Quantifying the modern recharge of the "fossil" Sahara aquifers

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[1] The North-Western Sahara Aquifer System (NWSAS), one of the world's largest groundwater systems, shows an overall piezometric decline associated with increasing withdrawals. Estimating the recharge rate in such a semiarid system is challenging but crucial for sustainable water development. In this paper, the recharge of the NWSAS is estimated using a regional water budget based on GRACE terrestrial water storage monthly records, soil moisture from the GLDAS (a land data system that assimilates hydrological information), and groundwater pumping rates. A cumulated natural recharge rate of 1.40 ± 0.90 km^3 yr^{-1} is estimated for the two main aquifers. Our results suggest a renewal rate of about 40% which partly contradicts the premise that recharge in this area should be very low or even null. Aquifer depletion inferred from our analysis is consistent with observed piezometric head decline in the two main aquifers in the region. Annual recharge variations were also estimated and vary between 0 and 4.40 km^3 yr^{-1} for the period 2003–2010. These values correspond to a recharge between 0 and 6.75 mm yr^{-1} on the 650,000 km^2 of outcropping areas of the aquifers, which is consistent with the expected weak and sporadic recharge in this semiarid environment. These variations are also in line with annual rainfall variation with a lag time of about 1 year. **Citation:** Gonçalvès, J., J. Petersen, P. Deschamps, B. Hamelin, and O. Baba-Sy (2013), Quantifying the modern recharge of the "fossil" Sahara aquifers, *Geophys. Res. Lett.*, *40*, 2673–2678, doi:10.1002/grl.50478.

1. Introduction

[2] 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 [*Scanlon et al.*, 2006]. The average value is essentially the result of rare humid years yielding a significant recharge, interspersed with periods of almost negligible or even null recharge. Various approaches have been proposed to assess the recharge with physical and chemical methods as well as modeling [*Scanlon and Cook*, 2002; *de Vries and Simmers*, 2002]. The major drawbacks are a questionable representativeness of local measurements and the uncertainties of model parameters when quantifying recharge at a regional scale. Satellite-based methods offer the opportunity to assess integrated processes at a regional scale. Although averaged over large areas (10^3 to 10^6 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 [*Strassberg et al.*, 2007; *Syed et al.*, 2008; *Longuevergne et al.*, 2010; *Grippa et al.*, 2011; *Henry et al.*, 2011; *Ogawa et al.*, 2011]. For instance, region-wide groundwater withdrawal rates were investigated in north India [*Rodell et al.*, 2009] and Australia [*Leblanc et al.*, 2009]. Aquifer storage characteristics (storage coefficient or specific yield, *Sun et al.* [2010]) and basin scale evapotranspiration [*Rodell et al.*, 2004] were also inferred from GRACE data. In this paper, we show that a basin scale water budget involving GRACE monthly mass solutions is also an operative and efficient way to estimate the region-wide recharge of a large confined-unconfined aquifer system. This alternative approach to usual hydrogeological model inversions is used to ascertain the regional groundwater recharge of the two main aquifers of the NWSAS.

2. Geological and Hydrogeological Context

[3] The NWSAS extends over 10^6 km^2 in the northern part of the Sahara desert. It is subdivided into three subunits: (i) the Grand Erg Occidental and (ii) the Grand Erg Oriental forming two endoreic watersheds separated by the M'Zab dorsal, and (iii) the Hamadah El Hamra plateau in the eastern part of the domain (see Figure 1). This intracratonic Triassic to Quaternary basin shows almost concentric outcrops decreasing in age from the border to the center and contains two main aquifer reservoirs. The deep confined Continental Intercalaire (CI) aquifer corresponds to continental formations from the middle Jurassic to the lower Cretaceous, the outcrop of which forms an almost continuous external ring over the basin, except in the Hamadah El Hamra. The unconfined to semiconfined Complexe Terminal (CT) is a multilayer aquifer comprising carbonaceous formations and sandstones from the Upper Createaceous to the Miocene. It is separated from the underlying CI aquifer by the Cenomanian argillaceous aquitard. The CT is recharged at outcrops by direct infiltration in the Grand Erg Oriental and by infiltration from runoff in the mountains (Jebel Mzab and Dahar). The groundwater flow lines of the CT converge mostly towards the Chott Djerid, a major depression

