., 2021).

The Grombalia aquifer is subject to an irregular climatic regime characterized by a succession of dry and rainy years. This aquifer is used by a fairly large number of wells and boreholes which are increasing annually. The immediate and main consequence of all these factors is the lowering of the piezometric level and the increased salinisation of the groundwater. Over the last decade, intensive exploitation of Grombalia's groundwater resources has largely influenced piezometry and water quality, exposing the system to saline intrusion due to increased groundwater abstraction near the coast. However, it should be noted that several recharge sites have been installed. This exploitation/recharge may therefore have a strong influence on the groundwater that needs to be assessed. Although other studies have focused on this aquifer, the complexity of determining all the multiple processes contributing to the salinization of the aquifer and the different recharge processes still need to be fully understood (Lachaal et al., 2018). As a result of several development activities throughout the years, the groundwater regime was affected in Grombalia plain. In order to create efficient management methods and improve ground water governance, scientific planning is required for the development of groundwater under various hydrogeological circumstances.

The purpose of this paper is to investigate the origins of groundwater recharge and assess their influence on the piezometric changes in the Grombalia region. This will be accomplished through the utilization of piezometric maps and the piezometric section approach. Additionally, conducting aquifer mapping on a suitable scale can assist in the planning, implementation, and evaluation of different management strategies aimed at ensuring the long-term sustainability of groundwater resources. Also, it will help achieve drinking water security, improved irrigation facilities, and sustainability in the development of water resources in the study area.

2. MATERIALS AND METHODS

2.1. Study area description

The Grombalia aquifer is located in north-eastern Tunisia, about forty kilometers south of Tunis (Figure 1). It corresponds to an ancient gulf, widely open to the northwest and which communicated with the paleogulf of Tunis. The region of Grombalia is classified in the upper semi-arid Mediterranean bioclimatic stage with mild winters. It’s characterized by an average annual rainfall of around 480 mm/year over a period of 41 years (1978 to 2019), a cold and humid winter, a hot and dry summer. The average annual temperature is 18°C and the evaporation is about 1300 mm/year (DGRE, 2019).

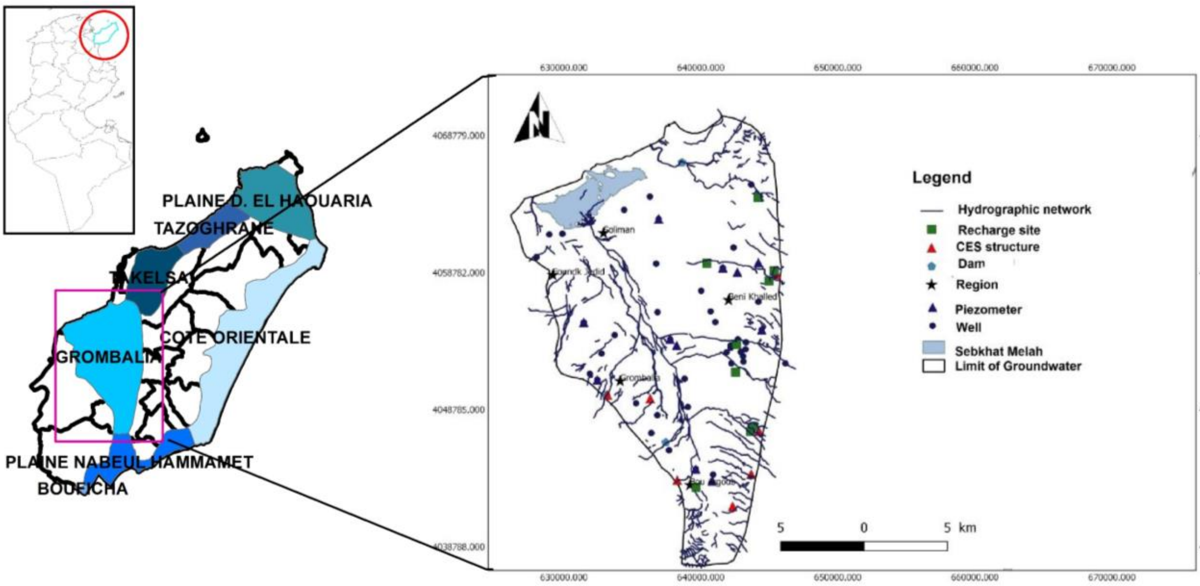

Figure 1. Study area location.

From a hydrological perspective, the Grombalia region can be described as a large basin that is predominantly open to the Gulf of Tunis. The Grombalia plain, which serves as the drainage area for this region, is encompassed by several primary wadis: Oued Saraya, Oued Defla, Oued Ejjorf, Oued El Bey, Oued Sidi said, and Oued Bezirk (Sebai et al., 2014). The Grombalia plain is characterized as a significant depression resulting from subsidence in the underlying basement, and it is filled with extensive Quaternary deposits. These deposits primarily consist of marine marls. The aquifer's reservoir is formed by permeable sandy layers, extending to a depth of approximately fifty meters (El Hani, 2007).

