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Quantifying the Modern Recharge of the "Fossil" Geothermal Sahara Aquifers by the Gravity Recovery and Climate Experiment (GRACE) Satellite Data

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ABSTRACT

The aquifer recharge rate is pivotal in hydrology and water management and yet remains one of the most challenging hydrogeologic measures to estimate, especially in arid and semiarid regions, where rates of only a few millimeters per year are expected.

Satellite-based methods offer the opportunity to assess integrated processes at a regional scale. Although averaged over large areas (103 to 106 km^2), the hydrological quantities provided by satellite-based methods represent valuable general estimates for regional systems where exhaustive field measurements are unrealistic, too time-consuming, and too costly. In this respect, the gravity data provided by Gravity Recovery and Climate Experiment (GRACE), a satellite system launched in 2002 by NASA and German Aerospace Center, allow us to monitor the time variation of total terrestrial water storage (water masses in the upper crust). The use of GRACE data for basin scale water mass balance is gaining popularity in the hydrologist community.

The Geothermal North Sahara Aquifer System (NSAS) supplies up to 90% of the water demand [OSS, 2008]. To satisfy growing needs, the global withdrawal rate in the aquifer increased from 0.5 to almost 3 km^3/yr from 1960 to 2010, causing an ongoing overall piezometric decline, especially since the 1970s. In this context, quantifying the recharge is crucial.

1. INTRODUCTION

The North Sahara Aquifer System (NSAS) extends over a surface area of 1,000,000 km^2 with 700,000 km^2 in Algeria, 250,000 km^2 in Libya and 80,000 km^2 in Tunisia. This basin is located in an arid zone, with rainfall ranging from 20 to 100 mm/yr. In the southern Tunisia geothermal field, which is in the major part of the basin, rainfall does not exceed 100mm. 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 in the bottom by the basement. Detrital formations of the Continental Intercalaire (CI) constitute the main geothermal aquifer of the system.

The CI aquifer is composed of a succession of clastic sediments of Lower Cretaceous age. Its thickness and lithology show significant lateral variation. The CI is laterally continuous over the whole basin. It is exposed around prominent mountains and plateaus such as the Saharan Atlas, the Tinrhert Plateau, the Tassili mountains, the Dahar and Jabal Nafussa, etc. The CI is a lithologically variable formation. It is composed mainly of sandy and clayey sandstones. Towards the centre of the basin the strata forming the reservoir have entirely continental facies. Towards the basin margins, especially in the east, a transition to lacustrine and then to marine facies takes place. At its maximum, the thickness of the CI exceeds 1500 m. In its southern region, faulting has led to a compartmentalization in the CI. In the Libyan part of the basin, the CI is equivalent to the Kiklah formation, which is of Triassic age.

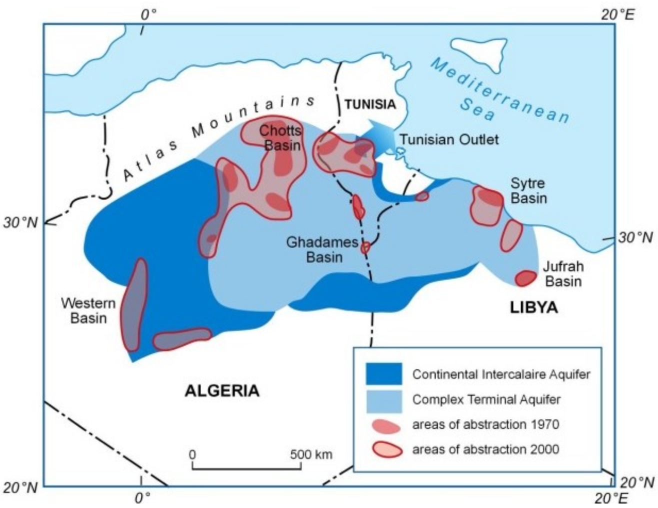


Figure 1: Hydrogeological sketch map of the extent of the Continental Intecalaire aquifer in the North Sahara Aquifer System

Based on isotopic techniques, the geothermal waters are about 25-50 thousand years old, corresponding to the last glacial maximum in Europe (Edmunds et al., 1997). Hydrogen and oxygen stable isotopes indicate a meteoric origin of the geothermal waters. 18-O ranges from -7.5 to -9‰. This signature is characteristic of paleowaters in northwest Africa. These isotopes show that the groundwater reservoirs are non-renewable (Edmunds et al., 1997).

