Assessment of the impacts of climate variability on total water storage across Africa: implications for groundwater resources management

Tales Carvalho Resende, Laurent Longuevergne, Jason Gurdak, Marc Leblanc, Guillaume Favreau, Nienke Ansems, Jac van Der Gun, Cheikh Gaye, Alice Aureli

► To cite this version:

Tales Carvalho Resende, Laurent Longuevergne, Jason Gurdak, Marc Leblanc, Guillaume Favreau, et al.. Assessment of the impacts of climate variability on total water storage across Africa: implications for groundwater resources management. *Hydrogeology Journal*, 2019, 27 (1), pp.493-512. 10.1007/s10040-018-1864-5 . insu-01891409

HAL Id: insu-01891409

<https://hal-insu.archives-ouvertes.fr/insu-01891409>

Submitted on 9 Nov 2018

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

**Assessment of the impacts of climate variability on total water storage across
Africa: implications for groundwater resources management**

Tales Carvalho Resende, UNESCO International Hydrological Programme (IHP), Paris, France¹

Laurent Longuevergne, University of Rennes, Géosciences Rennes - UMR 6118, Rennes, France

Jason J. Gurdak, San Francisco State University, Department of Earth & Climate Sciences, San
Francisco, United States

Marc Leblanc, University of Avignon-INRA, Hydrogeology Laboratory, UMR EMMAH,
Avignon, France

Guillaume Favreau, IRD, UMR HydroSciences, University of Montpellier, Montpellier, France;
IRD, University of Grenoble-Alpes, CNRS, Environmental Geosciences Institute, Grenoble,
France

Nienke Ansems, International Groundwater Resources Assessment Centre (IGRAC), Delft, The
Netherlands

Jac Van der Gun, Van der Gun Hydro-Consulting, The Netherlands

Cheikh B. Gaye, University Cheikh Anta Diop, Department of Geology, Dakar, Senegal

Alice Aureli, UNESCO International Hydrological Programme (IHP), Paris, France

¹ Correspondence author;; Email: t.carvalho-resende@unesco.org ; Tel: +33 1 45 68 18 35

18

19 **Key words:** GRACE, climate change, groundwater management, groundwater storage, Sub-
20 Saharan Africa

21

22 **Abstract**

23 The links between climate variability, depicted by times series of oceanic indices, and changes in
24 total water and groundwater storage are investigated across nine large aquifer basins of the
25 African continent. The Gravity Recovery and Climate Experiment (GRACE) mission's
26 observations represent a remarkable tool that can provide insight into the dynamics of terrestrial
27 hydrology in areas where direct in-situ observations are limited. In order to evaluate the impact
28 of inter-annual and multi-decadal climate variability on groundwater resources, this study
29 assesses the relationship between synoptic controls on climate and total water storage estimates
30 from (i) GRACE from 2002 to 2013 and (ii) a two-variables climate-driven model that is able to
31 reconstruct past storage changes from 1982 to 2011. The estimates are then compared to time
32 series of groundwater levels to show the extent to which total water storage covaries with
33 groundwater storage. Results indicate that rainfall patterns associated with the El Niño Southern
34 Oscillation (ENSO) are the main driver of inter-annual groundwater storage changes, whereas
35 the Atlantic Multi-Decadal Oscillation (AMO) plays a significant role in decadal to multi-
36 decadal variability. The combined effect of ENSO and AMO could trigger significant changes in
37 recharge to the aquifers and groundwater storage, in particular in the Sahel. These findings could

help decision-makers prepare more effective climate-change adaptation plans at both national and transboundary levels.

NOTE TO COPYEDITOR - PLEASE INSERT THE FOLLOWING AS A FIRST-PAGE FOOTNOTE:

This article is part of the topical collection “Determining groundwater sustainability from long-term piezometry in Sub-Saharan Africa”

1. Introduction

Africa faces major water resources management challenges, largely because water is unevenly distributed over the continent and over time. About 64% of the population rely on limited and highly variable amounts of water, and 25% of the population experience difficulties in water use due to accessibility or mobilizations issues (e.g. water infrastructure, flow controls, costs) (Vorosmarty et al., 2005). As a result of rapid population growth and higher industrial activity, water demand in Africa is projected to more than double by the end of the 21st century (Wada and Bierkens, 2014), which may compromise the future livelihoods of millions of people and their living standards. Global climate change and variability is expected to exacerbate this issue as it will bring more extreme climate conditions such as droughts (Prudhomme et al., 2014; Trenberth et al., 2014; Malherbe et al., 2016). Groundwater plays an important role in society’s adaptation to climate change and variability, especially because it is more resilient to the effects of climate change than surface water (Green et al., 2011; Treidel et al., 2012; Van der Gun, 2012; Taylor et al., 2013a). Groundwater’s unique buffer capacity provides a major strength to reduce the risk of temporary water shortage, and to create conditions for survival in areas where climate change is expected to cause water stress (Falkenmark, 2013).

An estimated 75% or more of Africans use groundwater as their main source of drinking water (UNEP, 2010), particularly in rural areas that rely on low-cost dug wells and boreholes. There is very limited reliable and comprehensive statistics on groundwater use in Africa, but previous assessments indicate an underutilized potential to support irrigated agriculture as most farming in Africa is currently rainfed (Wani et al., 2009). Groundwater is over-exploited for irrigation in many parts of the world (Famiglietti, 2014; Konikow 2015) including Asia where 14% of cultivated land is irrigated with groundwater (Siebert et al., 2010) but in Africa ~1% of the cultivated land (about 2×10^6 hectares) is irrigated with groundwater (Altchenko and Villholth, 2015). In contrast to other regions in the world such as Western Mexico, the High Plains in the central U.S., the Middle East, North-East Pakistan, North-West India, and North-East China, most of Sub-Saharan Africa has not yet experienced the “groundwater crisis” (Famiglietti, 2014) caused by the widespread over-abstraction of groundwater to support large-scale agriculture. Moreover, some major African aquifers tend to coincide with areas of relatively lower population density and water demand (e.g. the Sahel aquifer Basins, the Congo Basin in Central Africa, and the Kalahari Basins in Southern Africa) (Foster et al., 2006; Wada et al., 2010; Gleeson et al., 2012; MacDonald et al., 2012). Many African countries and/or joint bodies in charge of implementing transboundary water agreements thus have an opportunity to anticipate future groundwater use and management challenges through planning, sustainable utilization, and effective protection of groundwater resources (Tuinhof et al., 2011; Gorelick and Zheng, 2015).

However, the development of long-term effective and reliable groundwater management strategies for coping with water scarcity threats and climate variability and change in Africa is undermined by the lack of adequate data for decision-making (Bates et al., 2008). In recent

years, there has been a substantial decline in hydrometeorological data collection and management in Africa (Houghton-Carr and Fry, 2006; Robins et al., 2006). Decades ago, Africa had a relatively dense network of stations to measure rainfall, temperature and other weather data, but some weather centres have aged badly because of reductions in budgets for field maintenance and inspection, and many of these stations are no longer operating (Giles, 2005). The current density of hydrometeorological stations in Africa is eight times lower than the minimum recommended by the World Meteorological Organization (WMO, 1996). Many governments have a limited ability to collect the data needed for long-term water resources management, and current efforts have mainly focused on rainfall and river flow data collection. As a result, most African countries lack groundwater-monitoring stations and this limits the understanding of the response of groundwater to human and natural conditions (Gaye and Tindimugaya, 2012).

Over the last decade, significant advances in the remote sensing techniques have led to a more complete overview of the water cycle at the global scale. Launched in March 2002, the Gravity Recovery and Climate Experiment (GRACE) is the first satellite mission able to provide global observations of terrestrial water storage changes (ΔTWS) (Richey et al., 2015; Chen et al., 2016). Given that the dynamics of groundwater are affected by inter-annual to multi-decadal climate variability (Gurdak et al., 2007; Kuss and Gurdak, 2014), longer observations than GRACE's current 15 year record (2002 to 2017) are desirable to better evaluate the past and current evolution of groundwater resources, as well as to provide pointers for the future.

To overcome GRACE's time frame limitation and the lack of adequate long-term piezometry data, this study used an approach to reconstruct past water storage variations in major aquifers across Africa through a climate-driven model using precipitation and actual evapotranspiration

data from global datasets over the period of 1982 to 2011. Validation of the results is carried out by comparing the results of modeled total water storage changes ($\Delta TWS_{\text{MODEL}}$) with GRACE-based total water storage changes ($\Delta TWS_{\text{GRACE}}$) estimates from 2002 to 2013. The model and GRACE-based estimates are then compared to long-term piezometry measurements to show the extent to which total water storage changes covary with observed groundwater storage changes ($\Delta GWS_{\text{OBSERVED}}$). Using this approach also allows one to quantify teleconnections between total water and groundwater storage changes with global-scale climatic oscillations such as the El Niño Southern Oscillation (ENSO), North Atlantic Oscillation (NAO), and Atlantic Multidecadal Oscillation (AMO). Acronyms and abbreviations are given in the Appendix.

2. Background

2.1. Study areas

Nine large aquifer systems in Africa were selected for this study on the basis of hydrogeological, climate and governance conditions as presented in Table 1 and Figure 1. The distribution of aquifers in Africa is now reasonably mapped following long-term programmes launched in the 1960s by national and international agencies and supported variously by UNESCO, IAEA, and British, French, German and Dutch technical assistance. These efforts were subsequently integrated by the International Association of Hydrogeologists (IAH)/UNESCO/BGR WHYMAP Africa Groundwater Resources Map in 2008, which was the baseline for the first quantitative maps of groundwater resources in Africa (MacDonald et al., 2012). Approximately 45% of the African land surface is underlain by large sedimentary basins

hosting relatively homogeneous aquifers that may offer good conditions for groundwater abstraction. Approximately 11% of the land has a geologically complex structure, highly productive aquifers in heterogeneous folded or faulted regions in close vicinity to non-aquifers. Almost half of the territory (44%) consists of regions with only limited groundwater resources, generally in local and shallow aquifers in weathered crystalline bedrock or alluvial deposits that locally may be productive (BGR and UNESCO, 2008; Maurice et al., 2018).

With regards to storage, a considerable proportion of Africa's groundwater resources is located in the large sedimentary basins in (semi)arid zones (e.g. North Africa, Sahel, and the Kalahari and Karoo basins in Southern Africa) and tropical zones (e.g. the Congo Basin in Central Africa) (MacDonald et al., 2012). These basins usually contain multi-layered aquifer systems with major alluvial formations forming shallow unconsolidated aquifers underlain by consolidated sedimentary rocks forming deeper aquifers. Even in semi-arid parts of Africa the shallow unconsolidated aquifers can be recharged in response to episodic storm events, climate oscillations, and land-use change (Taylor et al. 2009, 2013b). In the Sahara/Sahel aquifers, isotope and hydrochemical investigations have revealed that recharge mainly occurs by direct infiltration of rainwater or by river/surface water interaction as in the case of the Senegal and Niger Rivers (Diaw et al., 2012; Nazoumou et al., 2015; Abdou Babaye et al., 2018). Stable and radioactive isotopes contents in shallow aquifers confirm the presence of modern infiltration water (Lapworth et al., 2013; Zouari, 2015). Recharge rate over these areas are usually low and range from 0.1 to 5% of annual precipitation (Scanlon et al., 2006). The recharge mechanisms and dynamics of the deeper aquifers is still uncertain. Data from the Sahara/Sahel tend to exhibit piston-flow behavior (i.e. new water "pushing" old water downwards). Depleted stable isotopes contents observed in some aquifers (Taoudeni and Iullemmeden basins) suggests the presence of

155 palaeoclimatic water or old-recent mixed groundwater (Fontes et al., 1991; Zouari, 2015).
156 However, the deeper aquifers can be considered as not being actively recharged as most of the
157 recharge dates back to more than 5000 years ago (Edmunds, 2008).