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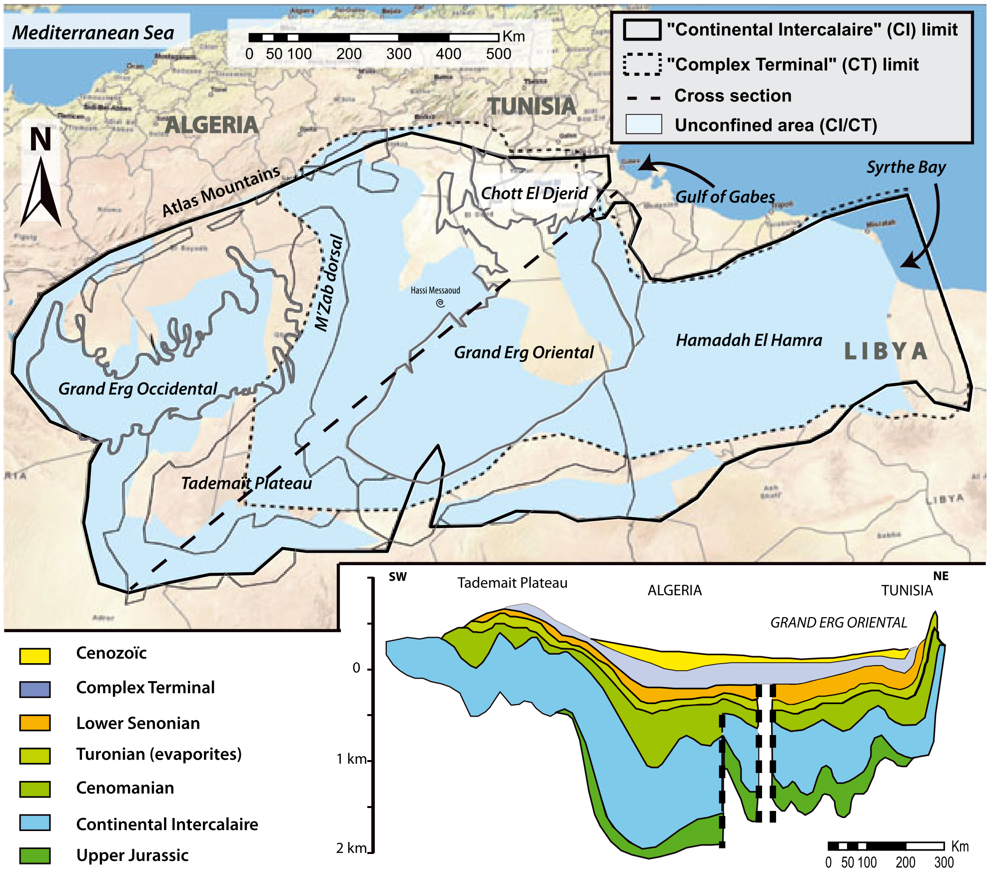

Figure 1. Situation map of the NWSAS. The inset shows a schematic cross-section and illustrates the main aquifers' geometry.

in the Grand Erg Oriental in Tunisia where an upward outflow occurs. Another discharge zone for the CT aquifer is the Syrte Bay of Libya. Besides the natural discharge, groundwater is withdrawn from the CT (see below). For the CI, recharge is thought to occur by direct infiltration also at outcrops in the Grand Erg Occidental and by infiltration from runoff in the surrounding mountains in the Atlas region, Jebel Nefusa and Dahar. The main outputs are the natural discharge towards the Tunisian and Libyan coasts (Gulf of Gabès and Syrte) and the important withdrawals resulting from irrigated agriculture and domestic uses of the oasis systems. Groundwater is often considered a nonrenewable or fossil resource [*Guendouz and Michelot*, 2008; *Church et al.*, 2011]. Indeed, we often speak of a negligible modern recharge assuming that most of the recharge occurred during past humid periods. However, this idea of a null present-day recharge has been seriously questioned in various groundwater modeling studies (see review in *Baba-Sy* [2005]). *Baba-Sy* [2005] reported model-based estimates of between 0.17 and 0.72 $km^3\ yr^{-1}$ and 0.47 and 0.74 $km^3\ yr^{-1}$ for the CI and the CT, respectively. Limited geochemical studies based on ^{14}C and ^{3}H also pointed to a substantial present-day recharge of the NWSAS [see, e.g., *Al-Gamal*, 2011]. The NWSAS supplies up to 90% of the water demand [*OSS*, 2008]. To satisfy growing needs, the global withdrawal rate in the two aquifers increased from 0.5 to almost 3 $km^3\ yr^{-1}$ from 1960 to 2010, causing an ongoing overall piezometric decline, especially since the 1970s. In this context, quantifying the recharge is crucial.

