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Dwindling Groundwater Resources in Tunisian NWSAS, from Global Recovery and Climate Experiment Satellite Gravity Observations

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ABSTRACT

The North-Western Sahara Aquifer System (NWSAS) extends over a total area of one million km^2. This transboundary aquifer system is shared by Algeria (700 000 km^2), Libya (250 000 km^2), and Tunisia (80 000 km^2). Tunisia is the most heavily irrigated region in the arid zone. The water reserves are estimated to be 60,000 billion m^3 distributed under two main superposed confined aquifers. These layers are, from the top, the Terminal Complex (TC) and the "Continental Intercalaire" (CI). The depth of the CI aquifer is comprised between 100 and 2500 m. The geothermal Continental Intercalaire aquifer is an extensive horizontal sandstone reservoir. The geothermal water is about 25-30 thousand years old and of the Sulphate-chloride type. The piezometric level is about 20 bars, and the production rate has reached an average of 4 mm^3/year, and several problems have emerged, among the most important being the pressure decline in the reservoir.

The GRACE satellite mission has recorded temporal changes in the Earth's gravity field in this region. These changes reveal a steady, large-scale mass loss that we attribute to excessive extraction of low enthalpy geothermal groundwater. Combining the GRACE data with hydrological models to remove natural variability, we conclude the region lost groundwater at a rate of 54 ± 9 km^3/year between April 2002 (the start of the GRACE mission) and December 2015. The GRACE data variations are very well fitted when compared with in situ observations. This is probably the largest rate of groundwater loss in any comparable-sized region on Earth. This trend, if sustained, will lead to a major water crisis in this region when this non-renewable resource is exhausted.

1. INTRODUCTION

Underground geothermal water storage is a vital resource for agricultural, industrial, and domestic consumption in the south region of Tunisia and for the ecosystems maintainance Fig.1. The basin's water reserves are estimated at 60,000 billion m^3 distributed over two superimposed aquifers: the Intercalary Continental (IC), with a depth that reaches 2,500 m in certain areas, and the Terminal Complex (TC), of a depth, comprised between 300 and 500 m. The annual recharge of the aquifers amounts to one billion m^3, and estimated withdrawals had increased from 0.6 billion m^3/year in the early 1970s to 2.7 billion m^3/year in 2012. In 50 years, the exploitation of the geothermal water resources has increased fivefold and driven the basin into a state of overexploitation that exceeded the threshold in the early 1980s.

Monitoring total water storage in the geothermal aquifer system on the Earth is essential for understanding the hydrological cycle and for achieving sustainable water management for a continually increasing population. Hydrologists and climate scientists construct global land surface models that use meteorological fields (e.g., precipitation, temperature) as boundary conditions, to estimate and predict water storage [1].

On the quantitative level, risks related to water deficit affect greenhouses agriculture first. The intensive use of the underground water resources resulted in a significant drawdown of the aquifer and led to the drop of artisianism and depletion of flow rate in deep wells and traditional water catchment and distribution systems (Foggaras). In order to bridge this gap of groundwater deficit and especially the geothermal water, there has been a tendency to multiply boreholes and dig deeper drillings. Consequently, the resource mobilization costs (energy bill of water pumping) have become a real constraint [2].

The complexity of water storage modeling and the difficulties of acquiring relevant data pose challenges for estimating the variability of stored water. Here, we describe results from a satellite-based observational technique that allows us to monitor regional changes in stored underground water directly.

2. DATA AND METHOD OF ANALYSIS

2.1. Description of Study area

The study area is mostly located in the Saharan platform, which is a flat plateau dipping gently to the southwest. The Saharan platform it is overlain by the sand dunes of the Great Erg Oriental, and by very large dry salt lakes (Chott Djerid, Chott El Fedjej, Chott El Gharsa). The deep geothermal field spans the three countries of extends over a surface area of 1,100,000 km^2 with 700,000 km^2 in Algeria, 250,000 km^2 in Libya, and 80,000 km^2 in Tunisia [2]. This basin is located in an arid zone, with rainfall ranging from 20 to 100 mm·yearr-1 [3]. In the southern Tunisia geothermal field, which is in the major part of the basin, rainfall does not exceed 100 mm [4]. The structure of the latter is, in fact, a large depression filled by thick layers of sedimentary formations (continental and marine). This sedimentation is limited at the bottom by the basement [5]. -The detrital formations of the Continental Intercalaire (CI) in the bottom range within a depth of 1000 to 2500 m. The huge groundwater reservoir is mainly confined to the continental formations of the Lower Cretaceous (Neocomian, Barremian, Aptian, Albian). In Tunisia, the aquifer covers the regions of Kebili, Tozeur, Gabes, and the extreme south. The most important production takes place at the Kebili geothermal field, where the depth to the top of the reservoir varies from 600 to 2,800 m. Wells' pressures correspond to 200 meters above wellhead with temperatures of around 70°C. The geothermal gradient in the study area is of the order of 3.5°C per 100 meters (Figure 2).