158 Most of these aquifers located in large sedimentary basins are transboundary. More than 75
159 transboundary aquifers have been identified in Africa, but as more information and knowledge
160 becomes available this number is likely to increase (IGRAC-UNESCO, 2015). The identified
161 transboundary aquifers represent approximately 42% of African continental land area and 30%
162 of the population. Arrangements for the management of these transboundary aquifers remain
163 insufficiently developed as groundwater has been traditionally considered a national matter. Only
164 three transboundary aquifers are under an operational agreement, namely the Nubian Sandstone
165 Aquifer System (NSAS), the North-Western Sahara Aquifer System (NWSAS), and the
166 Stampriet Transboundary Aquifer System (STAS). A Memorandum of Understanding was
167 signed in 2014 for the establishment of a consultation mechanism for the Iullemmeden,
168 Taoudeni/Tanezrouft Aquifer System (ITTAS) but has not entered into force yet. Africa is
169 however the continent with the highest proportion of transboundary surface water catchments
170 under an operational arrangement (Meyer, 2016; UNESCO and UNECE, 2017). Given that
171 aquifers and river/lake basins do not necessarily coincide, the most appropriate body to oversee
172 the management of a transboundary aquifer may not necessarily be a river or lake basin
173 organization (if existent). However, these arrangements and institutions could play a crucial role
174 in promoting cooperation over transboundary aquifers through action programmes.

175 **INSERT TABLE 1 HERE**

176 **INSERT FIGURE 1 HERE**

2.2. *Climate variability modes in Africa*

Exchanges between the Earth's atmosphere, oceans, cryosphere and continental hydrology give rise to some natural climate fluctuations, of various periodicities. Some of the most important global-scale climate oscillations on interannual to multidecadal timescales that influence local water resources include the El Niño Southern Oscillation (ENSO), North Atlantic Oscillation (NAO), Pacific Decadal Oscillation (PDO), and Atlantic Multidecadal Oscillation (AMO). These natural climate oscillations are monitored using scalar-valued indices, which characterize positive, negative, and neutral phases of a climate variability mode and to identify the strength of these phases.

ENSO is considered as the most important pattern of natural interannual climate variability on Earth (Palmer and Anderson, 1994). It is a coupled ocean-atmospheric phenomenon that has interannual variability with irregular 2- to 7-year cycles between the warm (El Niño) and cold (La Niña) phases that has been occurring for at least the past 700 years (Li et al., 2013). El Niño is characterized by stronger than average sea surface temperatures in the central and eastern equatorial Pacific Ocean, reduced strength of the easterly trade winds in the Tropical Pacific, and an eastward shift in the region of intense tropical rainfall. La Niña is characterized by the opposite – cooler than average sea surface temperatures, stronger than normal easterly trade winds, and a westward shift in the region of intense tropical rainfall. Three very strong El Niño events have occurred since the early 1980s, i.e. 1982–1983, 1997–1998, and more recently 2015–2016. Although ENSO is centered in the tropics, the changes associated with El Niño and La Niña events affect climate around the world. ENSO's influence upon annual rainfall levels have been reported all across Africa, particularly in Southern Africa (Manatsa et al., 2011). Droughts

occur most of the time during the warm phase of ENSO (Masih et al., 2014). On the other hand, the trend to more La Niña-like conditions since 2000 is a likely contributing factor driving the increase in Southern Africa rainfall (Maidment et al, 2015). As compared to the other African regions, the climate of Central Africa and its variability has been the subject of very few studies. The few existing studies suggest that there is not a significant relationship between ENSO and precipitation in Central Africa (Philippon et al., 2012; Taylor et al., 2013b). ENSO has also been linked to the devastating droughts of the 1970s and 1980s in the Sahel (e.g. Giannini et al., 2003). Drier (wetter) decades in the Sahel are usually correlated with El Niño (La Niña) events (e.g. Nicholson and Selato, 2000; Janicot et al., 2011). Several different ENSO indices have developed over time, but the Multivariate ENSO Index (MEI) is favored over other indices because it combines the significant features of all observed surface fields in the tropical Pacific. MEI monthly values were obtained from the NOAA Earth System Research Laboratory (NOAA, 2017).

The PDO is often described as a long-lived El Niño-like pattern of Pacific climate variability (Zhang et al. 1997). The PDO index is based upon patterns of variation in sea surface temperature of the North Pacific Ocean with warm and cold phases that can persist for 20-30 years. Unlike ENSO, the PDO is not a single physical mode of ocean variability, but rather the sum of several processes with different dynamic origins. The PDO monthly values were obtained from the NOAA Earth System Research Laboratory database (NOAA, 2017).

The NAO represents a north-south oscillation atmospheric mass between the Icelandic low-pressure system and the Azores high-pressure system. The positive phase of the NAO reflects below-normal surface pressure over the Icelandic to Arctic regions and above-normal surface

pressure over the subtropical Atlantic. The negative phase reflects the opposite. The NAO exhibits considerable interseasonal, interannual and multidecadal variability with irregular 1- to 24-year cycles (Hurrell 1995, Chelliah and Bell 2005), but has a dominant quasiperiod oscillation of 3 to 6 years and a less significant 8 to 10 year mode (Hurrell et al. 2003). The NAO is among the known modes of natural variability influencing North Africa precipitation on a variety of time-scales, especially in winter and early spring. Drier (wetter) decades in North Africa largely correspond to positive (negative) NAO phase (Lopez-Moreno et al., 2011). Correlations are however particularly stronger for negative NAO phases (Donat et al., 2014). For example, the negative phase of the NAO from the mid-1950s to late 1970s indicates relatively wet conditions with a gradual shift towards drier conditions in the early 1970s. Recent years have also been considered wetter. NAO monthly values were obtained from the NOAA Earth System Research Laboratory database (NOAA, 2017).

The AMO is an index of sea surface temperature over the North Atlantic Ocean (quasi-period cycles of roughly 50 to 70 years) with negative and positive phases that may last for 20-40 years each and lead to differences of about 15°C between extremes. Paleoclimatologic studies have confirmed that these changes have been occurring over the past 8000 years (Knudsen et al., 2011). The AMO was in positive phases from 1860 to 1880 and 1930 to 1960, and in negative phases from 1905 to 1925 and 1970 to 1990. The AMO flipped to a positive phase in the mid-1990s and it is believed that the AMO is gradually moving to a negative phase (McCarthy et al., 2015). Higher rainfall over the Sahel is associated to positive phases of the AMO (Diatta and Fink, 2014), while the opposite occurs in the Gulf of Guinea (Mohino et al., 2011). The AMO monthly values were obtained from the NOAA Earth System Research Laboratory database (NOAA, 2017).

The interaction of climate variability modes can enhance or diminish certain climatic forcings on local hydrologic processes (Hanson et al. 2004). When El Niño (La Niña) occurs with the warm (cold) PDO phase, rainfall tends to increase over the Sahara to the Gulf of Guinea and Southern Africa, while the opposite occurs in the Horn of Africa (Wang et al., 2014). Several studies suggest that the AMO modulates the ENSO and NAO variability (Dong et al. 2006; Dong and Sutton 2007; Timmermann et al. 2007; Zhang et al., 2012; García-García and Ummenhofer, 2015). Strengthened (weakened) La Niña effects coincide with a positive (negative) phase of the AMO (Geng et al., 2016). In the Sahel (Lake Chad), the severe impact of droughts of the 1970s and 1980s are tied to the combined effect of the negative phase of the AMO and El Niño events (Okonkwo et al., 2015). Finally, ENSO and AMO are well-known climate teleconnections that have been associated with extreme rainfall variability in Western/Central Africa (Ndehedehe et al., 2017). An inverse relationship exists between the AMO and the NAO decadal tendencies. When the AMO is negative, NAO tends more often to the positive state. Statistical analyses over the 20th century suggest that the AMO precedes NAO by 10-15 years (Peings and Magnusdottir, 2014). These findings provide an interesting possibility of decadal forecasting.

3. Methods

3.1. GRACE observations

There has been great interest in the use of GRACE satellites to monitor changes in water storage, especially in regions with limited ground-based data such as Africa (Henry et al., 2011; Ramilien et al., 2014; Richey et al., 2015; Chen et al., 2016; Hassan and Jin, 2016; Rateb et al., 2017). GRACE satellites provide a spatially filtered image of real TWS that needs to be processed to

produce information on changes in TWS. There are generally three approaches to process GRACE total water storage change signals: the scaling factor approach, the additive correction approach and the multiplicative correction approach. The validation of GRACE-based estimates is challenging because results can differ by up to 100% depending on which processing approach is used, in particular over i) (semi-)arid areas, ii) areas with intensive irrigation, and iii) relative small basins (i.e. $\leq 200,000 \text{ km}^2$) for which the additive correction approach may be more appropriate (Long et al., 2015). It is thus imperative to compare GRACE-based estimates with ground-based data to assess their validity.

Considering that most of the studied aquifer systems are located in arid and semi-arid areas, the additive correction approach as presented by Longuevergne et al. (2010) to provide total water storage estimates from 2002-2013 at a monthly basis has been used. This is based upon monthly spherical harmonic (SH) gravity field solutions R05 monthly data from CSR (Center for Space Research, Univ. of Texas at Austin, US), truncated at degree and order 60 (Bettadpur, 2007), including a destriping filter (Swenson and Wahr, 2006) and additional 300 km Gaussian smoothing. Alternate methods for leakage corrections encompass the mascon-type approach. The basic difference between spherical harmonics (SH) and mascons is that SH solutions are global whereas mascons can be applied at regional to global scales. A recent study has shown that although long-term trends for SH are lower than those for mascons, they remain highly correlated (Scanlon et al., 2016). The method used for detrending total water storage time series is fitting and removing a trend model consisting of a long-term linear and seasonal cycles by using linear regression (Sun et al., 2017). Results are compared with groundwater changes from piezometry ($\Delta \text{GWS}_{\text{OBSERVED}}$) and modeled changes in total water storage ($\Delta \text{TWS}_{\text{MODEL}}$) in order to identify any long-term covariance. Particular attention is given to aquifer systems whose area

is below the limit of the GRACE footprint (Karoo Sedimentary, Stampriet Transboundary Aquifer System and Volta Basin Aquifer).

3.2. A modelling approach to extend the GRACE timeframe

Trends during the GRACE era (2002 – 2017) are dominated by internal climate variability (i.e., arising from interactions and chaotic variability within the climate system, particularly in rainfall) rather than by the forced response (i.e., driven primarily by human induced changes in atmospheric composition) (Fasullo et al., 2016). Key to understanding reported changes during the GRACE record is quantifying the character of internal climate modes. The GRACE era only covers a very limited number of climatic oscillation cycles as some modes like the AMO, PDO, and NAO have oscillation periods longer than the GRACE observation record. Several studies indicate that low-frequency cycles like AMO and PDO are particularly influential in modulating high-frequency cycles such as ENSO. To bridge this gap, there is a need to extend the GRACE timeframe to the “past” using a model that is able to reconstruct the interannual to decadal climate-driven changes in water storage. A climate-driven model to estimate long-term water storage dynamics, independent from GRACE data, was developed and applied at the aquifer scale.