Exploitation of water resources of the system has seen a notable increase during the second half of the 20th century. The annual extraction was 0.6 billion m^3 in 1950, then increased to 1.7 Bm^3 in 1970 and has since reached 2.5 Bm^3. This situation is reflected by the following impacts:

- a notable decrease of artesian discharge,
- drying of main springs,
- generalization of pumping extraction with increasing drawdown,
- degradation of water quality in some areas that are more vulnerable to salinization

2. CLIMATE AND HYDROGRAPHY

The climate of the south of Tunisia is characterized by intense drought with a 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. 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 the 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.

The area is mostly located on the Saharan platform, which is a flat plateau dipping gently to the southwest, where 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).

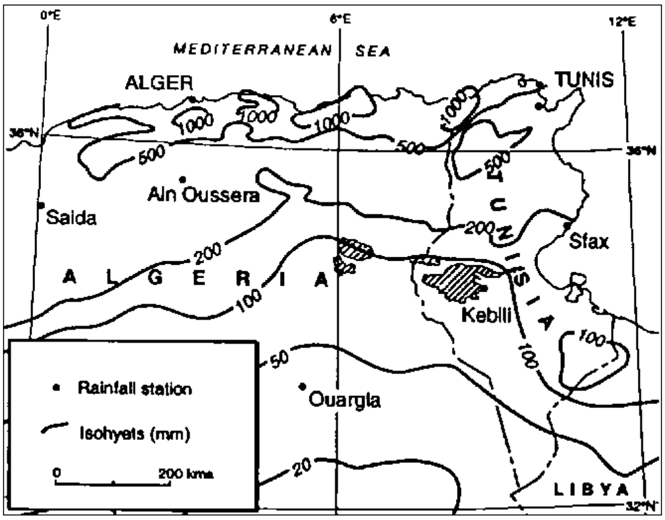


Figure 2: Rainfall over the North Sahara basin and its surroundings

3. HYDROGEOLOGY

3.1. Piezometrie

It is considered that the water piezometry of the CI is related to sand and sandstone Kbeur El Hajj because this piezometry connects those to other areas of southern Tunisia, where this water is recognized. This piezometry shows that the flow of the water is from the edges of the basin of the great Saharan erg oriental area to chott Fejjej, which is the outlet of the water. In this zone, the flow of the water is in the direction of the fault of Gafsa-Elhamma, which creates a threshold by the tectonic force from which the water rises along fractures and discharges in the Upper Cretaceous formations (limestone and dolomite of the Turonian Senonian). The surface of chotts fedjjej is the area of evaporation of water from upper levels of the nappe. The four aquifers are connected vertically by drainage phenomena that facilitate the loss of water level of the main base in the other aquifers.

3.2. Geology

In the study area, the aquifer of the Continental intercalaire is in the form of an artesian aquifer. It is the largest reserve of water in southern Tunisia. It defines the continental aquifer interlayer as the Cretaceous continental formations below, between the Neocomian and Albian, formations sand, sandstone with intercalations of clay, and whose depth ranges from 1000 to 2800 m. The continental interlayer is overlain by the Upper Cretaceous deposits, namely the Cenomanian, Turonian and Senonian salt, which can reach a thickness of about 220 m. The reservoir aquifer continental intercalaire is distinctive because of its volume, extending over 1,000,000km^2, and having an average thickness of several hundreds of meters. Large quantities of water were stored in Quaternary wet periods.