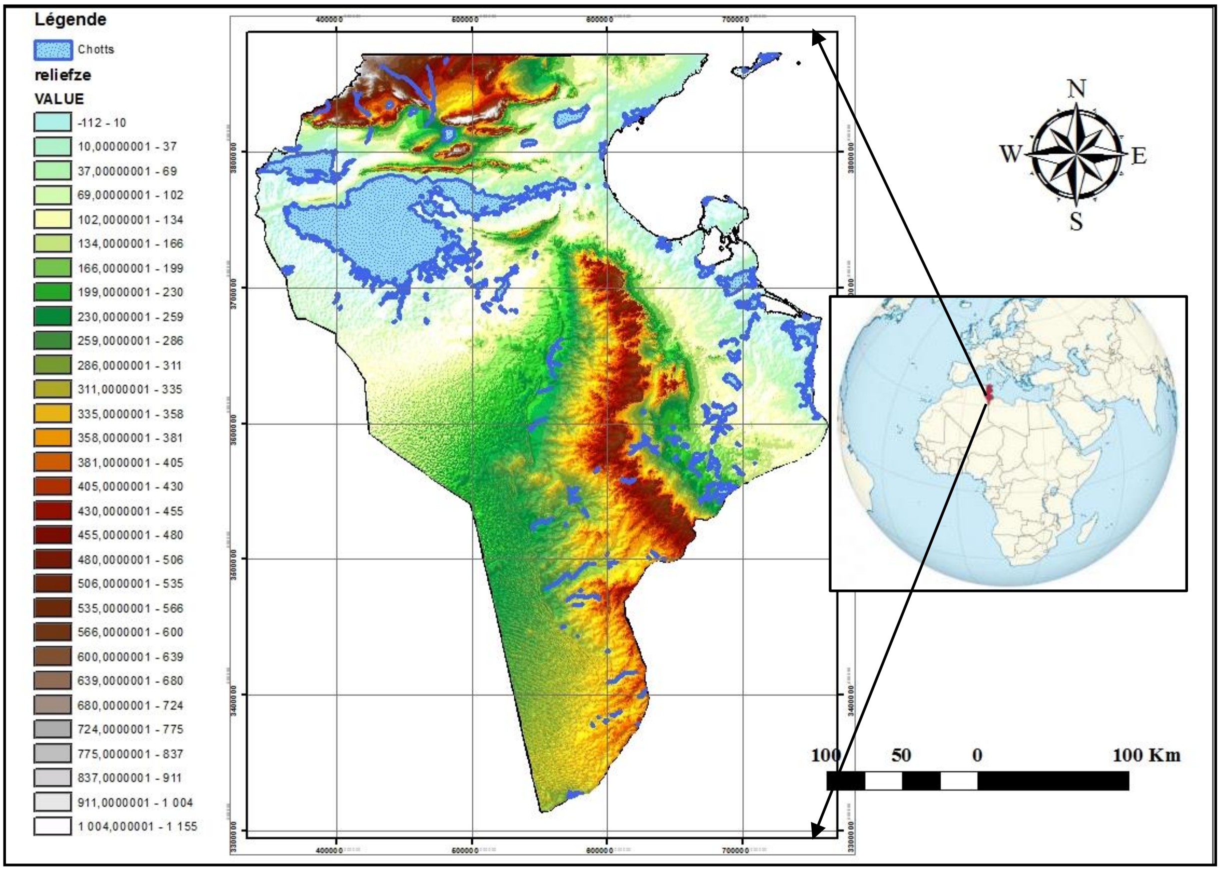

Figure1. Representation map of selected study areas of the Tunisian geothermal Continental Intercalaire aquifer. Rivers are delineated in blue, and the respective watershed boundaries with altitude colors. Blue to red gradient represents intensity on a 0 to 500m scale, respectively.