According to MacDonald et al. (2012), groundwater development stress is relatively low in most of the large African aquifers with renewable groundwater resources. This suggests that changes in groundwater storage in such aquifers tend to be dominated by climatic variations. For that reason, human influences (such as abstraction and land-use changes) are neglected in the simple simulation model. This model is based on elaboration of the general water balance equation:

$$\frac{dTWS}{dt} = P - E - R \quad (\text{Eq. 1})$$

where P is precipitation, E is actual evapotranspiration, R is runoff (or discharge at the basin outlet), and TWS is total water storage (sum of water stored in vegetation, ice, snow, lakes and streams, soil moisture and groundwater). All components are given in millimetres per month. Mean precipitation and actual evapotranspiration were computed by averaging data available from global datasets with spatial resolutions of $0.5^\circ \times 0.5^\circ$ at aquifer scale from 1982 to 2011 (Global Precipitation Climatology Centre dataset for precipitation (Becker et al., 2013), and Max Planck Institute dataset for actual evapotranspiration) (Jung et al., 2010). These datasets were selected because of their capability to capture the regionally averaged seasonal cycles (Mueller et al., 2011; Sun et al., 2018).

Integration of Eq. 1 gives:

$$\Delta TWS = \int P dt - \int E dt - \int R dt \quad (\text{Eq. 2})$$

ΔTWS is the change of total water storage over the time interval of integration, thus it includes the changes in water stored in vegetation, snow, ice, lakes and streams, soil moisture and groundwater. Integration over time of P , E , and R will generate a long-term trend in ΔTWS , which is attributed to integration of systematic errors in these variables. Unbiased datasets are therefore required. Considering that P is the dominant factor controlling long-term variations of E , and R , it is assumed that runoff is constant over time, i.e. contribution to storage as a linear trend (Bouwer et al., 2006; Liu et al., 2013). By doing so, when estimating storage changes by integration of R , a long-term trend related to runoff is removed. Thus, Eq. 2 becomes:

$$\Delta TWS_{\text{MODEL}} = \int P dt - \int E dt - \int R dt \approx \text{detrend}(\int P dt - \int E dt) \quad (\text{Eq. 3})$$

In absence of detailed field data on all these storage components it is difficult to isolate the change in groundwater storage (ΔGWS), but under certain circumstances – to be judged by the

modeller– it is plausible that ΔGWS is nearly equal to ΔTWS_{MODEL} . Such circumstances may, for instance, apply to relatively long integration intervals (several years) in arid and semi-arid regions where the assumed combined non-groundwater storage capacity is small compared to the simulated change in total water storage (ΔTWS_{MODEL}).

3.3. Ground-based measurements

Due to the general lack of continuous long-term groundwater level data, the selection of records for the validation of GRACE-based estimates was done based on the limited data available in literature and their representativeness. The selected records are usually located no farther than 20 km from surface water bodies (e.g. river, lake, oued) and tap shallow unconfined aquifers. The records provide groundwater levels at a monthly basis for different periods ranging from 5 to 20 years (Figure 2 and Table 2). In order to compare piezometry with total water storage, long-term groundwater level data were detrended by using the MATLAB function `detrend` that subtracts the mean or a best-fit line (in the least-square sense) from data. If the data do have a trend, detrending forces the mean to zero and reduces overall variation.

INSERT TABLE 2 HERE

INSERT FIGURE 2 HERE

3.4. Wavelet analysis

Wavelet transforms to analyze teleconnections between groundwater level, GRACE-based estimates, climate-driven model and climate indices time series were used both in amplitude and frequency. A MATLAB script developed by Grinsted et al. (2004) that enables doing continuous wavelet transform (CWT), cross wavelet transform (XWT) and wavelet coherence (WTC) plots was applied. CWT expands the time series into time frequency space, XWT finds regions in time frequency space where the time series show high common power and WTC finds regions in time frequency space where the two time series co-vary (but does not necessarily have high power) (Torrence and Compo, 1998; Labat et al., 2000; Grinsted et al., 2004; Labat 2005; 2008; Holman et al., 2011). Although the three methodological steps described previously were necessarily followed, the presentation of the results and discussion focuses on the WTC plots. High correlation between time series is indicated by light yellow zones. The arrows $\rightarrow$ and $\leftarrow$ in zones of the WTC figures indicate the positive (in-phase) and negative (anti-phase) relationships between two time-series, respectively. Meanwhile, the arrows $\downarrow$ and $\uparrow$ show that time series 1 lags time series 2 by 90° . The interpretation of lags in these zones can be however challenging and should be done carefully as a lead of 90° can also be interpreted as a lag of 270° or a lag of 90° relative to the anti-phase (opposite sign). A good indication to support that there is a connection and link between times series is that the phase-arrows generally point only in one direction for a given wavelength.

4. Results and discussion

4.1. Evaluation of GRACE-based and climate-driven model estimates

GRACE-based and climate-driven model total water storage changes ($\Delta TWS_{\text{GRACE}}$ and $\Delta TWS_{\text{MODEL}}$, respectively) are compared to groundwater levels in the studied aquifers to assess to what extent they covary with $\Delta GWS_{\text{OBSERVED}}$. All data were detrended in order to focus the analysis on the fluctuations in the data. However, it is worth mentioning that total water storage time series are nonlinear, nonstationary and tend to vary at multiple temporal scales, making filtering and detrending of total water storage a nontrivial task (Sun et al., 2017). The data were further normalized based on the mean and standard deviation of each dataset in order to provide a benchmark and comparison basis. Results suggest that changes in total water storage estimates describe generally well groundwater-level dynamics (Figure 3). These results are further verified by wavelet transform analysis that indicate that there exists a high correlation between GRACE-based and climate-driven model water storage estimates and groundwater level both at intra-annual and inter-annual scale (Figure 4a and Figure 4b). Given that comparison is done with groundwater level records from shallow boreholes that are located in the vicinity of surface water bodies (usually <20 km) which are likely to have a strong surface water / groundwater interaction, it is fair to conclude that $\Delta TWS_{\text{GRACE}}$, $\Delta TWS_{\text{MODEL}}$ and $\Delta GWS_{\text{OBSERVED}}$ representative of groundwater fluctuations in shallow unconfined aquifers are strongly correlated. This could also suggest that storage changes in deep aquifers are limited, thus supporting the assumptions that they are not being actively recharged and that they are exploited still largely at low rates. The near-synchronous signals of groundwater levels and the climate-driven model water storage estimates (Figure 3, Figure 4a and Figure 4b) reveal that shallow aquifers are highly responsive to rainfall temporal patterns, and reinforce the concept that natural climate variability, in particular changes in precipitation, considerably contributes to groundwater storage changes.

397 **INSERT FIGURE 3 HERE**

398 **INSERT FIGURE 4a HERE**

399 **INSERT FIGURE 4b HERE**

400

401 Results of the model allowed identifying four different types of groundwater storage dynamics
402 that are largely correlated with African climate zones. The model indicates that the North-
403 Western Sahara Aquifer System (NWSAS) located in Northern Africa had a decrease in storage
404 from early-1980s to late-1980s, an increase in early 1990s followed by a decrease from mid-
405 1990s to mid-2000s, an increase in mid-2000s, and a decrease since then (Figure 5). This is in
406 relatively good agreement with rainfall pattern and shallow groundwater fluctuation in the
407 vicinity of oueds in the Ouargla Plain in Algeria/Tunisia (Bellaoueur, 2008) and central Tunisia
408 (Massuel and Riaux, 2017) (Figure 2). The model's water storage increase in mid-2000s also
409 supports the assumption that the shallow aquifers (including outcrops of the deep aquifers) of the
410 North-Western Sahara Aquifer System are receiving a fraction of modern water as recharge from
411 infiltration of rainfall coming from the Sahara Atlas Mountains in Algeria and the Dahar and
412 Nafusa Mountains in Tunisia and Lybia (Baba-Sy, 2005; Al-Gamal, 2011). It should be noted
413 however that groundwater abstraction in the NWSAS has steeply risen over the past decades
414 because of tapping confined aquifers by drilling deep boreholes in the 1980s for water supply
415 and irrigation schemes (OSS, 2003). These boreholes have had very little maintenance since they
416 were drilled and recently observed water table rises in shallow aquifers could be locally
417 influenced by upward leakage through corroded borehole casing (Messekher et al., 2012).

418

INSERT FIGURE 5 HERE

419 The aquifers located in the Sahel (Nubian Sandstone Aquifer System, Lake Chad Basin, Irhazer-
420 Iullemmeden Basin, and Senegalo-Mauritanian Basin) have a similar multi-decadal behavior,
421 which is characterized by a significant decrease in groundwater storage from early-1980s to mid-
422 1990s followed by a partial recovery (Figure 6). As rainfall in the Sahel has generally increased
423 since mid-1990s, this result proves to be in good agreement with the observations from
424 piezometry indicating that the water table has risen since the mid-1980s in large parts of the
425 central Sahel (Favreau et al., 2009, 2012). It also supports the assumption that rainfall infiltration
426 is a primary source of recharge, though recharge from surface water bodies such as the Niger and
427 the Nile Rivers is non-negligible and limited to the vicinities of the rivers (perennial and
428 seasonal) and endoreic ponds (Nazoumou et al., 2015; Ngounou-Ngatcha et al., 2015). Aquifers
429 located in the tropics (Volta Basin and Karoo Carbonate) show an opposite behavior although
430 changes are not as pronounced as in the aquifers in the Sahel (Figure 7). This result is in line
431 with recent observations that indicate a drying trend in central equatorial Africa (west of
432 Albertine Rift) (Diem et al., 2014) and over Guinea regions, such as Benin and Nigeria (Bamba
433 et al., 2015).

434

INSERT FIGURE 6 HERE

435

INSERT FIGURE 7 HERE

436 Contrary to the aquifers in the Sahel, the aquifers in Southern Africa do not show a particular
437 multi-decadal pattern, but rather a strong inter-annual pattern. The model indicates a decrease in
438 storage from early-1980s to late-1980s, an increase in late-1980s/early-1990s, a decrease from

early-1990s to mid-1990s/late-1990s, an increase in late-1990s/early-2000s, a decrease from early-2000s to mid-2000s, and an increase since mid-2000s (Figure 8). This result is consistent with studies that revealed that long-term rainfall trends in Southern Africa are weak but exhibit an increased variability since 1970 (Richard et al., 2001).

INSERT FIGURE 8 HERE

4.2. Groundwater storage variability and its association with climate teleconnections

Groundwater storage variability and its association with climate teleconnections is studied by applying wavelet transforms between simulated changes in total water storage ($\Delta TWS_{\text{MODEL}}$) and climate indices (NAO, ENSO, and AMO). In Northern Africa, groundwater storage appears to be correlated to NAO (Figure 5c). WTC reveals three regions with high coherence (good correlation), i.e. 6-8 year band from 1990 to 1995 (Box 1 in Figure 5c), 1-2 year band from mid-1990s to mid-2000s (Box 2 in Figure 5c), and 2-3 year band from mid-2000s onwards (Box 3 in Figure 5c), which indicates that NAO exerts an influence on changes in groundwater storage. Positive (negative) NAO phase largely correspond to decreasing (increasing) groundwater storage. The results confirm that inter-annual correlations tend to be stronger for negative NAO phases (Box 2 and Box 3 in Figure 5c). This has been particularly true since the AMO shift back to a positive phase in mid-1990s, thus suggesting that the AMO exerts a low-frequency modulating influence on groundwater storage changes.