The Grombalia basin has been molded into a graben with a northwest to southeast orientation primarily due to the geological characteristics, specifically the normal faults of Borj Cedria and Hammamet. The Miocene and the Mio-Plio-Quaternary Formations are characterized by strong subsidence with variable depths (Figure 2).

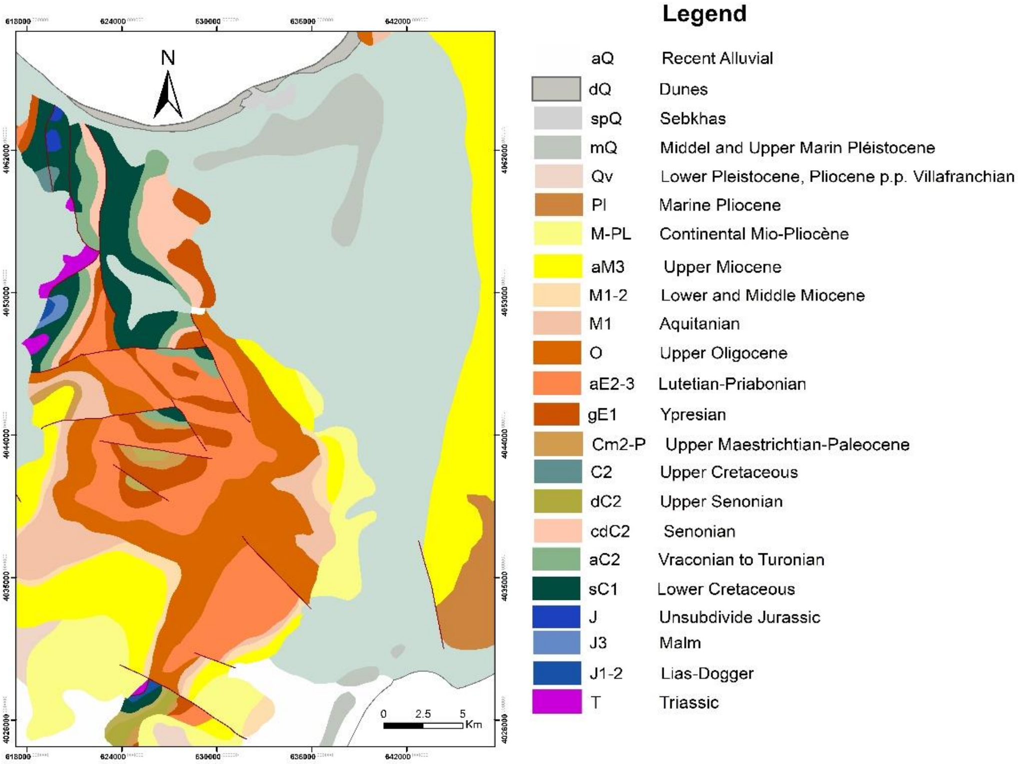

Figure 2. Geological map of the Study area

The groundwater flow system being investigated consists of both shallow and deep aquifer systems. These aquifers are separated by a clay unit that is approximately 15 meters thick. The shallow aquifer is composed of Quaternary sediments such as alluvium, sands, and sandy clays, which extend to a depth of 50 meters (Figure 2).

Within the study area, the irrigated areas are categorized into two distinct domains. The first domain comprises the Public irrigated perimeters, spanning approximately 130 km^2. These perimeters are primarily designated for the cultivation of citrus fruits, olive trees, vegetables, and field crops. They are situated in the delegations of Beni Khalled, Menzel Bouzelfa, Soliman, Grombalia, and Bou Argoub. The second domain encompasses privately owned irrigated areas. The water used for irrigation is abstracted from shallow and deep aquifers. It covers a total area of 70.8 km^2 (Figure 3).

2.2. Data collection

The methodology of this work includes two methods of analysis of the dynamics of the aquifer: piezometric maps to assess the spatial variability of the aquifer and piezometric sections to evaluate the piezometric fluctuation of the water table. These methods allow determining the impact of the different hydraulic works on the piezometry. The piezometric variation at the measuring points of the shallow aquifer reflects changes in the equilibrium of the aquifer system. This variation can be explained by different types of inputs (e.g. floods, rainfall, artificial recharge and irrigation). According to the main objective of this research eight piezometric maps of the highest water levels, measured in May, for each year and in the end of the rainy season were established based on the network stations of the Grombalia groundwater. This network stations consists of 56 surface wells and 11 piezometers, distributed over the entire area of the aquifer using the QGIS software (Figure 4). These piezometric maps were plotted for eight years and for various recharge situation. In fact, the chosen dates were below, May1987 (without recharge), May 1992 (with recharge: only one at the Gobba site1), May 1999 (with recharge: 3 sites), May 2005 (with recharge: 9 sites); May 2009 (no recharge), May 2015 (no recharge), May 2017 and May 2019 (current status: without artificial recharge).