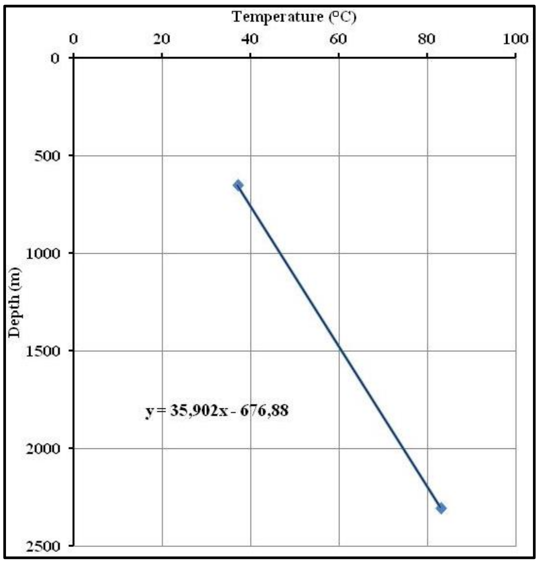

Figure 2. Geothermal gradient in Tunisian geothermal field (CI aquifer)

There is extensive irrigation for agriculture surrounding the study area, and the geothermal water is mostly for agricultural purposes (to complete the irrigation of oases and greenhouses heating). The study of the status of land use in the study area in 2012 appears that the evolution of the agricultural activity in the region during the past has resulted in the expansion of irrigated areas around oasis and the increasing number of drilling in order to exploit the deep-geothermal water resource.

The management of these schemes and oasis requires the instead of an updated information tool to help land managers and decisions to support the development and management of these regions in full agro socio-economic growth. It is essential to establish a new approach for the database adapted to the regional context.

The climate of the south of Tunisia is characterized by intense drought with low moisture content. The average annual temperature is around 25°C, with hot summers and cold winters. Extreme temperatures are above 50°C in summer [2], [6]. The rains are characterized by large inter-annual variability. In the northern Sahara, they are fine when they are at the center of downpours. These climatic characteristics affect Saharan hydrography. Thus, the flow of water in valleys is temporary and is lost in the closed depressions (chotts and sebkhats). When the valleys have no surface flow, they often have a sub-surface flow, which takes on a lot of importance to the scarcity of surface water [4], [3]. The Saharan Platform, which occupies 60% of Tunisia, is a semi-arid region with an annual rainfall of only 74 mm per year [3]. The study gives the arid climate of the Saharan area character superior to the inferior Sahara. The river system of the study area drains a large watershed that is the Chott. It is characterized by a variable rainfall regime in intensity and frequency. The average annual relative humidity is around 51% in Tozeur and Kebili 58%.

The area of the Tunisia geothermal Continental Intercalaire aquifer is not only distinguished by the importance of farming activities, but also tourism and industrial activity, particularly in specialized centers. However, agriculture remains a leading sector both as an economic sector in its contribution to employment, domestic production, particularly of certain products and finally as a form of exploitation of natural resources (water, soil and vegetation cover) and spatial planning. Indeed, it operates more than 80% of the mobilized water resources. Nevertheless, the current supply of deep geothermal groundwater of the area of the Tunisian geothermal aquifer is low compared to the current sampling and that planned for the future, and whatever the results of more detailed hydrological studies, these do not change the non-renewable nature of the Saharan water resources.

2.2. GRACE-Derived Total Water Storage Data

The method for monitoring total water storage uses gravity data from the GRACE (Gravity Recovery And Climate Experiment) satellite mission, launched in March 2002 [7]. The goal of the GRACE space mission is to measure the Spatio-temporal variations of the gravity field with unequaled precision. As gravity changes are an integral variation of mass, these Spatio-temporal gravity variations represent a redistribution of mass and is assumed to be caused by water changes. Among the application of GRACE data is the quantification of the terrestrial hydrological cycle through the measurement of the vertical integrated terrestrial water storage (TWS) changes inside aquifers, soil and surface reservoirs [8], including hydrology [9],[10].