3. Satellite-Based Estimates of the NWSAS Recharge

3.1. Regional Data

[4] 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. 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.

[5] 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,

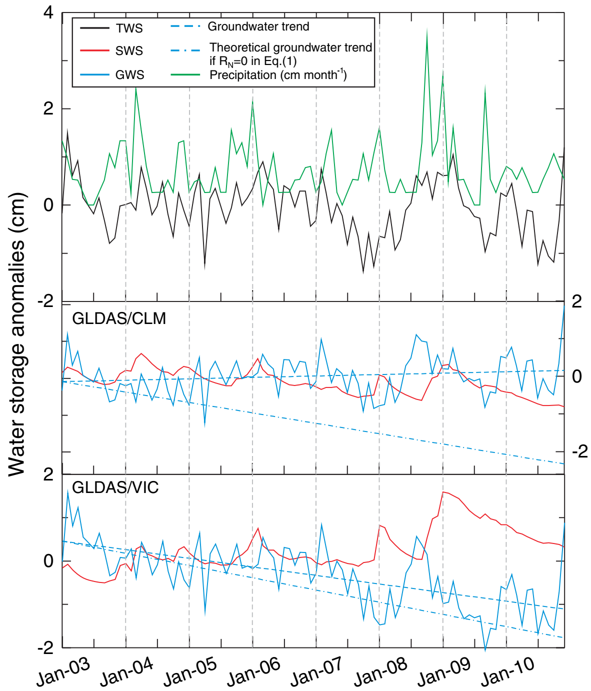

Figure 2. Monthly time series of water storage anomalies (cm) of TWS, modeled soil-water storage SWS, and calculated groundwater storage for each GLDAS model averaged over the NWSAS area. Precipitation is expressed as anomalies (in cm month^{-1}) from their average value over the time period January 2003 to December 2007. The groundwater trend is plotted as a linear regression and represents the drift of the seasonal signal. The theoretical linear drift in case $R_N = 0$ in equation (1) is shown for comparison.

provide us with a soil water content for a maximum soil column of 3.4 m. 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], i.e., $\frac{\partial \psi}{\partial z} \approx 0$, and thus $\frac{\partial \Theta}{\partial z} \approx 0$, where ψ and Θ are the pressure head (m) and soil moisture, respectively. 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.

3.2. Results

[6] Figure 2 illustrates the GRACE and GLDAS water storage anomalies averaged over the NWSAS area as time series over the study period; each of the two different land surface models is shown separately. The seasonal cycle of rainfall (from GLDAS), TWS, SWS, and GWS anomalies were assessed by averaging monthly values over the 8 years (including the two selected soil models for SWS and GWS). Figure 3 depicts the seasonal cycle which is characterized by a peak-to-peak amplitude of about 6 mm for TWS, 4 mm for SWS, and 3 mm for GWS. The GWS seasonal cycle lags behind precipitation by about 3 months, while TWS and SWS show lag times of about 2 months and 10 days, respectively. Interannual temporal trends of TWS, SWS, and GWS can be evaluated by means of linear regressions taking into account the available uncertainties [*Rodell et al.*, 2009]. For instance, TWS shows a weak variation over the period. Indeed, the slope of the linear trend fitted through the data ($\triangle$TWS) is –0.54 ± 0.25 mm yr^{-1} (see Table 1 and legend for calculation details). This variation is thus substantially lower than the maximum groundwater outflow of 3.2 mm yr^{-1}, inferred from the regional water budget with a natural and artificial outflow in the CT and CI aquifers of about 0.45 and 2.75 km^3 yr^{-1} [*Baba-Sy*, 2005] for the NWSAS' total area of 1 million km^2. The trends of SWS ($\triangle$SWS) calculated for each soil model are shown in Figure 2, and the values are summarized in Table 1. The mean value of $\triangle$SWS is –0.2 ± 1.20 mm yr^{-1} suggesting a small mean variation of the soil storage. A linear trend fitted through GWS = TWS – SWS data shown in Figure 2 produces the GWS temporal variation ($\triangle$GWS) for each soil model (see also Table 1). Depending on the selected soil model, the slope ($\triangle$GWS) of the linear