In contrast, a total of eight piezometric sections were chosen to evaluate the changes in piezometric levels across the entire aquifer area. Within each piezometric section, the starting point was determined as the location with the lowest piezometric level, while the endpoint was identified as the position with the highest piezometric level. This work is repeated for each map to determine the evolution according to time. The superposition of the eight curves corresponding to the different periods (May 1987, May 1992, May 1999, May 2005, May 2009, May 2015, May 2017 and May 2019) shows the variation of the piezometric level as a function of the distance x. The selected 8 sections aa', bb', cc', dd' ee', ff', gg' and hh' (Figure 4), pass through several natural and artificial recharge sites to explain the impact of each site for different dates.

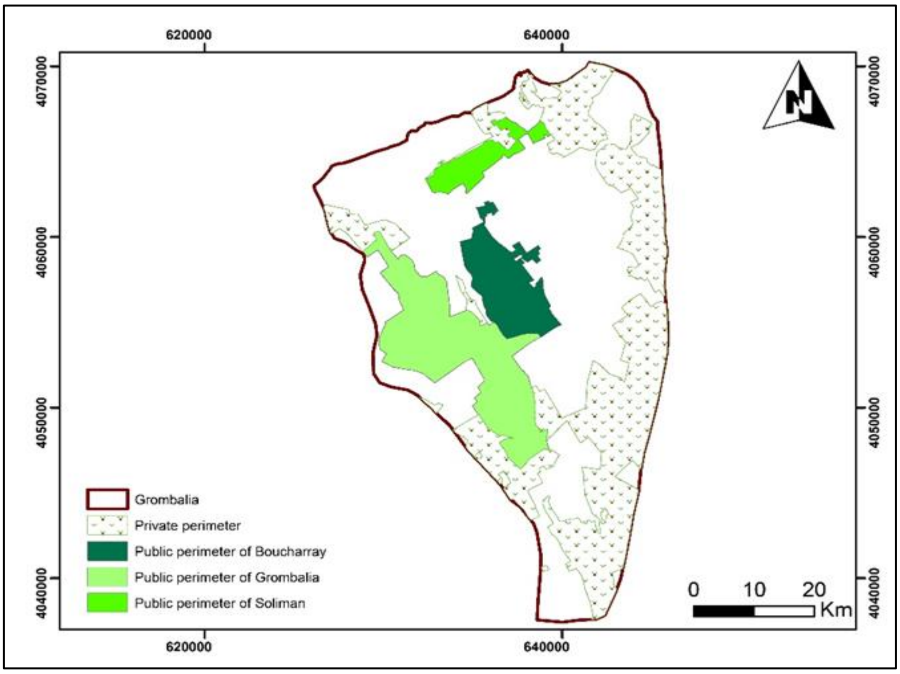

Figure 3. Irrigated areas in Grombalia plain

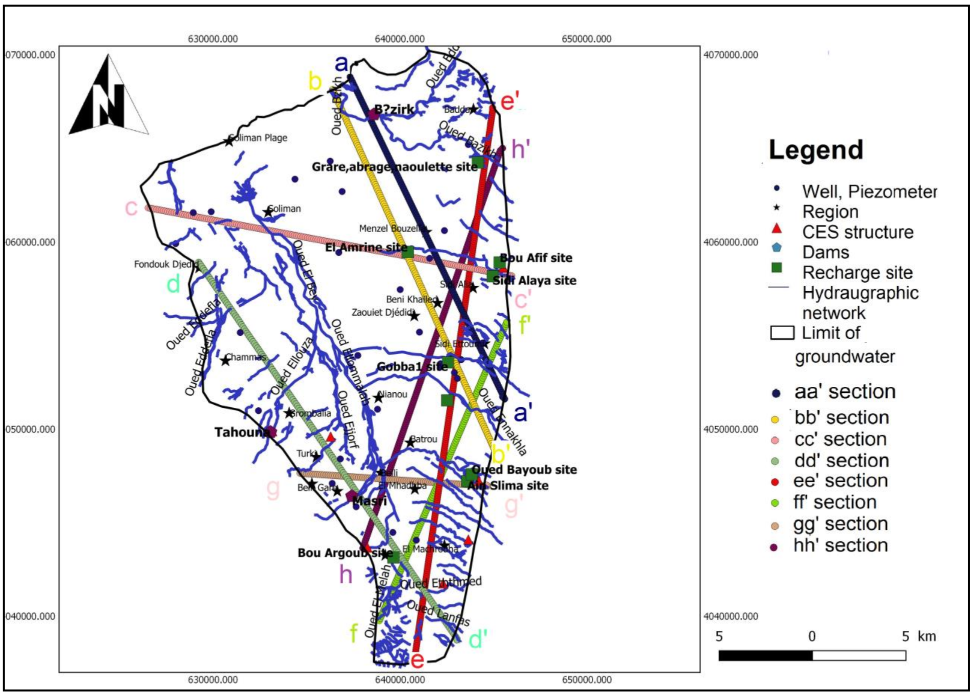

Figure 4. Piezometric Sections

3. RESULTS AND DISCUSSION

3.1. Exploitation and recharge of the Grombalia aquifers

The internal water resources is variable and defined as the average annual flow generated by annual rainfall and other recharge sources. Over time, climate and human activities were classified as the most known causes of water scarcity. In fact, the groundwater of the study area is exploited by 8840 surface wells and the deep aquifer is captured by 610 drillings. On the other hand, due to the local lack in water availability and in order to secure the agriculture and the industry, it is necessary to enhance available solutions of conservation of water resources. Indeed, the renewable resources of Grombalia aquifers were estimated at 132.5 Mm^3, of which 25.5 Mm^3 for deep aquifer and 107 Mm^3 for shallow aquifer. The average depth of wells is about 50 m but can exceed 100 m locally.