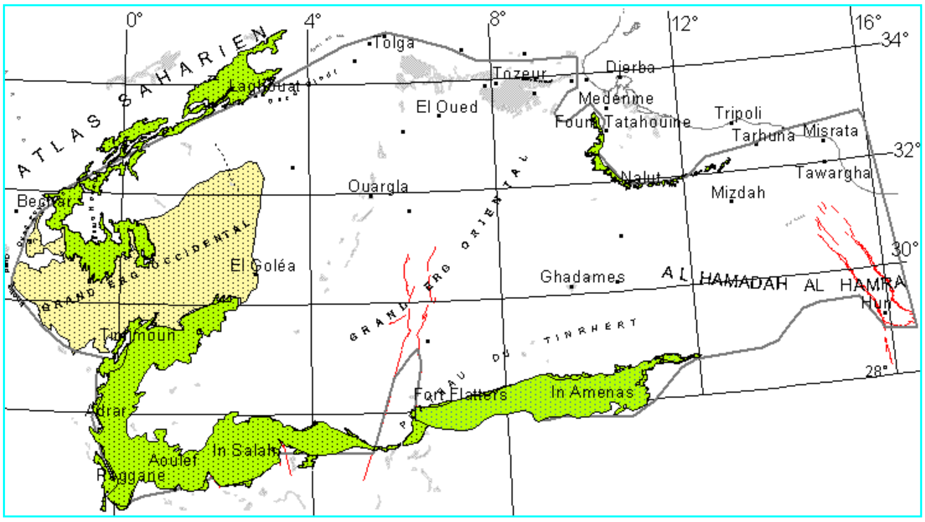


Figure 3: Recharge areas and direct infiltration outcrops of NWSAS

3.3. Recharge

$$Q = P . S . Ci$$

where: Q = flow infiltrated in outcrops

P = annual average rain

S = surface area of permeable outcrops

Ci = infiltration coefficient

The principal areas of current or former recharge are in the South Atlas Mountains of Algeria and Tunisia, the Tinrhet Plateau of Algeria and the Dahar Mountains of Tunisia. The main discharge area is in Tunisia, in the Chotts and the Golf of Gabes. The CI aquifer is one of the largest confined aquifers in the world.

3.4. Geothermal gradient

The geothermal gradient plot is an important milestone in geothermal energy. It shows the variation of temperature with depth at each point of the study area. Figure 3 shows the distribution of the thermal gradient in the CI aquifer. Thermal gradients are measured from water temperatures at the wellhead, and the observed geothermal gradient varies widely from one place to another, sometimes it is not more than 3°C/100 m.

The geothermal gradient is calculated for each drilling through the following relationship:

$$G = \Delta T \, \Delta Z \left[{}^{\circ}C/100m\right]$$

where T : Temperature (°C) and Z : Depth [m]

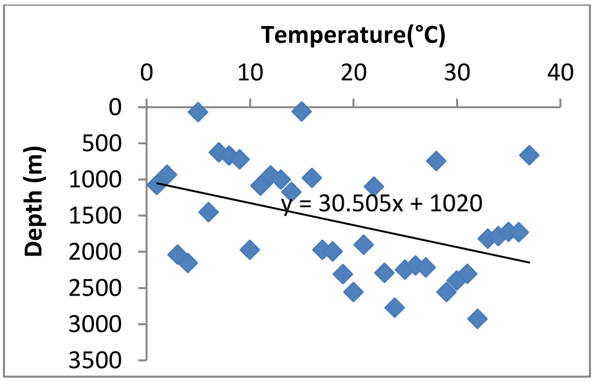


Figure 4: Plot of variations of temperature vs depth (m)

3.5. Hydrochemistry

The geochemical data acquired so far from the aquifers show clear variations from one level aquifer system to another reflecting differences in aquifer composition, recharge mechanisms, groundwater flow directions, groundwater age, groundwater mixing conditions, and hydraulic connections between aquifers.