The annual trends in terrestrial water storage (TWS) are extracted from monthly 01/2002 to 12/2015. The time series are obtained from the spherical harmonics' coefficients provided by the datacenters at the GFZ RL05a in Potsdam, GermanyData: GFZ RL05a monthly solutions filtered with DDK5. The data acquired over the study area from the Global Recovery and Climate Experiment (GRACE), portail [11]. The GRACE data have been widely used to study water storage at various scales over different parts of the globe [12]; [13]; [14]; [15]; [16].

2.3. Estimating Equivalent Water Heights

Many previous studies as [17],[18], [9], [19], [20] and [10] all of them have determined the possibility to detect the groundwater component changes of total water storage, and Equivalent Water height can be extracted from the GRACE released data.

This approach, shown in equation [1], estimated monthly groundwater storage variations as the residual of the water storage balance, by the surface water and soil moisture storage are in a static situation from those of total water storage observed by GRACE.

$$G = S - SW - SM \qquad [1]$$

Where G is groundwater storage, S is total water storage, SW is surface water storage, SM is soil moisture, and the primes indicate anomalies with respect to the mean of the particular component during the study period. With respect to the mean of the particular component during the study period. The surface water is the sub.

We have the driest part of the Sahara Desert to assess the quality of RL05a –DDK5. We compute the Equivalent Water Heights signal amplitudes and interpret them as a measure of errors as zero amplitudes are expected in that area. This gives us an estimate of the point-wise error (within the spatial resolution, which is about 100 km).

Next, we compute the mean mass variation over the region. This gives us an estimate of error when average over a region with a surface area of about 10286 km² or 1 °² (mean latitude 33.703°N). We do this for 138 dates 144 months and average the errors overall months to compute error for the region.

Finally, the optimal filter, which is routinely applied, causes smoothing. The amount of smoothing depends on the signal amplitudes. Therefore, we have computed filters by assuming different signal amplitudes when designing the filter. The assumed amplitudes to 0.4 cm of annual Equivalent Water Height depletion corresponds to the actual signal amplitude in areas with the largest continental mass variations.

2.4. Estimating Equivalent Water Height

Gravity anomalies, obtained for each grid node by subtracting the average value over a reference period (January 2002 to December 2015), were directly accessible from the database, expressed as equivalent water height in centimeters (measurement error of 9.7 mm calculated according to [24]).

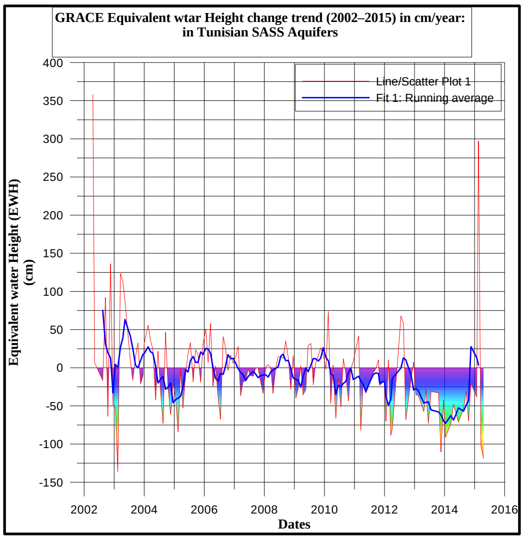

Figure 3. Equivalent water Height change trend (2002–2015) in cm/year in Tunisian Geothermal Continental Intercalaire aquifer.

According to the GRACE data (Global Recovery And Climate Experiment) of the GFZ model, RLO5a, DDK5, the German center, collected between January 2002 and December 2015, the geothermal Continental Intercalaire aquifer in Tunisian field has an average decrease of the equivalent water height of 0.51 cm/year. In the Djerid region of Tozeur, the total height of the water equivalent records an average drop of 0.59 cm/year, whereas, in the area of Kebili Nefzaoua, the decline is 0.64 cm/year. From January 2002 until December 2015, the trend of the curve of change in total water stock (TWS) deduced from GRACE data (RL05) of the GFZ German center is -135 mm in the study area. This has an average loss of water volume of about 10 Gt (1010 tons of water) ie, 1000 Million m^3/year, which exceeds the said volume by announced by the service DGRE (821 million m3 / year) [21]. The rate of water loss clearly shows the overexploitation of groundwater in the study area. This difference in 179 mm^3 results from the volume exploited through uncontrolled exploitation.