The concentration of pumping wells is predominantly observed in the areas of Menzel Bouzelfa, Beni Khalled, and Soliman. The exploitation of deep ground waters has increased from 5.15 Mm^3 in 1990 to 25.5 Mm^3 in 2019. The exploitation of the shallow aquifer followed similar trend from 89.7 Mm^3 in 1990 to 107 Mm^3 in 2019. Field visits and discussion with farmers present that due to the dramatic drop in the piezometric level some users switched recently to pumping deep wells resulting in an increase of the abundant shallow boreholes.

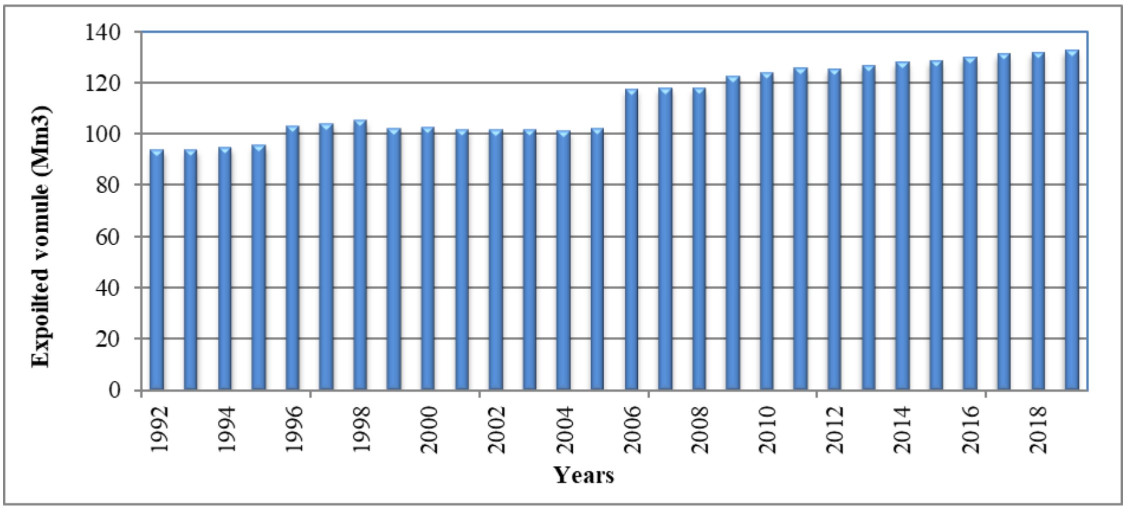

Figure 5: Exploited volume for Grombalia aquifer during 1992-2019 period

Furthermore, the public irrigation areas and backup citrus plantations, primarily situated in the delegations of Bou Argoub and Menzel Bou-zelfa, rely on public wells drilled into the deep aquifer for their water supply. In fact, the exploited volume of Grombalia aquifer were increasing between 1989 and 2019, from 94.85 Mm^3 to 132.5 Mm^3, respectively (Figure 5).

In order to restore and conserve water resources, decision makers in the Cap Bon region were oriented towards artificial recharge. In fact, artificial recharge was used to maintain and increase reliable water supplies in the studied aquifer. Moreover, these sites were chosen based on the stratification of aquifer system and spatial variability of hydraulic conductivity which are suitable for artificial recharge (DGRE). The artificial recharge for Grombalia aquifer was started since the nineties (1992) with variable volumes. The most important artificial recharge volumes for Grombalia aquifer were registered on 2005 and 1998 with 2.1 Mm^3/year and 1.6 Mm^3/year, respectively (Figure 6). Since 2011, the artificial recharge volume injected has declined to 0, 0.121, and 0.117 Mm^3/year in 2012, 2013, and 2014 respectively (Figure 6). This situation is mainly due to the deterioration of most artificial recharge stations that were invaded by floods and to the absence of maintenance activities.