Generally the groundwaters in all the CI aquifers are dominated by SO_4 and Cl balanced by Ca and Na (Figure 5). The chemical compositions and evolution in the aquifers are in general agreement with the general groundwater dynamics. Groundwaters from the CI aquifers have low TDS compared to groundwaters from the upper aquifers. This reflects the differences in the composition of the aquifers. Locally however some low TDS groundwaters indicate the replenishment via upward leakage of groundwater from the CI aquifers.

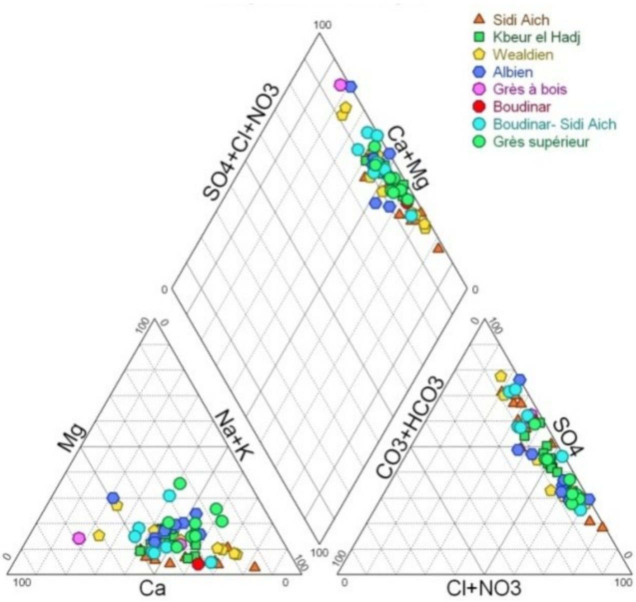
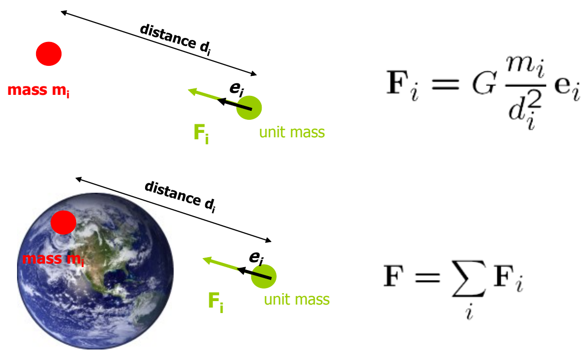


Figure 5: Piper diagram plot of the waters from CI aquifers in southern Tunisian geothermal field

4. THEORETICAL BACKGROUND

The basic equation of a gravity field is given by Newton's law of universal gravitation: Every point mass attracts every other point mass by a force pointing along the line intersecting both points. The force is directly proportional to the product of the two masses and inversely proportional to the square of the distance between the point masses. By applying the superposition principle this law also holds for continuous mass distributions such as the Earth.

Traditionally, the gravity field has been treated as essentially steady-state over human life-times. Even more, at school we learn that gravity is about 10 m/s^2 at the Earth's surface. Though this may be true at the 0.1 m/s^2 level, a closer look reveals that gravity changes as function of location. This is mainly due to the distribution of mass in the Earth's interior, in particular the flattening of the Earth at the poles and a non-homogeneous mass distribution inside the Earth and the effect of ocean bottom and land topography. However, Newton's law of universal gravitation also tell us that any redistribution of mass changes the gravity field as function of time. The time varying component of the gravity field is 3-5 orders of magnitude smaller than the solid earth sources of static field anomalies. Therefore, for many applications of gravity this component is either neglected or accounted for by applying corrections based on physical models. So far, mostly earth tides have been corrected for and the remaining contributors were neglected partially due to lack of information, partially due to the limited amplitude.



$$Fi = G\frac{mi}{{d_i}^2} * e_i$$

$$F = \sum_i F_i$$

where G: Gravity[m².s-1] mi : mass i[kg] di : distance between the two masses[m] Fi : Attraction force

The Community Land Model version 2 (CLM) are available for this period. These GLDAS simulations, for which the main inputs are surface meteorological fields, provide us with soil water content for a maximum soil.