The influence of the AMO on groundwater storage appears to be much more direct in the Sahel. The AMO appears to exert a multi-decadal influence as a positive (negative) phase largely corresponds to increasing (decreasing) aquifer storage (Figure 6). For instance, all aquifers in the

460 Sahel show a significant modeled decrease in aquifer storage during a negative phase of the
461 AMO from the early-1980s to mid-1990s followed by an increase in groundwater storage during
462 a positive phase of the AMO since the mid-1990s. Mega-droughts in the Sahel are considered to
463 be linked to the combined effect of the negative phase of the AMO and El Niño events
464 (Shanahan et al., 2009; Masih et al., 2014). Such combination also appears to have a substantial
465 adverse effect on groundwater storage as it could potentially result, depending on recharge
466 processes in play, in both reduced recharge to the aquifers and in water level declines attributed
467 to climate-induced pumping (Gurdak 2017; Russo and Lall 2017). The AMO exerts an opposite
468 influence in the aquifers located in the tropics (Volta Basin and Karoo Carbonate), as positive
469 (negative) phase largely corresponds to (increasing) decreasing groundwater storage (Figure 7).
470 Total water storage and consequently groundwater storage inter-annual variability both in the
471 Sahel and in Equatorial Africa are likely to be impacted by ENSO, as WTC plots for the Nubian
472 Sandstone Aquifer System and the Senegalo-Mauritanian Basin (Figure 9) and for the Volta
473 Basin and Karoo Carbonate Aquifers (Figure 10) reveal several regions with high coherence
474 (good correlation). These regions largely coincide with El Niño events (1982-1983, 1986-1988,
475 1991-1992, and 1997-1998) and La Niña events (1998-2000). A recent study by Siam and Eltahir
476 (2017) revealed a strong correlation between ENSO, rainfall and flow in the Nile basin. El Niño
477 years usually lead to drought conditions, whereas La Niña years are more flood-prone.
478 Considering that recharge of the shallow aquifers mainly occurs by rainfall infiltration and
479 river/surface water interaction, it could be assumed that El Niño (La Niña) years could lead to
480 decreased (increased) groundwater storage. This assumption could be extended to the Sahel
481 and/or Equatorial Africa as similar observations have been found for Lake Chad (Okonkwo et
482 al., 2015), the Senegal and Niger River basins (Diaw et al., 2012; Nazoumou et al., 2015), and

Lake Volta (Owusu et al., 2008). Due to the relative shortage of long-term climate data, any assumption on cause-effect relationship in the correlation results of the model and climate indices in Central Africa is particularly more complex as there has been only a very limited number of studies of the climate of this region (Philippon et al., 2012). Central Africa has the lowest gauge density in sub-Saharan Africa (Washington et al., 2013) and has seen a dramatic decline in the number of rain gauges, especially after 1980s (Asefi-Najafabady and Saatchi, 2013, Zhou et al., 2014). Studies diverge in their conclusions in this region. According to Gao et al. (2016), drier conditions are associated with El Niño events while Taylor et al. (2013) suggest that the influence of ENSO varies spatially and studies in has indicated an opposite pattern as El Niño years are associated to increases in recharge generated by heavy rainfall (Taylor et al., 2013).

INSERT FIGURE 9 HERE

INSERT FIGURE 10 HERE

WTC plots for the Stampriet Transboundary Aquifer System and the Karoo Sedimentary Aquifer in Southern Africa also reveal important correlation between groundwater storage and ENSO events with El Niño (La Niña) events usually leading to drier (wetter) conditions and decreasing (increasing) water levels (Figure 8). The dynamics of these aquifers are not similar and thus indicates that other climate modes might also be exerting an influence in Southern Africa. Previous studies present clear evidence of the importance of the Indian Ocean Dipole (IOD) index in modulating rainfall variability in Eastern Africa (Taylor et al., 2013b). The IOD has traditionally been linked to ENSO (Marchant et al., 2006; Fan and Liu, 2017). Major ENSO warm (El Niño) events combined with a positive phase of the IOD have led to wet extremes and

significant recharge in the Karoo Sedimentary Aquifer (Figure 11). Conclusions about the correlation between the IOD and groundwater storage changes for the Nubian Aquifer Sandstone System and the Karoo Carbonate Aquifer are more challenging because the influence of IOD varies across the aquifer basin (Awange et al., 2014; Onyutha and Willems, 2017) and because of the lack of data, respectively.

INSERT FIGURE 11 HERE

5. Conclusions

A two-variables climate-driven model using precipitation and actual evapotranspiration data from global datasets was developed to reconstruct past total water storage changes in Africa from 1982 to 2011. Although the model has the important limitation of not considering human influences such as abstraction, land-use changes, and dam management, it offers robust pointers to assess the monthly dynamics of groundwater storage at very little computational cost as model-based total water storage changes $\Delta TWS_{\text{MODEL}}$ and observed groundwater storage changes $\Delta GWS_{\text{OBSERVED}}$ (representative of shallow groundwater fluctuations) are strongly correlated. GRACE-based $\Delta TWS_{\text{GRACE}}$ estimates are also highly correlated with model-based $\Delta TWS_{\text{MODEL}}$ and $\Delta GWS_{\text{OBSERVED}}$. As GRACE Follow-On (GRACE-FO) mission is scheduled to be launched in early 2018, $\Delta TWS_{\text{GRACE}}$ estimates will thus prove to be a well-founded tool to provide a general overview at basin scale of groundwater storage changes that are associated to shallow groundwater fluctuations and that are likely to have a strong interaction with surface

water. The near-synchronous signals of groundwater levels, GRACE and the climate-driven model estimates reveal that shallow aquifers are highly responsive to rainfall temporal patterns. Obtained results indicate that recharge from rainfall patterns associated to NAO and ENSO are the main drivers of inter-annual groundwater storage changes in Northern Africa and Sub-Saharan Africa, respectively. The AMO plays a significant role in decadal to multi-decadal variability, particularly in the Sahel as positive (negative) AMO phase largely corresponds to increasing (decreasing) groundwater storage. The AMO has been in a positive phase since mid-1990s and as a result, this has contributed to a water table rise in large parts of the Sahel. A change of phase could have an overwhelming impact on surface-water and groundwater resources, as mega-droughts in the early 1980s in the Sahel are tied to the combined effect of a negative phase of the AMO and a positive phase of the ENSO. These devastating droughts could trigger significant groundwater storage changes, resulting in reduced recharge to the shallow aquifers and water level declines attributed to climate-induced pumping from dug-wells and shallow boreholes.

The findings of this study could be beneficial to decision-makers and help to adequately prepare effective climate variability and change adaptation plans both at national and transboundary level. National groundwater governance frameworks in Africa usually need either reviewing and upgrading water laws and policies or completing water law with regulations (FAO, 2015). Integrating climate variability aspects into water laws and policies (e.g. drought and flood management plans, provisions for Managed Aquifer Recharge (MAR) schemes), strengthening national meteorological, hydrological and groundwater-monitoring networks, and in particular strengthening links between water decision-makers and meteorological institutions are crucial measures for improving groundwater governance with special reference to climate change.

Integrated Water Resources Management (IWRM) is now widely accepted by water decision-makers as the way forward for efficient, equitable and sustainable development and management of the world's limited water resources and for coping with conflicting demands (UNESCO, 2009). IWRM structures in Africa are rolled out across the continent with the present focus on the establishment of river basin / catchment organizations at national and transboundary level. However, groundwater is still poorly integrated into these organizations' IWRM and climate adaptation plans. MAR is a promising adaptation approach to reduce vulnerability to climate variability and aquifer over-exploitation. Findings from this study illustrate that MAR operations might take advantage of temporal patterns in precipitation to enhance recharge during the corresponding wet phases of ENSO, NAO, and AMO. Institutions in charge of the management of groundwater resources at national and transboundary level, as well as river basin / catchment organizations, should strengthen their support to MAR programs and initiatives to incentivize local water managers to store excess renewable water in aquifers during wet periods which can be used to off-set limited surface-water supplies during dry periods. The findings suggest that preferred periods for artificial recharge are negative phases of the NAO in Northern Africa, positive phases of the AMO in the Sahel, and La Niña years in Southern Africa. Finally, it is worth emphasizing that developing long-term effective and reliable strategies for coping with water scarcity threats and climate variability and change will also have to overcome the fact that there are still large uncertainties and limited adequate data for decision-making. In this regard, it is also important to undertake joint actions in data collection interpretation and reporting as a means to promote inter-basin/inter-aquifer collaboration, to harmonise strategies and promote exchange of experiences.

References:

- Abdou Babaye, M.S., Orban, P., Ousmane, B., Favreau, G., Brouyère, S., Dassargues, A. (2018) Characterisation of recharge mechanisms in a Precambrian basement aquifer in semi-arid south-west Niger. *Hydrogeology Journal*, <https://link.springer.com/article/10.1007/s10040-018-1799-x>
- Al-Gamal, S. (2011) An assessment of recharge possibility to North-Western Sahara Aquifer System (NWSAS) using environmental isotopes. *Journal of Hydrology*, 398, pp. 184-190, doi:10.1016/j.jhydrol.2010.12.004.
- Altchenko, Y.; Villholth, K. G. (2015) Mapping irrigation potential from renewable groundwater in Africa – a quantitative hydrological approach, *Hydrology and Earth System Sciences*, 19, pp. 1055-1067, doi:10.5194/hess-19-1055-2015.
- Asefi-Najafabady, S., Saatchi, S. (2013) Response of African humid tropical forests to recent rainfall anomalies. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 368(1625), 20120306, doi:10.1098/rstb.2012.0306.
- Awange, J.L., Forootan, E., Kuhn, M., Kusche, J., Heck, B. (2014) Water storage change and climate variability within the Nile Basin between 2002 and 2001. *Advances in Water Resources*, 73, pp. 1-15, doi : 10.1016/j.advwatres.2014.06.010.
- Baba-Sy, J. (2005) Recharge et paléorecharge du système aquifère du Sahara septentrional, Ph.D. Thesis, Univ. Tunis, Tunisia.
- Bamba, A., Dieppois, B., Konaré, A., Pellarin, T., Balogun, A., Dessay, N., Kamagaté, B., Savané, I. and Diédhiou, A. (2015) Changes in Vegetation and Rainfall over West Africa during the Last Three Decades (1981-2010). *Atmospheric and Climate Sciences*, 5, pp. 367-379, doi:10.4236/acs.2015.54028.

593 Bates, B.C., Kundzewicz Z.W., Wu S. and J.P. Palutikof (eds) (2008) Climate Change and
 594 Water. Technical Paper of the Intergovernmental Panel on Climate Change, IPCC Secretariat,
 595 Geneva, 210 pp.

596 Becker, A., Finger, P., Meyer-Christoffer, A., Rudolf, B., Schamm, K., Schneider, U. and Ziese,
 597 M. (2013) A description of the global land-surface precipitation data products of the Global
 598 Precipitation Climatology Centre with sample applications including centennial (trend) analysis
 599 from 1901–present, *Earth System Science Data*, 5, pp. 71-99, doi:10.5194/essd-5-71-2013.