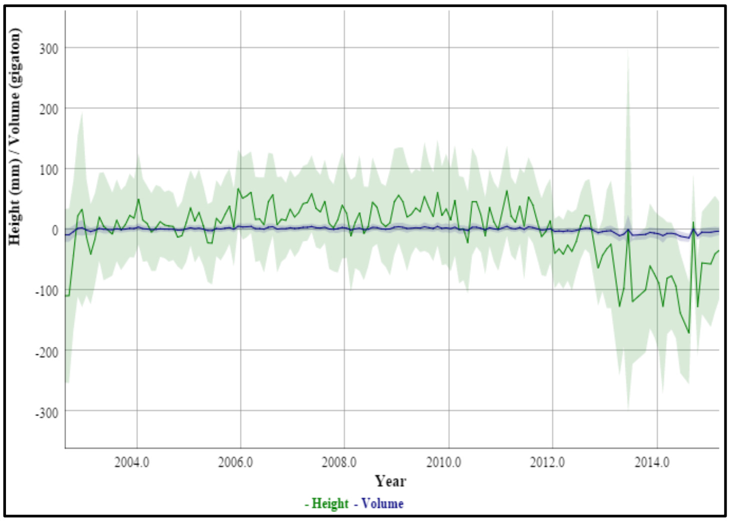

Figure 4. Height/volume gigaton changes for the Tunisian geothermal field (Made with www.thegraceplotter.com, courtesy of CNES/GRGS)

Numerous studies have demonstrated that the GRACE data capture natural water storage variations very well when compared with observations [9]; [18] [22]; [23]; [24]. However, the amplitude of the annual variations in GRACE-observed Equivalent water height is generally similar to that simulated models, a result that is apparent in Fig. 5.

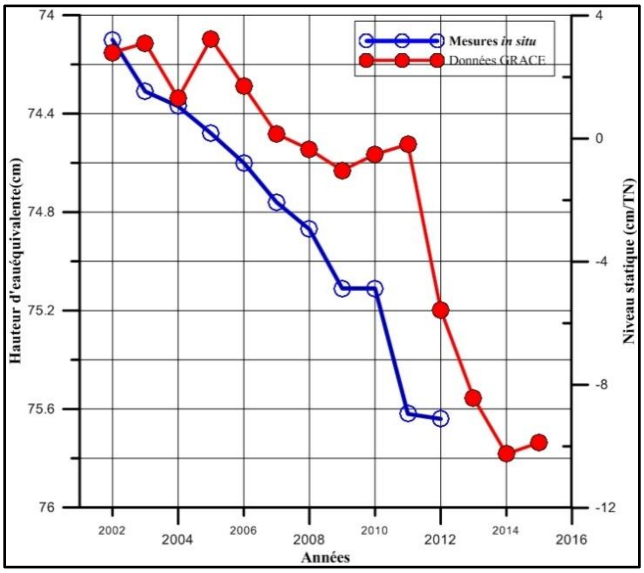

Figure 5. Annual variations in GRACE-observed Equivalent water height in Tunisian geothermal field

3. RESULTS

The GRACE data of monthly Equivalent Water Heights (EWH) anomalies were compared with the in situ observed data for the study region. However, it needs further discussion. Figure 6.

According to the previous studies, the derived GRACE data capturing natural Equivalent Water Heights variation demonstrated that it could be compared very well with observations data [9]; [23]; [24) and [18]. The three distinct and interconnected geographic areas (Djérid, Furrow Chotts, the extreme south, and the Sahara platform) exhibit a response variability with respect to the volume of sample and piezometric that records continuous decompression.