In arid or semiarid regions characterized by a thick unsaturated zone of several tens of meters, the vertical water flow rapidly becomes steady with depth and driven by gravity alone [*Nimmo et al., 1994]*. Consequently, soil-moisture variations can be considered limited to the first few meters of soil.

Among the four soil models, only VIC and CLM show seasonal amplitudes consistent with GRACE solution on the NWSAS area. These two soil models were alternatively used in this study.

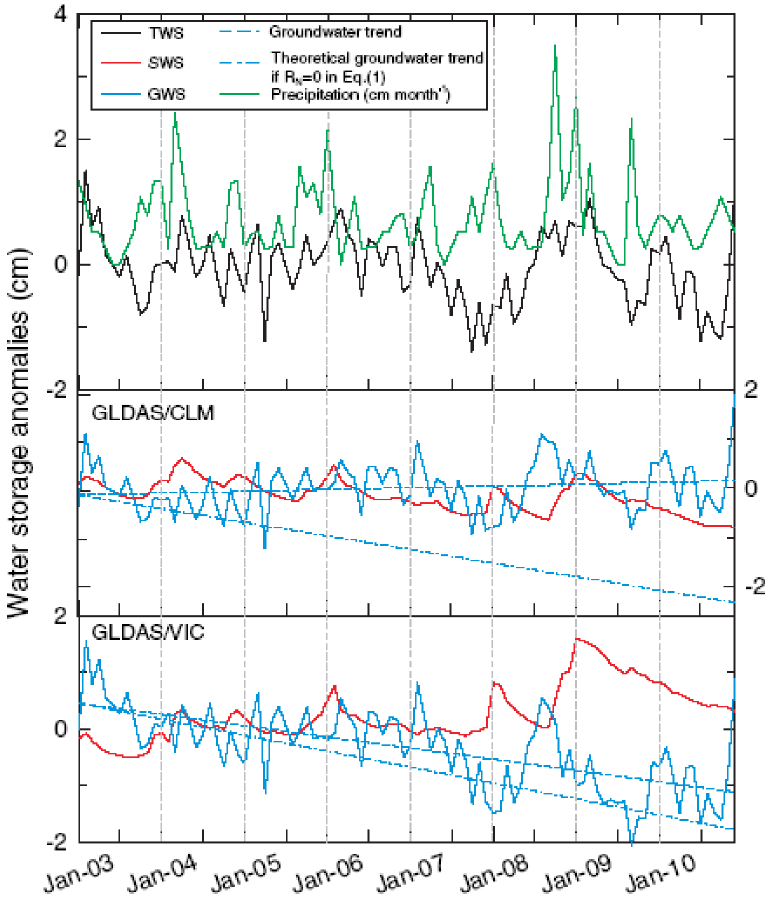


Figure 6: Monthly time series of water storage anomalies (cm) of TWS, modeled soil-water storage SWS, and calculated groundwater storage for each GLDAS model averaged over the NWSAS area.

Precipitation is expressed as anomalies (in cm/month) from their average value over the time period January 2003 to December 2007. The groundwater trend is plotted as a linear regression and represents the drift of the seasonal signal.

The regional groundwater mass balance can be expressed as follows:

GWS = *–QW – QD + RN + RA, (1)*

where *QW is the total water withdrawn from the aquifers* by pumping wells, *QD is the natural discharge, and RN* and *RA are the natural and artificial recharges, respectively* (see Table 1). *QW and QD were estimated at about 2.75* and 0.45 mm yr–1, respectively [*Baba-Sy, 2005]*.