600 Bellaoueur, A.A. (2008) Etude hydrogéologique des eaux souterraines de la région de Ouargla
 601 soumise à la remontée des eaux de la nappe phréatique et perspectives de solutions palliatives
 602 (Sahara Nord-Est Septentrional – Algérie) (Hydrogeological study of groundwater in the Ouargla
 603 region subjected to upwelling of the water table and prospects of palliative solutions (North-
 604 Eastern Sahara - Algeria)). MSc. Thesis, Univ. El-Hadj Lakhdar – Batna, Algeria.

605 Bettadpur, S. (2007) Level-2 gravity field product user handbook, GRACE 327-734, GRACE
 606 Proj. Cent. For Space Res., Univ. of Texas, Austin.

607 BGR and UNESCO (2008) Groundwater Resources of Africa [map]. World-wide
 608 Hydrogeological Mapping and Assessment Programme (WHYMAP).
 609 https://www.whymap.org/whymap/EN/Maps_Data/Additional_maps/addimaps_node_en.html.
 610 Cited 6 June 2017.

611 Bouwer, L.M., Aerts, J.C., Droogers, P., Dolman, A.J. (2006) Detecting the long-term impacts
 612 from climate variability and increasing water consumption on runoff in the Krishna river basin
 613 (India), *Hydrology and Earth System Sciences*, 10, pp. 703-713, doi: 10.5194/hess-10-703-2006.

614 Chelliah, M. and Bell, G.D. (2004) Tropical multidecadal and interannual climate variations in
 615 the NCEP–NCAR reanalysis. *Journal of Climate*, 17, pp. 1777–1803, doi: 10.1175/1520-0442.

616 Chen, J., Famiglietti, J.S., Scanlon, B.R., Rodell, M. (2016) Groundwater Storage Changes:
617 Present Status from GRACE Observations. *Surveys in Geophysics*, 37(2), pp. 397 – 417, doi:
618 10.1007/s10712-015-9332-4.

619 Cuthbert, M.O., Gleeson, T., Reynolds, S.C., Bennett, M.R., Newton, A.C., McCormack, C.J.
620 and Ashley, G.M. (2017) Modelling the role of groundwater hydro-refugia in East African
621 hominin evolution and dispersal, *Nature Communications*, 8, doi:10.1038/ncomms15696.

622 Diatta, S., Fink, A. H. (2014) Statistical relationship between remote climate indices and West
623 African monsoon variability. *International Journal of Climatology*, 34, pp. 3348–3367,
624 doi:10.1002/joc.3912.

625 Diaw, F., Stichler, W., Mloszewski, P. (2012) Isotopic and geochemical characteristics of
626 groundwater in the Senegal River delta aquifer: implication of recharge and flow regime.
627 *Environmental Earth Sciences*, 66, 4, pp. 1011-1020, doi: 10.1007/s12655-010-0710-4.

628 Diem, J.E., Ryan, S.J, Hartter, J., Palace, M.W. (2014) Satellite-based rainfall data reveal a
629 recent drying trend in central equatorial Africa. *Climatic Change*, 126(1-2), pp. 263–272, doi:
630 10.1007/s10584-014-1217-x.

631 Donat, M. G., Peterson, T. C., Brunet, M., King, A.D., Almazroui, M., Kolli, R.K., Boucherf, D.,
632 Al-Mulla, A.Y., Nour, A.Y., Aly, A.A., Ali Nada, T.A., Semawi, M.M., Al Dashti, H.A., Salhab,
633 T.G., El Fadli, K.I., Muftah, M.K., Eida, S.D., Badi, W., Driouech, F., El Rhaz, K., Abubaker,
634 M.J.Y., Ghulam, A.S., Erayah, A.S., Mansour, M.B., Alabdouli, W.O., Al Dhanhani, J.S. and Al
635 Shekaili, M .N. (2014) Changes in extreme temperature and precipitation in the Arab region:
636 long-term trends and variability related to ENSO and NAO. *International Journal of*
637 *Climatology*, 34, pp. 581–592, doi:10.1002/joc.3707.

638 Dong, B., Sutton, R.T. (2007) Enhancement of ENSO Variability by a Weakened Atlantic
 639 Thermohaline Circulation in a Coupled GCM. *Journal of Climate*, 20, pp. 4920–4939,
 640 doi:10.1175/JCLI4284.1.

641 Dong, B., Sutton, R.T., Scaife, A.A. (2006) Multidecadal modulation of El Niño – Southern
 642 Oscillation (ENSO) variance by Atlantic Ocean sea surface temperatures, *Geophysical Research*
 643 *Letters*, 33, doi:10.1029/ 2006GL025766.

644 Edmunds, W.M. (2008) ‘Groundwater in Africa – Palaeowater, climate change and modern
 645 recharge’ in Adelana S.M.A. and MacDonald A.M. (eds) Applied groundwater research in
 646 Africa. IAH Selected Papers in Hydrogeology 13. Amsterdam: Taylor and Francis.

647 El Shazli, Ahmed (2018) Water balance of the Aswan High Dam Reservoir. Ph.D. Thesis, Kiel
 648 University.

649 Falkenmark, M. (2013) Adapting to climate change: towards societal water security in dry-
 650 climate countries. *International Journal of Water Resources Development*, 29, pp. 123-136,
 651 doi:10.1080/07900627.2012.721714.

652 Famiglietti, J.S. (2014) The global groundwater crisis. *Nature Climate Change*, 4, pp. 945-948,
 653 doi :10.1038/nclimate2425.

654 Fan, L. and Liu, Q. (2017) Indian Ocean Dipole Models Associated with Different Types of
 655 ENSO Development. *Journal of Climate*, 30, pp. 2233–2249, doi: 10.1175/JCLI-D-16-0426.1.

656 FAO (2015) Global Diagnostic on Groundwater Governance (Special edn. For World Water
 657 Forum 7). Groundwater Governance – A Global Framework for Action, GEF Groundwater
 658 Governance Project. <http://www.groundwatergovernance.org>. Cited 6 June 2017.

659 Fasullo, J.T., Lawrence, D.M., Swenson, S.C. (2016) Are GRACE-era Terrestrial Water Trends
 660 Driven by Anthropogenic Climate Change? *Advances in Meteorology*, vol. 2016,
 661 doi:10.1155/2016/4830603.

662 Favreau, G., Cappelaere, B., Massuel, S., Leblanc, M., Boucher, M., Boulain, N. and Leduc, C.
 663 (2009), Land clearing, climate variability, and water resources increase in semiarid southwest
 664 Niger: A review. *Water Resources Research*, 45, doi:10.1029/2007WR006785.

665 Favreau, G., Nazoumou, Y., Leblanc, M., Guéro, A., Goni, I.B. (2012) Groundwater resources in
 666 the Iullemmeden Basin, West Africa. In: Treidel, H., Martin-Bordes, J.L., Gurdak, J.J. (Eds.)
 667 Climate Change Effects on Groundwater Resources: A Global Synthesis of Findings and
 668 Recommendations”. *International Contributions to Hydrogeology*, 27, 7, pp. 113-128, CRC
 669 Press Inc., Leiden, The Netherlands.

670 Fontes, J.C., Andrew, J.N., Edmunds, W.M., Guerre, A., Travi, Y. (1991) Paelorecharge by the
 671 Niger River (Mali) deduced from groundwater geochemistry, *Water Resources Research*, 27, 2,
 672 pp. 199-214, doi:10.1029/90WR01703.

673 Foster, S., Tuinhof, A., Garduño, H. (2006) Groundwater Development in Sub-Saharan Africa: A
 674 Strategic Overview of Key Issues and Major Needs. World Bank GWP Associate Program.
 675 Sustainable Groundwater Management: Concepts and Tools. Case Profile Collection No. 15.

676 Gao, H., Zhang, S., Fu, R., Li, W. and Dickinson, R.E. (2016) Interannual Variation of the
 677 Surface Temperature of Tropical Forests from Satellite Observations. *Advances in Meteorology*,
 678 doi:10.1155/2016/4741390.

679 García-García, D., Ummenhofer, C.C. (2015) Multidecadal variability of the continental
 680 precipitation annual amplitude driven by AMO and ENSO, *Geophysical Research Letters*, 42,
 681 pp. 526–535, doi:10.1002/2014GL062451.

682 Gaye, C.B., Tindimugaya, C. (2012) Challenges and opportunities for sustainable groundwater
683 management in Africa. International Symposium, Enhancing Water Management Capacity in a
684 Changing World, Sao Paulo, June 2012.

685 Geng, X., Zhang, W., Stuecker, M.F., Liu, P., Jin, F.F., Tan, G. (2016) Decadal modulation of
686 the ENSO-East Asian winter monsoon relationship by the Atlantic Multidecadal Oscillation,
687 *Climate Dynamics*, 11, doi:10.1007/s00382-016-3465-0.

688 Giannini, A., Saravanan, R., Chang, P. (2003) Oceanic forcing of Sahel rainfall on interannual to
689 interdecadal time scales. *Science*, 302, pp. 1027-1030, doi:10.1126/science.1089357.

690 Giles, J. (2005) Solving Africa's climate data problem. *Nature*, 435, pp. 862-863, doi:
691 10.1038/435862a.

692 Gleeson, T., Wada, Y., Bierkens, M.F.P., van Beek, L.P.H. (2012) Water balance of global
693 aquifers revealed by groundwater footprint, *Nature*, 488, pp. 197-200, doi:10.1038/nature11295.

694 Gning, A.A. (2015) Etude et modélisation hydrogéologique des interactions eaux de surface-
695 eaux souterraines dans un context d'agriculture irriguée dans le delta du fleuve Sénégal
696 (Hydrogeological study and modeling of surface water-groundwater interactions in an irrigated
697 agriculture context in the Senegal River delta), Ph.D. Thesis, Univ. De Liège, Belgium.

698 Gorelick, S.M., Zheng, C. (2015) Global change and the groundwater management challenge,
699 *Water Resources Research*, 51(5), pp. 3013-3051, doi:10.1002/2014WR016825.

700 Green, T., Taniguchi, M., Kooi, H., Gurdak, J.J., Allen, D.M., Hishcock, K.M., Treidel, H. and
701 Aureli, A. (2011) Beneath the surface of global change: Impacts of climate change on
702 groundwater. *Journal of Hydrology*, 405, pp. 532-560, doi:10.1016/j.jhydrol2011.05.002.

703 Grinsted, A., Moore, J.C., Jevrejeva, S. (2004) Application of the cross wavelet transform and
704 wavelet coherence to geophysical time series, *Nonlinear Processes in Geophysics*, 11, pp. 561–
705 566, doi:10.5194/npg-11-561-2004.

706 Gurdak, J.J. (2017) Groundwater: Climate-induced pumping. *Nature Geoscience*, 10(71),
707 doi :10.1038/ngeo2885.

708 Gurdak, J.J., Hanson, R.T., McMahon, P.B., Bruce, B.W., McCray, J.E., Thyne, G.D. and
709 Reedy, R.C. (2007) Climate variability controls on unsaturated water and chemical movement,
710 High Plains aquifer, USA. *Vadose Zone Journal*, 6(2), pp. 533-547, doi:10.2136/vzj/2006.0087.

711 Hanson, R.T., Newhouse, M.W., Dettinger, M.D. (2004) A methodology to assess relations
712 between climatic variability and variations in hydrologic time series in the southwestern United
713 States. *Journal of Hydrology*, 287, pp. 252-269, doi:10.1016/j.jhydrol.2003.10.006.