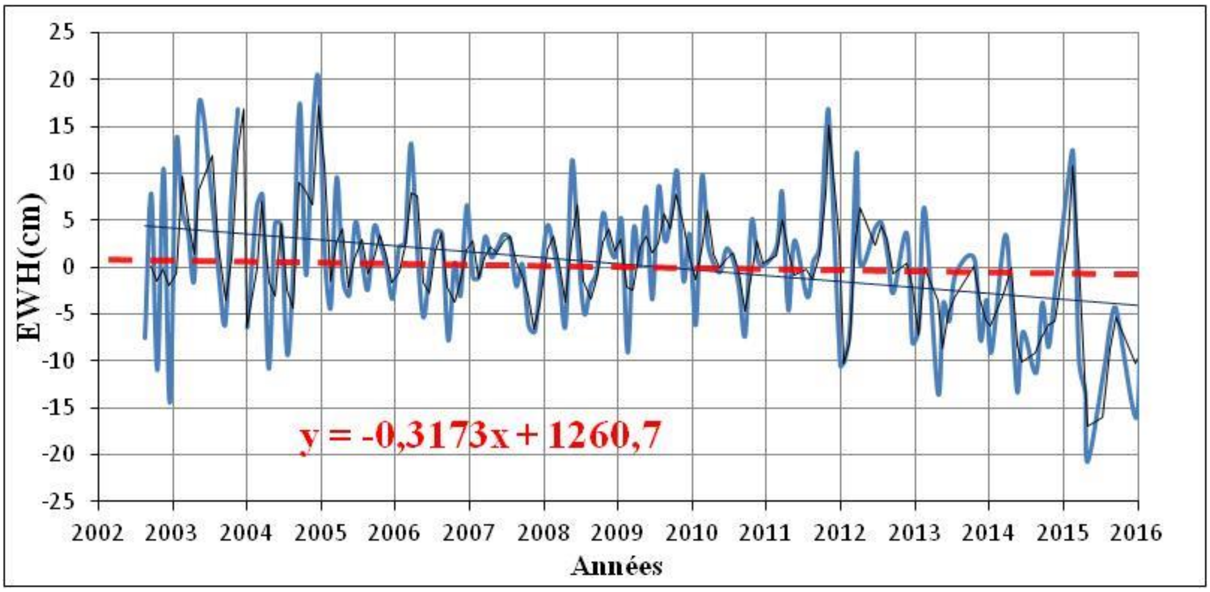

Figure 6. Time series of yearly GRACE EWH Values (in equivalent water height, cm)

Indeed, the effect of overexploitation is manifested by the decline in drilling artesian load (1 to 1.5 m/year) at the chotts furrow and, consequently, the gradual reduction of artesian flow. This chronic decline seems to lead to an inescapable catastrophe of the body water around chotts by the reversal of the flow direction. According to the graphical representation of the variation of the EWH (Figure 6), it can be seen that a series of equivalent water height has an average decrease of 0.3173 cm/year.

4. DISCUSSION

The three distinct and interconnected geographic areas (Djerid, furrow Chotts, the extreme south, and the Sahara platform) exhibit response variability with respect to the volume of sample and piezometric that records continuous decompression. Indeed, the effect of overexploitation is manifested by the decline in drilling artesian load (1 to 1.5m/year) at the chotts furrow and, consequently, the gradual reduction of artesian flow. This chronic decline seems to lead to an inescapable catastrophe of the geothermal water body around chotts by the reversal of the flow direction.

According to the GRACE data (Global Recovery And Climate Experiment) of the GFZ model, RLO5a, DDK5, and the German center, collected between January 2002 and December 2015, the geothermal aquifer in Tunisian field has an average decrease of the equivalent water height 0.51 cm/year. In the Djerid region of Tozeur, the total height of the water equivalent records an average drop of 0.59 cm/year, whereas, in the area of Kebili Nefzaoua, the decline is 0.64 cm/year. From January 2002 until December 2015, the trend of the curve of change in total water stock (TWS) deduced from the GRACE data (RL05) of the GFZ German center is -135 mm in the study area. This has an average loss of water volume of about 10 Gt (1010 tons of water) ie, 1000 Million m^3/year, which exceeds the said volume by announced by the administrative service (821 million m^3 / year). The rate of water loss clearly shows the overexploitation of groundwater in the study area — this difference in 179 mm^3 results from the volume exploited by uncontrolled exploitation.

5. SYNTHESIS AND CONCLUSIONS

In this paper, we used a regional scale of equivalent water height involving gravity data from the GRACE satellite system and groundwater observations of the regional geothermal Continental Intercalaire aquifers of the Tunisian field. Indeed, we found a mean validation of data derived from the GRACE mission, namely the equivalent water height, which showed conclusive and mainly promising results. It was also found that these data could be used as additional information to remote uncontrollable areas. Yet, the results obtained in this work can be improved by a large-scale specialization. Indeed, this approach needs to be validated on the whole system of the Continental Intercalaire aquifer. For the objective of sustainable geothermal reservoir development, comprehensive management strategies are recommended, including monitoring water level drawdown and extracting more thermal energy. The GRACE data can be used as new tools for underground water monitoring. The geothermal groundwater resources are overexploited, and the loss of artesianism will impact the economic viability of agriculture systems.

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