5. SATELLITE-BASED ESTIMATES OF THE NWSAS RECHARGE

The soil-moisture anomalies were obtained from land surface models outputs of the Global Land Data Assimilation System (GLDAS, Rodell et al. [2004b]) covering the time period considered here. Four land surface models, i.e., Noah, Mosaic, Variable Infiltration Capacity (VIC), and the Community Land Model version 2 (CLM) are available for this period. These GLDAS simulations, for which the main inputs are surface meteorological fields, provide us with a soil water content for a maximum soil column of 3.4 m.

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6. RESULTS

We retrieved 96 monthly 1° data sets from the **GRACE** open access files (http://grace.jpl.nasa.gov) covering the NWSAS area for the time period from January 2003 to December 2010.

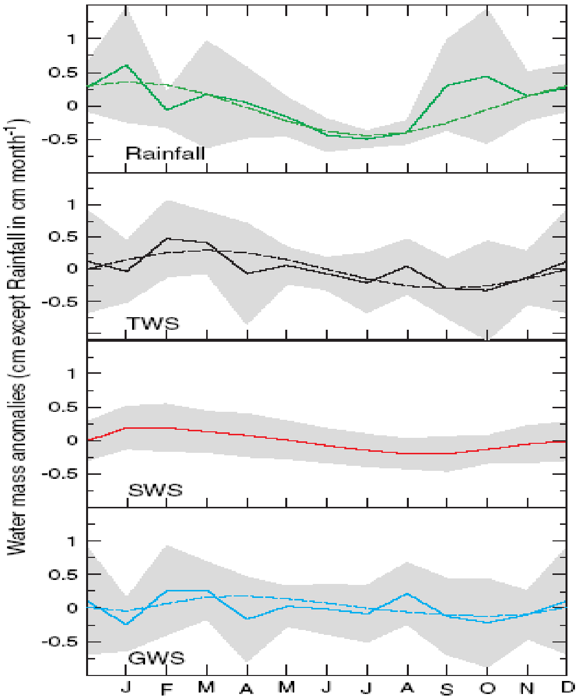

Figure 7. Mean seasonal cycle of the rainfall, TWS, SWS, and GWS. Mean and standard deviation (gray area) are calculated using eight values (8 years) for rainfall and TWS and 16 values for SWS and GWS, which account for the two soil-moisture models.

Gravity anomalies, obtained for each grid node by subtracting the average value over a reference time period (January 2003 to December 2007), were directly accessible from the database, expressed as equivalent water thickness in centimeters (measurement error of 9.7 mm calculated according to *Swenson and Wahr [2006]).*

Therefore, GRACE allows us to assess the temporal variations of terrestrial water storage (**TWS**), which cumulates both the soil water and groundwater storage variations [*Rodell et al.,* 2009]. Consequently, the soil water storage (**SWS**) must be removed from TWS in order to obtain the groundwater storage (**GWS = TWS – SWS**), all expressed as anomalies from their average value obtained over the same period as the GRACE solution.

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Our regional scale water budget points to a substantial natural recharge of 1.40±0.90 km^3/yr regardless of the soil model used.

A mean uptake of 2.75 km^3/yr and a mean natural discharge of 0.45 km^3/yr yields a renewal rate (ratio recharge to discharge) of almost 40%, contrary to the popular perception of purely fossil aquifers.

7. CONCLUSION

In this paper, we used a regional scale mass balance budget involving gravity data from the GRACE satellite system, soil moisture inferred from GLDAS models driven by meteorological forcing, and groundwater observations to estimate present-day recharge of the regional aquifers of the NWSAS. Despite the low values of ΔGWS (few mm yr–1) in the NWSAS in comparison to those observed in North India (few cm/yr) by *Rodell et al. [2009], the approach using* GRACE data is still relevant and yields reliable recharge values. Indeed, we found a mean recharge over the period 2003–2010 of 1.40 ± 0.90 km^3/yr. This recharge, which corresponds to about 2 mm/yr, represents 2.5 % of the average rainfall (88 mm/yr). Despite the non-negligible renewal rate of 40%, the NWSAS groundwater resources are overexploited, and the loss of artesianism will impact the economic viability of oasis systems.

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