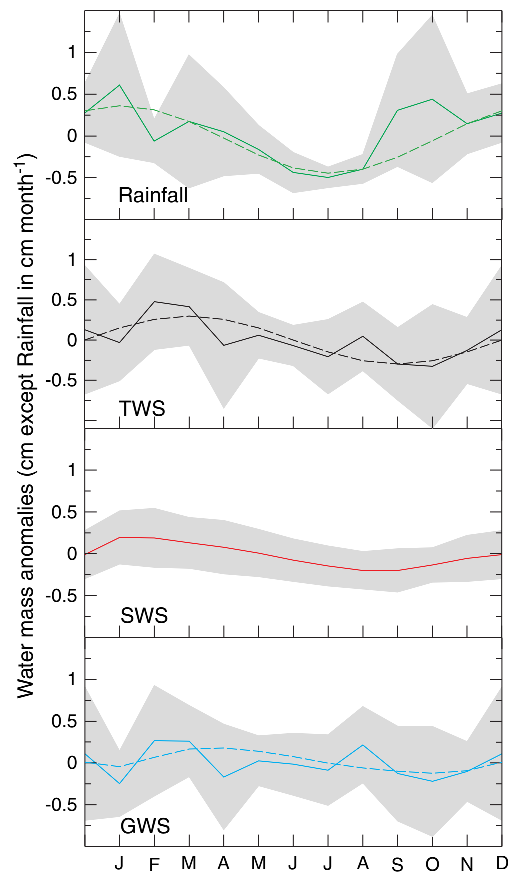

Figure 3. Mean seasonal cycle of the rainfall, TWS, SWS, and GWS. Mean and standard deviation (gray area) are calculated using eight values (8 years) for rainfall and TWS and 16 values for SWS and GWS, which account for the two soil-moisture models. Dashed lines represent the fitted seasonal cycle identified from the mean monthly values (solid line). For TWS and the rainfall, sinusoidal functions were fitted. No periodic fit was used for SWS which shows a clear seasonal cycle. The less clear periodic behavior of GWS was inferred by subtracting SWS from the fitted seasonal cycle of TWS.

Table 1. Values and Uncertainties for △TWS, △SWS, △GWS, and the Regional Total Recharge R_N [a]

Water Budget Fluxes (mm yr^{-1})		Q_W = 2.75 ± 0.25	Q_D = 0.45 ± 0.15	R_A = 0.41 ± 0.41
Soil model	△TWS (mm yr^{-1})	△SWS (mm yr^{-1})	△GWS (mm yr^{-1})	R_N (mm yr^{-1})
CLM	–0.54 ± 0.32	–0.93 ± 0.10	0.40 ± 0.20	3.20 ± 0.50
VIC	–0.54 ± 0.32	1.44 ± 0.15	–2.00 ± 0.25	0.85 ± 0.55
Mean	–0.54 ± 0.32	–0.20 ± 1.20	–0.54 ± 1.40	2.14 ± 1.40