714 Hassan, A., Jin, S.G. (2016) Water storage changes and balances in Africa observed by satellite
715 gravimetry and hydrologic models. *Geodesy and Geodynamics*, 7(1), pp. 39–49,
716 doi:10.1016/j.geog.2016.03.002.

717 Henry, C.M., Allen, D.M., Huang, J. (2011) Groundwater storage variability and annual recharge
718 using well-hydrograph and GRACE satellite data. *Hydrogeology Journal*, 19, 2, pp. 741-755,
719 doi: 10.1007/s10040-011-0724-3.

720 Holman, I.P., Rivas-Casado, M., Bloomfield, J.P., Gurdak, J.J. (2011) Identifying non-stationary
721 groundwater level response to North Atlantic ocean-atmosphere teleconnection patterns using
722 wavelet coherence. *Hydrogeology Journal*, 19, pp. 1269-1278, doi:10.1007/s10040-011-0755-9.

723 Houghton-Carr, H.A., Fry, M. J. (2006) The decline of hydrological data collection for
724 development of integrated water resource management tools in Southern Africa, Climate

725 Variability and Change – Hydrological Impacts, Proceedings of the Fifth FRIEND World
 726 Conference, IAHS Publ. 308.

727 Hurrell, J.W. (1995) Decadal trends in the north atlantic oscillation: regional temperatures and
 728 precipitation. *Science*, 4, pp. 676-679, doi:10.1126/science.269.5224.676.

729 Hurrell, J.W., Kushnir, Y., Ottersen, G., Visbeck, M. (2003) An overview of the North Atlantic
 730 Oscillation. In: Hurrell, J.W., Kushnir, Y., Ottersen, G., Visbeck, M. (eds) *Geophysical*
 731 *Monograph Series*. American Geophysical Union, Washington, D.C., pp. 1-35.

732 IGRAC (2017) Global Groundwater Monitoring Network – GGMN. <https://ggmn.un-igrac.org>.
 733 Cited 6 June 2017.

734 IGRAC-UNESCO (2015) *Transboundary Aquifers of the World* [map]. Edition 2015. Scale 1 :
 735 50 000 000. Delft, Netherlands : IGRAC, 2015.

736 Janicot, S., Ganiaux, G., Chauvin, F., de Coetlogon, G., Fontaine, B., Hall, N., Kiladis, G.,
 737 Lafore, J.P., Lavaysse, C., Lavender, S.L., Leroux, S., Marteau, R., Mounier, F., Philippon, N.,
 738 Roehrig, R., Sultan, B. and Taylor, C.M. (2011) Intraseasonal variability of the West African
 739 monsoon, *Atmospheric Science Letters*, 12(1), pp. 58-66, doi: 10.1002/asl.280.

740 Jung, M., Reichstein, M., Ciais, P., Seneviratne, S.I., Sheffield, J., Goulden, M.L., Bonan, G.,
 741 Cascatti, A., Chen, J., de Jeu, R., Dolman, A.J., Eugster, W., Gerten, D., Gianelle, D., Gobron,
 742 N., Heinke, J., Kimball, J., Law, B.E., Montagnani, L., Mu, Q., Mueller, B., Oleson, K., Papale,
 743 D., Richardson, A.D., Rouspard, O., Running, S., Tomelleri, E., Viovy, N., Weber, U., Williams,
 744 C., Wood, E., Zaehle, S. and Zhang, K. (2010) Recent decline in the global land
 745 evapotranspiration trend due to limited moisture supply. *Nature*, 467, pp. 951-954,
 746 doi:10.1038/nature09396.

747 Knudsen, M.F., Seidenkrantz, M-S., Jacobsen, B.H. (2011) Tracking the Atlantic Multidecadal
748 through the last 8,000 years. *Nature Communications*, 2, p. 178, doi:10.1038/ncomms1186.

749 Konikow, L.F. (2015) Long-Term Groundwater Depletion in the United States. *Groundwater*,
750 53(1), pp. 2-9, doi:10.1111/gwat.12306.

751 Kuss, A.J.M., Gurdak, J.J. (2014) Groundwater level response in U.S. principal aquifers to
752 ENSO, NAO, PDO, and AMO. *Journal of Hydrology*, 519, pp. 1939-1952,
753 doi:10.1016/j.jhydrol.2014.09.069.

754 Labat, D. (2005). Recent advances in wavelet analyses: Part 1. A review of concepts. *Journal of*
755 *Hydrology*, 314, pp. 275-288, doi:10.1016/j.jhydrol.2005.04.003.

756 Labat, D. (2008). Wavelet analysis of the annual discharge records of the world's largest rivers.
757 *Advances in Water Resources*, 31(1), pp. 109-117, doi:10.1016/j.advwatres.2007.07.004.

758 Labat, D., Ababou, R., Mangin, A (2000) Rainfall–runoff relations for karstic springs. Part II:
759 Continuous wavelet and discrete orthogonal multiresolution analyses. *Journal of Hydrology*,
760 238, pp. 149–178, doi:10.1016/S0022-1694(00)00322-X.

761 Lapworth, D.J., McDonald, A.M., Tijani, M.N., Darling, W.G., Gooddy, W.G., Bonsor, H.C.,
762 Araguas-Araguas, L.J. (2013) Residence times of shallow groundwater in West Africa:
763 implications for hydrogeology and resilience to future changes in climate. *Hydrogeology*
764 *Journal*, 21, 3, pp. 673-686, doi: 10.1007/s10040-012-0925-4.

765 Li, J., Xie, S.P., Cook, E.R., Morales, M.S., Christie, D.A., Nathaniel, C.J., Chen, F., D'Arrigo,
766 R., Fowler, A.M., and Gou, X. and Fang, K. (2013) El Niño modulations over the past seven
767 centuries. *Nature Climate Change*, 3, pp. 822-826, doi :10.1038/nclimate1936.

768 Liu, M., Tian, H., Yang, Q., Yang, J., Song, X., Lohrenz, S.E. and Cai, W.J. (2013) Long-term in
 769 evapotranspiration and runoff over the drainage basins of the Gulf of Mexico during the 1901-
 770 2008, *Water Resources Research*, 49, 4, doi: 10.1002/wrcr.20180.

771 Long, D., Longuevergne, L., Scanlon, B.R. (2015) Global analysis of approaches for deriving
 772 total water storage changes from GRACE satellites. *Water Resources Research*, 51 (4), pp.2574-
 773 2594, doi:10.1002/ 2014WR016853.

774 Longuevergne, L., Scanlon, B.R., Wilson, C.R. (2010) GRACE hydrological estimates for small
 775 basins: Evaluating processing approaches on the High Plains Aquifer, USA, *Water Resources*
 776 *Research*, 46, doi:10.1029/2009WR008564.

777 López-Moreno, J.I., Vicente-Serrano, S.M., Morán-Tejeda, E., Lorenzo-Lacruz, J., Kenawy, A.
 778 and Beniston, M. (2011) Effects of the North Atlantic Oscillation (NAO) on combined
 779 temperature and precipitation Winter modes in the Mediterranean mountains: observed
 780 relationships and projects for the 21st century. *Global and Planetary Change*, 77, pp. 62–76, doi:
 781 10.1016/j.gloplacha.2011.03.003.

782 Lutz, A., Minyila, S., Saga, B. Diarra, S., Apambire, B. and Thomas, J. (2015) Fluctuation of
 783 Groundwater Levels and Recharge Patterns in Northern Ghana. *Climate*, 3, pp. 1-15, doi:
 784 10.3390/cli3010001.

785 MacDonald, A.M., Bonsor, H.C., Dochartaigh, B.E.O. and Taylor, R.G. (2012) Quantitative
 786 maps of groundwater resources in Africa. *Environmental Research Letters*, 7(2), doi:
 787 10.1088/1748-9326/7/2/024009.

788 Maidment, R.I., Allan, R.P., Black, E. (2015) Recent observed and simulated changes in
 789 precipitation over Africa. *Geophysical Research Letters*, 42(19), pp. 8155-8164, doi:
 790 10.1002/2015GL065765.

791 Malherbe, J., Dieppois, B., Maluleke, P., van Staden, M. and Pillay, D.L. (2016) South African
 792 droughts and decadal variability. *Natural Hazards*, 80(1), pp. 657-681, doi: 0.1007/s11069-015-
 793 1989-y.

794 Manatsa, D., Matarira, C., Mukwada, G. (2011) Relative impacts of ENSO and Indian Ocean
 795 dipole/zonal mode on east SADC rainfall. *International Journal of Climatology*, 31, pp. 558–
 796 577, doi:10.1002/joc.2086.

797 Massuel, S. and Riaux, J. (2017) Groundwater overexploitation: why is the red flag waved? Case
 798 study on the Kairouan aquifer (central Tunisia). *Hydrogeology Journal*, 25, 6, pp. 1607-1620,
 799 doi: 10.1007/s10040-017-1568-2.

800 Marchant, R., Mumbi, C., Behera, S., Yamagata, T. (2006) The Indian Ocean dipole – the
 801 unsung driver of climatic variability in East Africa. *African Journal of Ecology*, 45, 1, doi:
 802 10.1111/j.1365-2028.2006.00707.x.

803 Masih, I., Maskey, S., Mussa, F.E.F. and Trambauer, P. (2014) A review of droughts on the
 804 African continent: a geospatial and long-term perspective. *Hydrology and Earth System
 805 Sciences*, 18, pp. 3635–3649, doi: 10.5194/hess-18-3635-2014.

806 Maurice L., Taylor, R.G., Tindimugaya, C., MacDonald, A. M., Johnson, P., Kaponda, A., Owor
 807 M., Sanga, H., Bonsor, H.C., Darling, W.G., and Gooddy, D. (2018) Characteristics of high-
 808 intensity groundwater abstractions from weathered crystalline bedrock aquifers in East Africa.
 809 *Hydrogeology Journal*, THIS ISSUE

810 McCarthy, G.D., Haigh, I.D., Hirschi, J.J.M., Grist, J.P. and Smeed, D.A. (2015) Ocean impact
 811 on decadal Atlantic climate variability revealed by sea-level observations. *Nature*, 521, pp. 508–
 812 510, doi : 10.1038/nature14491.

813 Messekher, I., Chabour, N., Menani, M.R. (2012) Remontée de la nappe phréatique du Souf :
814 consequences et solutions envisagées (Rise of the Souf water table: consequences and solutions
815 envisaged). Annals of the University of Bucarest.

816 <http://annalsreview.geo.unibuc.ro/2012/Ishak.pdf>. Cited 6 June 2017.

817 Meyer, C. (2016) Développement d’outil pour la cartographie de l’indicateur 6.5.2 des ODD sur
818 la coopération internationale dans le domaine de l’eau (Development of a tool for mapping SDG
819 indicator 6.5.2 on transboundary water cooperation). MSc. Thesis, Univ. Paris 10, France.

820 Mohino, E., Rodriguez-Fonseca, B., Mechoso, C.R., Gervois, S., Ruti, P. and Chauvin, F. (2011)
821 Impacts of the Tropical Pacific/Indian Oceans on the Seasonal Cycle of the West African
822 Monsoon. *Journal of Climate*, 24, pp. 3878-3891, doi :10.1175/2011JCLI3988.1.