3.2. Piezometric maps (highest water levels)

The variation in the piezometric level of a water table at a monitoring point reflects the variations in the balance of the aquifer system which is due to inputs, i.e. rainfall, artificial recharge and irrigation, and outputs often represented by its exploitation and underground flow towards the outlet.

The depicted maps illustrate a southwest to northeast direction of groundwater flow. The primary drainage axes align in a south-north orientation, with some axes in the western section of the aquifer draining from west to east. Notably, all isopiezometric lines converge towards the Foundek Jedid-Soliman region.The recharge zones of the aquifer are more present in the eastern part of the aquifer (Beni Khalled-Menzel Bou Zelfa zone and Bou Argoub-Grombalia zone).

The number of isopiezometric lines shows the groundwater flow and its direction. The number of isopiezometric lines and the distance between them indicates that there are two configurations. The years 1987, 1992, 2015 and 2017 have fairly large distances between isopieze lines, which shows that the flow velocity is very low and is mainly explained by years with almost zero recharge corresponding to dry years.

The isopiezometric values varies from 65 m to 25 m, with the highest values located near the Sidi Toumi wadi and Sidi Bou Afif recharge site. The lowest values, reaching 15 m, are located at Foundek Jedid-Soliman.

For the years 1999, 2005, 2009 and 2019, the The isopiezometric lines are very close, corresponding to wet years and a higher flow velocity, hence a fairly high recharge rate. The maximum values (95 m) are located at Sidi Toumi wadi, which is one of the main natural recharge sites.

Two cones of exploitation towards the areas of Boucharray, Menzel Bouzelfa, Foundek Jedid-Soliman, Grombalia city and Douar Ben Attia area, the isopiezometric curves show a depression of the piezometric surface. This is due to intensive agriculture exploitation of the groundwater during this period (Figure 7). The downstream of Wadi Ellommaleh, when the isopiezometric curves show a concavity, the isopiezometric lines converge, in this zone the Wadi drains the groundwater. This zone constitutes a relief depression.

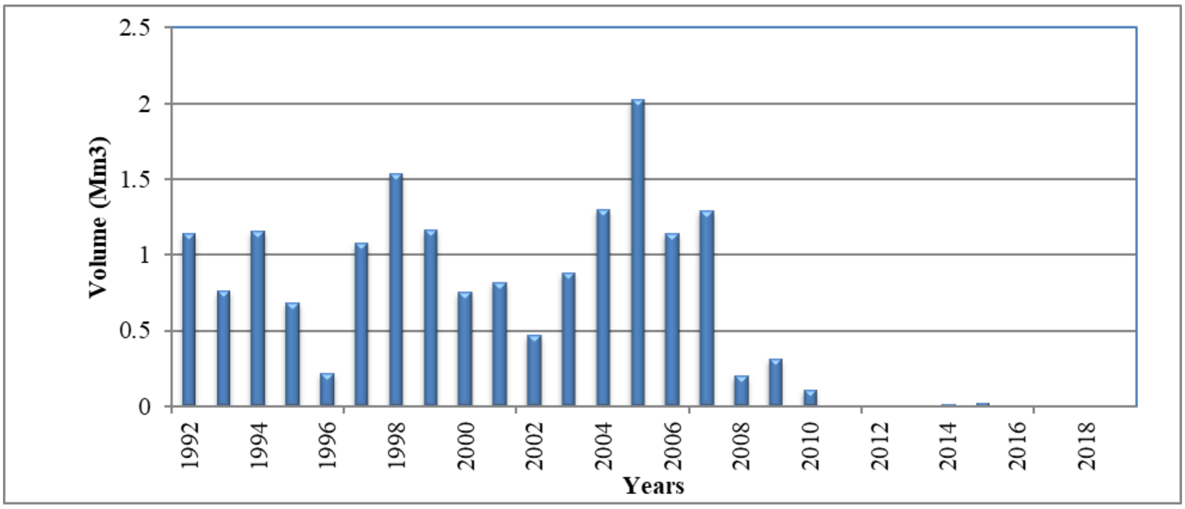

Figure 6. Artificial recharge volume for Grombalia aquifer during 1992-2019 period