[a]Slope (variables trend) and slope uncertainty were calculated using the weighted least square linear regression (WLS) function of R (http://www.R-project.org) where the weights are 1 for SWS data (no uncertainty provided) and $1/\sigma^2_{\mathrm{mes}}$ with σ_{mes} = 9.7 mm, the measurement error for both TWS and $GWS = TWS - SWS$ (in the absence of known error for SWS). Note that owing to the constant weights and to the exact value of time (*x* abscissa), WLS reduces in fact to an ordinary linear regression. The uncertainty for each soil model R_N was obtained using $\sigma_{R_N} = \sqrt{\sigma^2_{\triangle \mathrm{GWS}} + \sigma^2_{Q_W} + \sigma^2_{Q_D} + \sigma^2_{R_A}}$ where σ_i are the uncertainties of the quantities *i*. Mean values (last row) and their uncertainty were calculated using the weighted mean and standard deviation. The weights are $(1/\sigma^2_j)$ where σ_j is the uncertainty of the variable associated with each soil model *j*.

trend is –2.0 or 0.4 mm yr^{-1} with a weighted mean of –0.54 mm ± 1.4 mm yr^{-1} (see Table 1 and legend for calculation details). This depletion rate of the NWSAS contradicts the assumption of *Church et al.* [2011] and *Konikow* [2011], who only take into consideration the total pumping rate (2.75 mm yr^{-1}, see below) and thus postulate a null recharge. Figure 2 shows the theoretical trend of groundwater storage that would be obtained in case of zero natural recharge (blue dotted line). The difference between theoretical and observed trends of GWS strongly suggests the existence of a natural recharge which is estimated below.

[7] The regional groundwater mass balance can be expressed as follows:

$$\triangle \mathrm{GWS} = -Q_W - Q_D + R_N + R_A, \quad (1)$$

where Q_W is the total water withdrawn from the aquifers by pumping wells, Q_D is the natural discharge, and R_N and R_A are the natural and artificial recharges, respectively (see Table 1). Q_W and Q_D were estimated at about 2.75 and 0.45 mm yr^{-1}, respectively [*Baba-Sy*, 2005]. In the absence of any quantitative determination of the uncertainties of these values, we assumed a conservative range of 0.25 and 0.15 mm yr^{-1} for Q_W and Q_D. R_A corresponds to the artificial recharge of the phreatic aquifer (i.e., CI or CT outcrops or quaternary formations) due to excess oasis irrigation [*Kamel et al.*, 2006; *Tarki et al.*, 2011]. Oasis irrigation represents 80 to 90% of the groundwater withdrawals from the CI and CT aquifers. Although water losses by leakage from the irrigation systems are difficult to quantify, some authors reported values as high as 30% of the irrigation volume [*Marlet et al.*, 2009]. A plausible value of 15% for the fraction of irrigation water returning to the surface aquifer and a related uncertainty of 15% are used here. These values yield an artificial recharge of 0.41 with an associated uncertainty of 0.41 mm yr^{-1}. Figure 2 shows the values of ΔGWS obtained using each GLDAS soil model and the natural recharge calculated using $R_N = \Delta GWS + Q_W + Q_D - R_A$, with the average values of Q_W, Q_D, R_A. R_N values of between 0.85 and 3.40 mm yr^{-1} are found. The natural recharge of the aquifers R_N combines the errors for the different terms involved in equation (1) yielding uncertainties of about 0.50 mm yr^{-1} depending on the soil model (see Table 1). The plausible estimate of the natural recharge is taken as the mean value, i.e., 2.14 mm yr^{-1} with an uncertainty of 1.40 mm yr^{-1} (see Table 1). It is noteworthy that R_N is the total natural recharge of the aquifers. We then have to take into account the fact that the CI and the CT aquifers are in contact with the surface and thus exposed to the recharge, over 65% of the NWSAS area, i.e., almost 650,000 km^2 (see Figure 1). The cumulated recharge of these aquifers can thus be taken at 65% of the total recharge (2.14 km^3 yr^{-1}). The remaining part probably corresponds to the recharge of the quaternary formations. Therefore, a value of 1.40 ± 0.90 km^3 yr^{-1} is proposed for the recharge of the CI and the CT aquifers. This estimate is based on the assumption of a homogeneous recharge over the entire area. An estimation of the annual recharge of the CI and the CT giving values between 0 and 4.40 km^3 yr^{-1} is presented in the auxiliary material.