823 Mueller, B. Seneviratne, Jimenez, C., Corti, T., Hirschi, M., Balsamo, G., Ciais, P., Dirmeyer, P.,
824 Fisher, J.B., Guo, Z., Maignan, F., McCabe, Reichle, R., Reichstein, M., Rodell, M., Sheffield,
825 J., Teuling, A.J. Teuling, Wang, K., Wood, E.F. and Zhang, Y. (2011) Evaluation of global
826 observations-based evapotranspiration datasets and IPCC AR4 simulations, *Geophysical*
827 *Research Letters*, 38, 6, doi:10.1029/2010GL046230.

828 Nazoumou, Y., Favreau, G., Babaye, M.S.A., Goni, I.B. (2015) Climate variability, land use and
829 groundwater storage in a large sedimentary aquifer of the Sahel region (Iullemeden Basin,
830 Niger). Proceedings of the 42nd IAH Congress, Rome, Italy.

831 Ndehedehe, C.L., Awange, J.L., Kuhn, M. Agutu, N.O. and Fukuda, Y. (2017) Climate
832 teleconnections influence on West Africa’s terrestrial water storage. *Hydrological Processes*, pp.
833 1-19, doi :10.1002/hyp.11237.

834 Ngounou-Ngatcha, B.N., Favreau, G., Le Coz, M., Nazoumou, Y., Boucher, M. and Goni, I.
835 (2015) Long term changes in groundwater storage in the Lake Chad Basin, central Africa, as a

836 function of drought periods and lake fluctuations. Proceedings of the 42nd IAH Congress, Rome,
837 Italy.

838 NOAA (2017) Climate Indices: Monthly Atmospheric and Ocean Time Series. Earth System
839 Research Laboratory, Physical Sciences Division.

840 <https://www.esrl.noaa.gov/psd/data/climateindices/list/>. Cited 6 June 2017.

841 Nicholson, S.E., Selato, J.C. (2000) The influence of La Nina on African rainfall. *International*
842 *Journal of Climatology*, 20, pp. 1761–1776, doi: 10.1002/1097-0088.

843 Okonkwo, C., Demoz, B., Sakai, R. Ichoku, C., Anarado, C. and Adegoke, J. (2015) Combined
844 effect of El Niño southern oscillation and Atlantic multidecadal oscillation on Lake Chad level
845 variability. *Cogent Geoscience*, 1, pp. 1-19, doi:10.1080/23312041.2015.1117829.

846 Onyutha, C. and Willems, P. (2017) Space-time variability of extreme rainfall in the River Nile
847 basin. *International Journal of Climatology*, 34, 14, pp. 4915-4924, doi: 10.1002/joc.5132

848 OSS (2003) Système Aquifère du Sahara Septentrional – Gestion commune d’un bassin
849 transfrontière, Rapport de synthèse, 1^{ère} edition (North-Western Sahara Aquifer System - Joint
850 Management of a Transboundary Basin, Summary Report, 1st edition). ISBN:9973-856-03-1.

851 Owusu, K., Waylen, P.R., Qui, Y. (2008) Changing rainfall inputs in the Volta basin:
852 implications for water sharing in Ghana. *GeoJournal*, 71(4), pp. 201-210, doi: 10.1007/s10708-
853 008-9156-6.

854 Palmer, T.N., Anderson, D.L.T. (1994) The prospects for seasonal forecasting—A review paper.
855 *Quarterly Journal of the Royal Meteorological Society*, 120, pp. 755–793,
856 doi:10.1002/qj.49712051802.

857 Peings, Y., Magnusdottir, G. (2014) Forcing of the wintertime atmospheric circulation by the
858 multidecadal fluctuations of the North Atlantic ocean. *Environmental Research Letters*, 9(3),
859 doi : 10.1088/1748-9326/9/3/034018.

860 Philippon, N., Rouault, M., Richard, Y. and Favre, A. (2012) The influence of ENSO on winter
861 rainfall in South Africa. *International Journal of Climatology*, 32, pp. 2333–2347,
862 doi:10.1002/joc.3403.

863 Prudhomme, C., Giuntoli, I., Robinson, E.L., Clark, D.B., Arnell, N.W., Dankers, R., Fekete,
864 B.M., Franssen, W., Gerten, D., Gosling, S.N., Hagemman, S., Hannah, D.M., Kim, H., Masaki,
865 Y., Satoh, Y., Stacke, T., Wada, Y. and Wisser, D. (2014) Hydrological droughts in the 21st
866 century, hotspots and uncertainties from a global multimodel ensemble experiment. *Proceedings*
867 *of the National Academy of Sciences*, 111(4), pp. 3262–3267, doi: 10.1073/pnas.1222473110.

868 Ramilien, G., Frappart, F., Seoane, L. (2014) Application of the Regional Water Mass Variations
869 from GRACE Satellite Gravimetry to Large-Scale Water Management in Africa. *Remote*
870 *Sensing*, 6, pp. 7379–7405, doi:10.3390/rs6087379.

871 Rateb, A., Kuo, C.Y., Imani, M. Tseng, K.H., Lan, W.H., Ching, K.E. and Tseng, T.P. (2017)
872 Terrestrial Water Storage in African Hydrological Regimes Derived from GRACE Mission Data:
873 Intercomparison of Spherical Harmonics, Mass Concentration, and Scalar Slepian Methods.
874 *Sensors*, 17(3), doi : 10.3390/s17030566.

875 Richard ,Y., Fauchereau, N., Pocard, I., Rouault, M. and Trzaska, S. (2001) 20th Century
876 droughts in southern Africa: spatial and temporal variability, teleconnections with oceanic and
877 atmospheric conditions. *International Journal of Climatology*, 21, pp. 873–885,
878 doi:10.1002/joc.656.

879 Richey, A.S., Thomas, B.F., Lo, M.H., Reager, J.T., Famiglietti, J.S., Voss, K., Swenson, S. and
 880 Rodell, M. (2015) Quantifying renewable groundwater stress with GRACE, *Water Resources*
 881 *Research*, 51, pp. 5217–5238, doi:10.1002/2015WR017349.
 882 Robins, N.S., Davies, J., Farr, J.L., Calow, R.C. (2006) The changing role of hydrogeology in
 883 semi-arid southern and eastern Africa, *Hydrogeology Journal*, 14, 8, pp. 1483-1492,
 884 doi:10.1007/s10040-006-0056-x.
 885 Russo, T.A., Lall, U. (2017) Depletion and response of deep groundwater to climate-induced
 886 pumping variability. *Nature Geoscience*, 10, pp. 105-108, doi : 10.1038/ngeo2883.
 887 Scanlon, B.R., Keese, K.E., Flint, A.L., Flint, L.E., Gaye, C.B., Edmunds, W.M. and Simmers, I.
 888 (2006) Global synthesis of groundwater recharge in semiarid and arid regions. *Hydrological*
 889 *Processes*, 20, pp. 3335–3370, doi:10.1002/hyp.6335.
 890 Scanlon, B.R., Zhang, Z., Save, H., Wiese, D.N., Landerer, F.W., Long, D., Longuevergne, L.
 891 and Chen, J. (2016) Global evaluation of new GRACE mascon products for hydrologic
 892 applications. *Water Resources Research*, 56, 12, pp. 9412-9429, doi: 10.1002/2016WR019494.
 893 Shanahan, T.M., Overpeck, J.T., Anchukaitis, K.J., Beck, J.W., Cole, J.E., Dettman, D.L., Peck,
 894 J.A., Scholz, C.A. and King, J.W. (2009), Atlantic forcing of persistent drought in West Africa,
 895 *Science*, 324(5925), pp. 377–380, doi:10.1126/science.1166352.
 896 Siam, M.S., Eltahir, E.A.B. (2017) Climate change enhances interannual variability of the Nile
 897 river flow. *Nature Climate Change*, 7, pp. 350-354, doi :10.1038/nclimate3273.
 898 Siebert, S., Burke, J., Faures, J.M., Frenken, K., Hoogeveen, J., Doll, P. and Portmann, F.T.
 899 (2010) Groundwater use for irrigation – a global inventory. *Hydrology and Earth System*
 900 *Sciences*, 14, pp. 1863-1880, doi:10.5194/hess-14-1863-2010.

901 Sun, A. Y., Scanlon, B.R., Agha Kouchal, A., Zhang, Z. (2017) Using GRACE satellite
 902 gravimetry for assessing large-scale hydrological extremes, *Remote Sensing*, 9, 12, pp. 1287-
 903 1312, doi: 10.3390/rs9121287.

904 Sun, Q., Miao, C., Duan, Q., Ashouri, H., Sorooshian, S., Hsu, K.L. (2018) A review of global
 905 precipitation data Ssets: Data Sources, estimation, and intercomparisons, *Reviews of*
 906 *Geophysics*, 56, doi: 10.1002/2017RG000574.

907 Swenson, S., Wahr, J. (2006) Post-processing removal of correlated errors in GRACE
 908 data, *Geophysical Research Letters*, 33, doi:10.1029/2005GL025285.

909 Taylor, R.G., Koussis, A.D., Tindimugaya, C. (2009) Groundwater and climate in Africa – a
 910 review. *Hydrological Sciences Journal*, 54, pp. 655-664, doi:10.1623/hysj.54.4.655.

911 Taylor, R.G., Scanlon, B., Doll, P., Rodell, M., van Beek, R., Wada, Y., Longuevergne, L.,
 912 Leblanc, M., Famiglietti, J.S., Edmunds, M., Konikow, L., Green, T.R., Chen, J., Taniguchi, M.,
 913 Bierkens, M.F.P., MacDonald, A., Fan, Y., Maxwell, R.M., Yechieli, Y., Gurdak, J.J., Allen,
 914 D.M., Shamsudduha, M., Hiscock, K., Yeh, P.J.F., Holman, I. and Treidel, H. (2013) Ground
 915 water and climate change, *Nature Climate Change*, 3, pp. 322-329, doi:10.1038/nclimate1744.

916 Taylor, R.G., Todd, M.C., Kongola, L., Maurice, L., Nahozya, E., Sanga, H. and MacDonald,
 917 A.M. (2013) Evidence of the dependence of groundwater resources on extreme rainfall in East
 918 Africa. *Nature Climate Change*, 3, pp. 374-378, doi:10.1038/nclimate1731.

919 Timmermann, A., Okumura, Y., An, S.I., Clement, A., Dong, B., Guilyardi, E., Hu, A.,
 920 Jungclaus, J.H., Renold, M., Stocker, T.F., Stouffer, R.J., Sutton, R., Xie, S.P. and Yin, J. (2007),
 921 The influence of a weakening of the Atlantic meridional overturning circulation on ENSO,
 922 *Journal of Climate*, 20(19), pp. 4899–4919, doi:10.1175/JCLI4283.1.

923 Torrence, C., Compo, G.P. (1998) A practical guide to wavelet analysis. *Bulletin of the American*
924 *Meteorological Society*, 79(1), pp. 61-78.

925 Treidel, H., Martin-Bordes, J.L., Gurdak, J.J. (eds) (2012) Climate change effects on
926 groundwater resources: A global synthesis of findings and recommendations, International
927 Association of Hydrogeologists (IAH) – International Contribution to Hydrogeology, Taylor &
928 Francis publishing, 414 p., ISBN 978-0415689366.

929 Trenberth, K.E., Dai, A., van der Schrier, G., Jones, P.D., Barichivich, J., Briffa, K.R. and
930 Sheffield, J. (2014) Global warming and changes in drought. *Nature Climate Change*, 4, pp. 17-
931 22, doi:10.1038/nclimate2067.