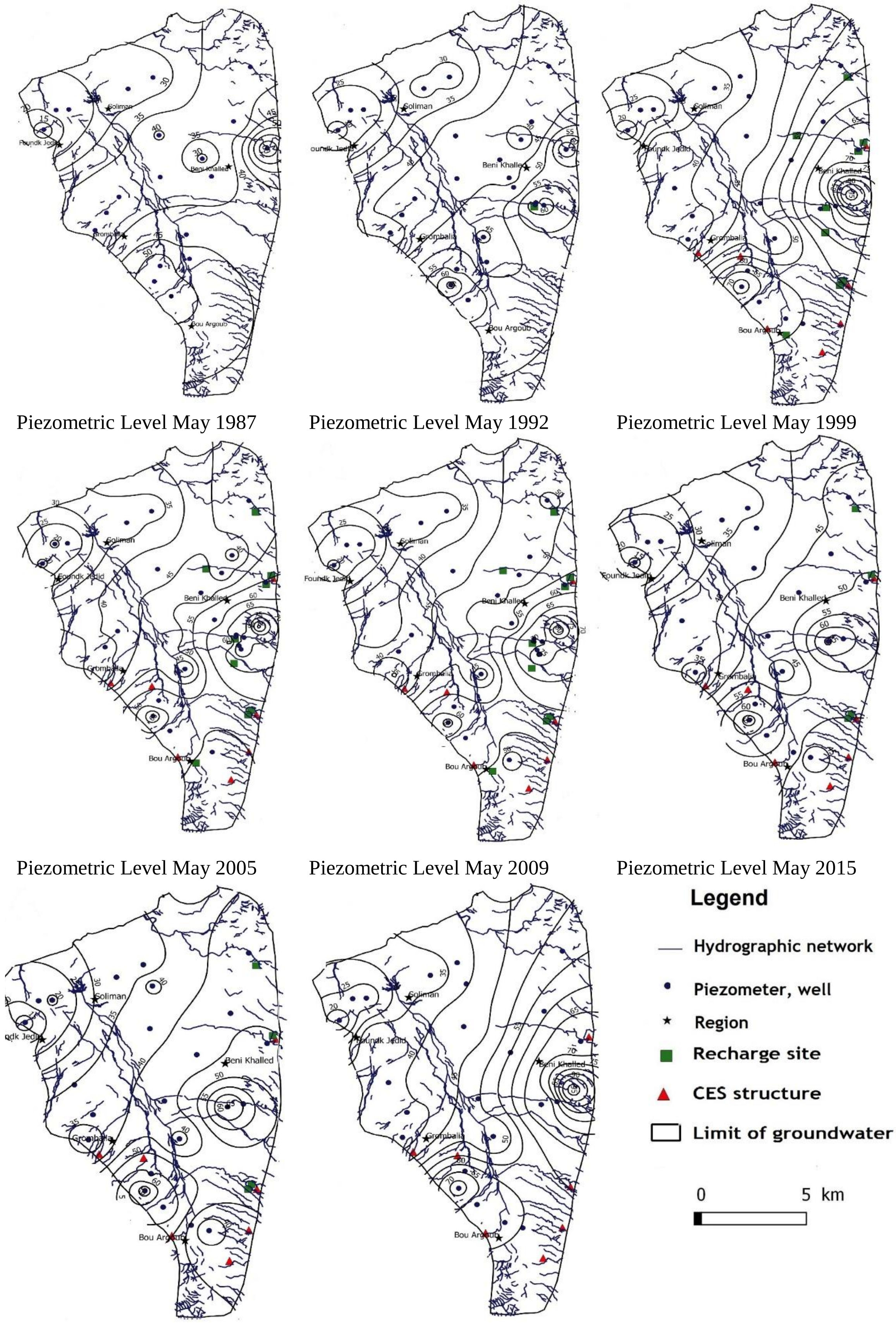

Figure 7. Piezometric maps of (a) May 1987, (b) May 1992, (c) May 1999, (d) May 2005, (e) May 2009, (f) May 2015, (g) May 2017 and (h) May 2019

In El Gobba 1 and 2, Sidi Alaya, El Amrine and Bou Argoub recharge sites, the piezometric level increases, the iso-piezometric curves show a convexity, and it is a supply pulse which is due to the artificial recharge of the groundwater.In the Sidi Toumi–Beni Khalled area, the lines are divergent, the isopiezometric curves show a convexity around the Wadi Sidi Toumi. This is a recharge area which can be explained by the rainfall contribution (Figure 7). The September 2018 flood resulted in a significant rise in the piezometric level across the entire water table, indicating a noticeable increase in groundwater levels. This increase is around 15 m at Beni Khalled and Sidi Alya, 10 m at Menzel Bouzelfa and Bou Argoub, and 5m at Soliman and Fondouk Jedid.

3.3. Piezometric sections

The piezometric description of groundwater shows the shape of the isopiezometric curves and allow to position the recharge zones of the groundwater table and the pumping zones.

These sections were selected based on the location of the recharge sites and hydrographic network, the private and public irrigation perimeters and the areas (Figure 8). As a result of the extreme events of September 2018, a significant increase in the piezometric level in May 2019 over all the aquifer surface was observed, mainly in the Sidi Toumi area. Except for 2019, the piezometric sections in 2005 and 2009 show higher piezometric levels compared to the other periods. In this period the nine recharge sites were operational.