4. Discussion

[8] Our regional scale water budget points to a substantial natural recharge of 1.40 ± 0.90 km^3 yr^{-1} regardless of the soil model used. A mean uptake of 2.75 km^3 yr^{-1} and a mean natural discharge of 0.45 km^3 yr^{-1} yields a renewal rate (ratio recharge to discharge) of almost 40%, contrary to the popular perception of purely fossil aquifers. This recharge value is a regional interannual mean that can be directly compared to values calculated at the basin scale by regional groundwater modeling. Such models, once calibrated, provide natural recharge estimates of 1.0 ± 0.2 km^3 yr^{-1} [*Baba-Sy*, 2005]. Regional piezometric monitoring in the NWSAS [*Besbes and Horriche*, 2007] provides us with an alternative estimate. Indeed, a low decline of the hydraulic head was observed between 1950 and 1970, suggesting that the total outputs (pumpings and natural discharge) were almost balanced by the recharge. Adding the withdrawal rate between 1950 and 1970 (mean and standard deviation) and the value of the natural discharge reported by *Baba-Sy* [2005] yields 0.95 ± 0.06 km^3 yr^{-1}. Although slightly lower than our estimate, these three estimates are relatively consistent. Any attempt to directly compare recharge estimate (or mean residence time) derived from geochemical tracers and geophysical methods is attractive but remains in fact challenging, mainly because both approaches focus on different time and space scales. Tritium would be the best candidate for such purposes, but data are too scarce to quantify the modern recharge. These data however consistently testify to an actual recharge in the investigated areas of the CI and CT outcrops [*Al-Gamal*, 2011].

[9] The mean depletion of the aquifers ΔGWS obtained in this study is 0.54 mm yr^{-1}. Using this result, the piezometric decline can then be examined in relation to the aquifers storativity by *Marsily* [1986]

$$\Delta GWS = S_y \Delta h, \tag{2}$$

where h (m) is the hydraulic head and S_y is the storage coefficient or the specific yield used for confined or unconfined aquifers, respectively. Using mean reported values of 10^{-3} and 10^{-2} for the confined and unconfined parts of the CI and CT [*UNESCO*, 1972; *OSS*, 2008] yields Δh values of 0.54 and 0.054 m yr^{-1} for confined and unconfined areas, respectively. Drawdown values from wells monitored from 1950 to 2000 are about 0.5 and 0.1 m yr^{-1} for confined and unconfined parts, respectively [*Besbes and Horriche*, 2007]. Our estimates are thus fairly close to the field values, but this comparison should be considered with caution since the drawdowns increased from 1950 to 2000 following the total withdrawal rise from 0.5 to 2.5 km^3 yr^{-1}.

5. Conclusions

[10] In this study, 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 △GWS (few mm yr^{-1}) in the NWSAS in comparison to those observed in North India (few cm yr^{-1}) 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^{-1}. This recharge, which corresponds to about 2 mm yr^{-1}, represents 2.5 % of the average rainfall (88 mm yr^{-1}). Despite the nonnegligible renewal rate of 40%, the NWSAS groundwater resources are overexploited, and the loss of artesianism will impact the economic viability of oasis systems. This justifies ongoing studies for more sustainable groundwater management of NWSAS. Nonetheless, the significance of our results is limited to the target period 2003–2010. Changes in Land Cover (LC) and Land Use (LU) may have been affecting the recharge processes and rate since the beginning of NWSAS exploitation. In Sahelian and Saharan regions, changes in environmental modifications related to rural development (land clearance, irrigation) have led to contrasting effects on recharge. *Favreau et al.* [2009] showed that land clearing due to changes in agricultural practices in southwest Niger increased runoff, favoring groundwater recharge beneath ephemeral ponds. Conversely, in Tunisia, human activities, such as soil and water conservation works, small and large dams, and pumping for irrigation, have deeply modified the regional water balance resulting in a decrease in the water table [*Leduc et al.*, 2007]. However, it is difficult to determine how LC/LU currently affects the recharge and will continue to affect it in the future. A regionalization of the mass balance budget will likely help decipher the processes that control the recharge of the NWSAS.

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