The highest piezometric levels correspond to potential recharge areas, whether natural or artificial. The North-West and North-East zones have the lowest piezometric levels, corresponding to areas of high groundwater extraction. The maximum piezometric level for 2019 in the recharge zones varies from 75 m to 95 m. In the extraction zones, the minimum piezometric levels are 30 m in the overexploited Soliman zone and 40 m in the Bouargoub zone.

The lowest piezometric levels correspond to 1987 which is a dry year. The maximum piezometric level does not exceed 50 m with a minimum level close to 15 m. The 2019 piezometric level increase about 40m compared to May 2017 in the Sidi Toumi area. Between 2019 and 1987, the maximum piezometric difference is 55 mm and is located at the Sidi Toumi wadi and the Sidi Alaya site.

It is clear that Wadi Ejjorf, Wadi Sidi Toumi, Wadi Ejdida, Wadi El Bey, Wadi Jraba, Wadi Saïda and Wadi Bou Argoub contributes a lot to the natural recharge of the Grombalia aquifer. A pick at all the recharge sites marked between 1999 and 2009, mainly at El Gobba 1 and 2, Sidi Alaya, El Amrine and Bou Argoub (Figure 8).

Many extraction zones are mentioned in the figures by local depression, they essentially represent the irrigated perimeters of Soliman-Fondok Jedid, Boucharray, Bou Argoub, Gobba Chammas-Grombalia, Niano and Beni Khalled-Zouit Jedidi. An overexploitation in those areas by pumping through the surface wells. These depressions could be attenuated for a rainy year and for a decrease of pumping in irrigated perimeters.

3.4. Explanatory factors of piezometric changes

Aquifer recharge occurs naturally as a result of a hydrological process by which surface water percolates through the soil, through the river system, or it can be achieved artificially. It is then necessary to determine the proportions and the dominant type according to the area and the period.

In Grombalia plain, through the analysis of correlations between piezometric changes, annual rainfall, flooding dates and artificial recharges, It is evident that there are three distinct types of correlation:

- In Beni Khaled area, characterized by the absence of artificial recharges sources, present a strong correlation between annual rainfall and piezometric changes which confirm that the rainfall is the main source of recharge. This can only be explained by the geological texture, characterized by sand and sandstone lithology.
- In Douar Ben Attia, Bouargoub and Fondouk Jdid zones, the aquifer is fed by rainfall and by the hydrographic network. Indeed, those zones, which are characterized by alternating gravels, sands and conglomerates, the aquifer is fed by Wadi Oued Ellouza and Wadi Bouargoub.
- In Bouchrik and Boucharray areas, there are the Quaternary lagoon represented by sandy clays and beds of sand with limestone dolls, with low permeability. In the Eddokhania zone, there are sandy limestone banks with rich macrofauna with very low permeability. In those areas, the sources of recharge are mainly the artificial recharge such as such as the Ettoumi wadi recharge site and the Gobba1 recharge site.

Concerning the piezometric sections, the increase of water level is correlated to groundwater use for irrigation. Besides the natural direct recharge, the recharge of groundwater is further augmented by the return flow from irrigation practices. It is important to highlight that in addition to utilizing local water resources, the incorporation of water resources from North-West Tunisia, specifically the Medjerda river, in agricultural activities has contributed to increased

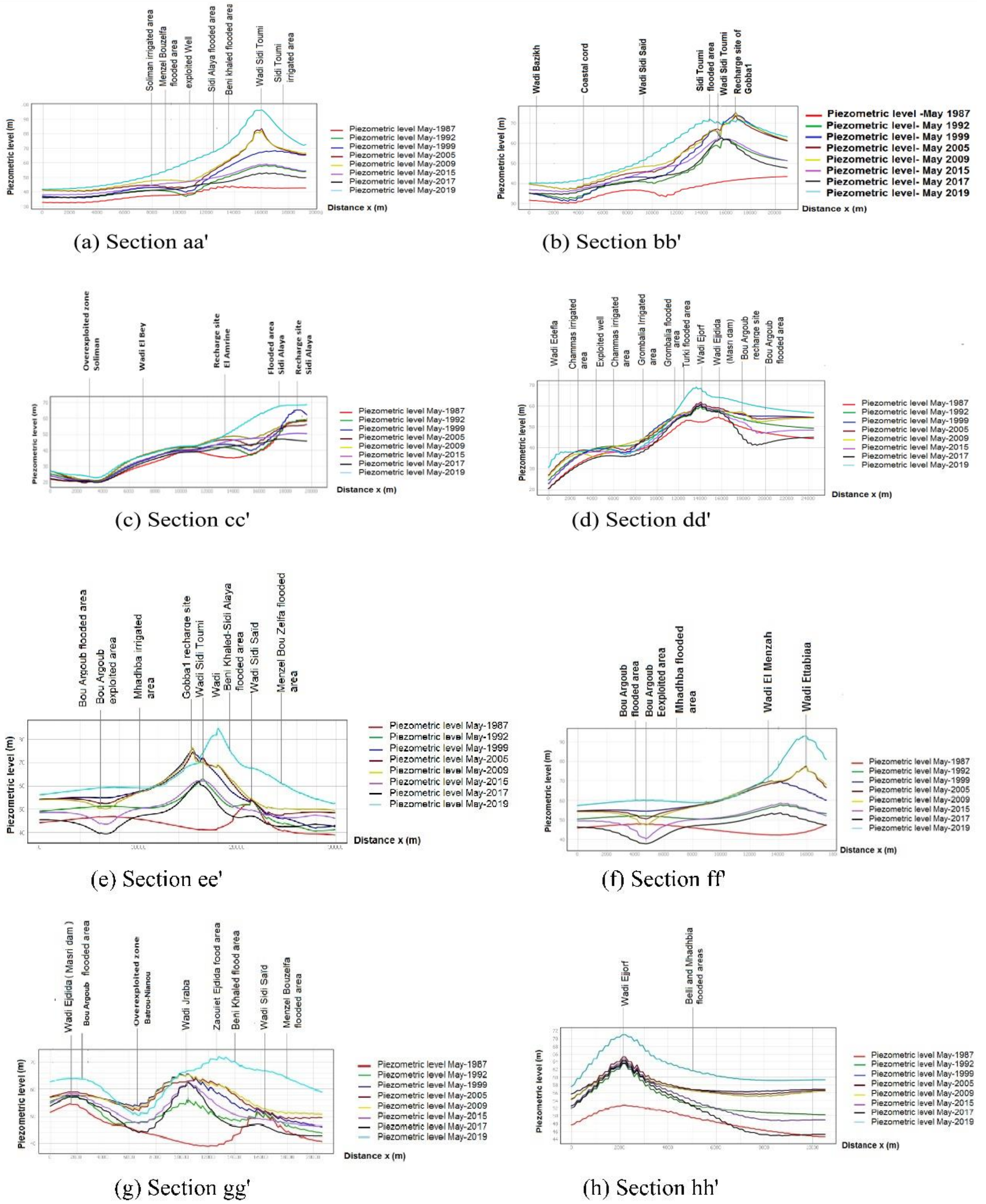

Figure 8. Piezometric sections (a) aa', (b) bb', (c) cc', (d) dd', (e) ee', (f) ff', (g) gg' and (h) hh'

infiltration and has helped replenish the rising water levels through the return flow (Lachaal et al., 2018).

Groundwater is extensively utilized by farmers for citrus irrigation, particularly in the regions of Beni Khalled, Menzel Bouzelfa, and Soliman. These agricultural practices, in turn, contribute to the recharge of groundwater through the return of irrigation water. Consequently, there is a correlation between the rise in the piezometric level and the increased abstraction of water from the aquifer, as well as the intensified use of water for irrigation purposes.

The water resources management in the Grombalia region is very complex. Therefore, the need for a new integrated water management strategy is essential. The new strategy should be based on new and novel monitoring as well as modelling approach.

4. CONCLUSION

The findings of this study carried in Grombalia plain in the north eastern part of Tunisia, will be used by planners, policy makers, and other stakeholders as resource management tools for conceptual and quantitative regional groundwater flow models and long-term aquifer monitoring. The analysis of correlations between rainfall and piezometric levels allow indicating the areas of direct recharge from rainfall. The interpretation of piezometric maps for different dates allows to describe the spatial variability of Grombalia aquifer.

The utilization of piezometric sections enables the creation of piezometric evolution curves across the entire expanse of the aquifer, providing a comprehensive understanding of the changes in piezometric levels. These sections allow us to distinguish between the different types of recharge, and to show which of these recharge sources is the most important.

In fact, in Gromablia aquifer, the sources of groundwater dynamics are natural water recharge, agriculture water consumption and artificial recharge. Floods and extreme events, the release of the dams, recharge from Wadis are considered as the main natural water recharge resources. During the period 1999 and 2009, the artificial recharge sites have a very positive impact on maintaining and improving the piezometric level.

The development of agriculture through irrigated areas and water-consuming crops has led to overexploitation of the water table in this area by pumping through surface wells. This overexploitation impacted significantly the lowering of the aquifer level. This situation is aggravated by the increase in the recurrence of dry periods.

The piezometric section technique is important to choose the best recharge sites and allows to adjust the recharge in the hydrodynamic models of the aquifers. Indeed the positive response of the aquifer in the area of Sidi Toumi and the area of Bou Argoub, for which we propose the construction of artificial recharge sites.

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