932 Tuinhof, A., Foster, S., van Steenberg, F., Talbi, A. and Wishart, M. (2011) Appropriate
933 groundwater management policy for Sub-Saharan Africa in face of demographic pressure and
934 climatic variability. GW MATE strategic overview series, 5, Washington, DC: World Bank.

935 UNESCO (2009) IWRM implementation in basins, sub-basins and aquifers: state of the art
936 review. World Water Assessment Programme, Side publications series, Insights, ISBN 978-92-3-
937 104105-1.

938 UNESCO (2016) Stampriet Transboundary Aquifer System assessment, Governance of
939 Groundwater Resources in Transboundary Aquifers,
940 <http://unesdoc.unesco.org/images/0024/002452/245265e.pdf>. Cited 6 June 2017

941 UNESCO and UNECE (2017) Step-by-step methodology for monitoring transboundary
942 cooperation, Integrated Monitoring Guide for SDG 6. [http://www.unwater.org/publications/step-](http://www.unwater.org/publications/step-step-methodology-monitoring-transboundary-cooperation-6-5-2/)
943 [step-methodology-monitoring-transboundary-cooperation-6-5-2/](http://www.unwater.org/publications/step-step-methodology-monitoring-transboundary-cooperation-6-5-2/). Cited 6 June 2017

944 Van der Gun, J. (2012) Groundwater and global change: trends, opportunities and challenges.
945 World Water Assessment Programme, Side publication series, ISBN 978-92-3-001049-2.

946 Vasollo, S. (2017) Personal communication.

947 Vorosmarty, C.J., Douglas, E.M., Green, P.A. and Revenga, C. (2005) Geospatial indicators of
 948 emerging water stress: an application to Africa. *Ambio*, 34(3), pp. 230-236.

949 Wada, Y., Bierkens, M.F.P. (2014) Sustainability of global water use: past reconstruction and
 950 future projections. *Environmental Research Letters*, 9, doi: 10.1088/1748-9326/9/10/104003.

951 Wada, Y., van Beek, L.P.H., van Kempen, C.M. (2010) Global depletion of groundwater
 952 resources. *Geophysical Research Letters*, 37(20), doi:10.1029/2010GL044571.

953 Wang, S., Huang, J., He, Y. Guan, Y. (2014) Combined effects of the Pacific Decadal
 954 Oscillation and El Niño-Southern Oscillation on Global Land Dry–Wet Changes. *Scientific
 955 Reports*, 4, doi:10.1038/srep06651.

956 Wani S.P., Sreedevi T.K., Rockström J. et al. (2009) Rain-fed agriculture – Past trend and future
 957 prospects. In Wani S.P., Rockström J., Oweis, T. (eds) Rain-fed agriculture: Unlocking the
 958 Potential. Comprehensive Assessment of Water Management in Agriculture Series. CAB
 959 International, Wallingford, UK, pp. 1-35.

960 Washington, R., James, R., Pearce, H. Pokam, W.M. and Moufouma-Okia, W. (2013) Congo
 961 Basin rainfall climatology: Can we believe the climate models? *Philosophical Transactions of
 962 the Royal Society, London, Ser. B*, 368(1625), doi:10.1098/rstb.2012.0296.

963

964 WMO (1996) The adequacy of hydrological networks: a global assessment. *Tech. Document no.*
 965 *740*. WMO, Geneva, Switzerland.

966 Zhang, Y., Wallace J.M., Battisti, D.S. (1997) ENSO-like interdecadal variability. *Journal of
 967 Climate*, 10, pp. 1004–1020, doi:10.1175/1520-0442.

968 Zhang, W., Jin, F.F., Zhao, J.X. and Li, J. (2012) On the bias in simulated ENSO SSTA
 969 meridional widths of CMIP3 models, *Journal of Climate*, doi:10.1175/JCLI-D-12-00347.1.
 970 Zhou, L., Tian, Y., Myneni, R.B., Ciais, P., Saatchi, S., Liu, Y.Y., Piao, S., Chen, H., Vermote,
 971 E.F., Song, C. and Hwang, T. (2014) Widespread decline of Congo rainforest greenness in the
 972 past decade, *Nature*, 509, pp. 86-90, doi: 10.1038/nature13265.
 973 Zouari, K. (2015) Progress in the implementation of the project RAF 7011 on the assessment of
 974 shared aquifer systems in the Sahel region. International Symposium on Isotope Hydrology:
 975 Revisiting Foundations and Exploring Frontiers, 11-15 May 2015, IAEA Headquarters, Vienna,
 976 Austria.

977

978 **Acknowledgements:**

979 This study is a contribution to UNESCO International Hydrological Programme (IHP) *Groundwater*
 980 *Resources Assessment under the Pressures of Humanity and Climate Change* (GRAPHIC) project.
 981 The authors are grateful to the support provided by Richard Taylor (UCL), Aurélien Dumont and
 982 Marina Rubio (UNESCO-IHP – Groundwater Systems and Settlements Section) on the review of this
 983 paper.

984

985

986 **Appendix: Acronyms and abbreviations**

987

TWS	Total water storage
Δ GWS	Groundwater storage changes
Δ GWS _{OBSERVED}	Observed groundwater storage changes
Δ TWS	Total water storage changes
Δ TWS _{GRACE}	GRACE-based changes in total water storage
Δ TWS _{MODEL}	Simulated changes in total water storage
AMO	Atlantic Multidecadal Oscillation
CWT	Continuous wavelet transform
ENSO	El Niño Southern Oscillation
GRACE	Gravity Recovery And Climate Experiment
IOD	Indian Ocean Dipole
ITTAS	Iullemeden, Taoudeni/Tanezrouft Aquifer System
IWRM	Integrated Water Resources Management
MAR	Managed Aquifer Recharge
MEI	Multivariate ENSO Index
NAO	North Atlantic Oscillation
NSAS	Nubian Sandstone Aquifer System
NWSAS	North-Western Sahara Aquifer System
PDO	Pacific Decadal Oscillation
STAS	Stampriet Transboundary Aquifer System
WTC	Wavelet coherence
XWT	Cross wavelet transform

Table 1 – Basic hydrogeological, socio-economic and governance overview of the studied aquifers

Aquifer No. (Fig. 1)	Aquifer	Zone	Population (approx. no. of inhabitants)	Approx. area (km²)	Rainfall (mm/year)	Aquifer type	Institutional arrangement
1	North-Western Sahara Aquifer System (NWSAS)	Northern Africa	4,000,000	1,300,000	10-300	Sand, sandstone, sandy clay, calcareous, dolomite	Observatory of the Sahara and the Sahel (OSS)
2	Nubian Sandstone Aquifer System (NSAS)	Northern Africa	67,000,000	2,800,000	1-550	Nubian and Post-Nubian	Joint Authority
3	Senegalo-Mauritanian Basin	Sahel	12,000,000	330,000	20-1,850	Quaternary - Maestrichtien	Senegal River Basin Development Authority (potential)
4	Irhzar-Iulluemedden Basin	Sahara-Sahel	13,000,000	580,000	80-900	Sedimentary deposit including Terminal Continental and Intercalary Continental (Cretaceous – Tertiary)	Consultation mechanism to be operationalized
5	Lake Chad Basin	Sahara-Sahel	22,000,000	2,300,000	40-1,400	Sedimentary: Upper Quaternary, lower Pliocene and Continental Terminal (Tertiary)	Lake Chad Basin Commission (potential)
6	Volta Basin	Tropical/Equatorial Africa	14,000,000	145,000	500-1,100	Sedimentary rocks	Volta Basin Authority (potential)
7	Karoo-Carbonate	Equatorial Africa	10,000,000	600,000	1,000-1,800	Limestone/sandstone	International Commission of the Congo-Oubangui-Sangha Basin (potential)
8	Stampriet Transboundary Aquifer System	Southern Africa	50,000	90,000	200-350	Kalahari group aquifers and Karoo supergroup aquifers	Orange-Senqu River Commission
9	Karoo Sedimentary	Southern Africa	6,000,000	170,000	350-1,200	Consolidated sedimentary rocks	Orange-Senqu River Commission (potential)

Table 2 – Ground-based measurements in the studied aquifers

Aquifer No.	Aquifer	Groundwater-level time frame	Well/Borehole depth	Source
1	North-Western Sahara Aquifer System (NWSAS)	1982-2011	Shallow piezometer (located near the boundaries of the aquifer)	Massuel and Riaux, 2017
2	Nubian Sandstone Aquifer System (NSAS)	1998-2004	Shallow piezometer (vicinity of Lake Nasser)	El Shazli, 2018
3	Senegalo-Mauritanian Basin	1997-2002	Shallow piezometer (vicinity of Senegal River)	Gning et al., 2015
4	Irhazer-Iullemmeden Basin	1991-2015	<75m (<75km from the Niger River)	Updated from Favreau et al., 2009
5	Lake Chad Basin	2006-2011	85m (Maiduguri - vicinity of Lake Chad)	Vasollo, 2017
6	Volta Basin	2006-2011	Shallow piezometer	Lutz et al., 2015
7	Karoo-Carbonate	N/A	N/A	N/A
8	Stampriet Transboundary Aquifer System	1986-2008	Shallow piezometer (<50m)	UNESCO, 2016
9	Karoo Sedimentary	1994-1999	Shallow piezometer (<10m)	IGRAC, 2017

N/A : not applicable

FIGURE CAPTIONS:

Figure 1 – Location of the studied aquifers in Africa

Figure 2 – Groundwater level fluctuation in the studied aquifers

Figure 3 – Normalized observed groundwater $\Delta GWS_{OBSERVED}$ (red), GRACE-based ΔTWS_{GRACE} (blue) and model-based total water storage variability ΔTWS_{MODEL} (green) in the studied aquifers

Figure 4 – Wavelet coherence (WTC) plots in the studied aquifers: **a** Northern Africa and Sahara-Sahel, and **b** Tropical/Equatorial Africa and Southern Africa
(Note: x-axis is date (year) and y-axis is period in years. Correlation coefficients vary from 0 (dark blue) to 1 (light yellow))

5	Senegalo-Mauretanian Basin	N/A	1998 2003	2003 2012
---	----------------------------	-----	---	--

b		Groundwater level / GRACE	Groundwater level / Model	GRACE / Model
6	Volta Basin	2007 2010	2007 2010	2003 2012
7	Karoo Carbonate	N/A	N/A	2003 2012
8	Stampriet Transboundary Aquifer System	2003 2009	1990 2005	2003 2012

9	Karoo Sedimentary	N/A	<p>A vector field plot showing a flow pattern over a triangular domain. The domain is bounded by a vertical line on the left, a horizontal line at the top, and a diagonal line on the right. The x-axis is labeled with 1995 and 1999, and the y-axis with 1 and 2. The plot features a color gradient from blue to yellow, with a central yellow region. A vector field of small arrows is overlaid, indicating a flow that is generally directed downwards and to the right, with a more complex pattern in the central yellow region.</p>	<p>A vector field plot showing a flow pattern over a triangular domain. The domain is bounded by a vertical line on the left, a horizontal line at the top, and a diagonal line on the right. The x-axis is labeled with 2003 and 2012, and the y-axis with 1 and 2. The plot features a color gradient from blue to yellow, with a central yellow region. A vector field of small arrows is overlaid, indicating a flow that is generally directed downwards and to the right, with a more complex pattern in the central yellow region.</p>
---	-------------------	-----	--	---

Figure 5 – Groundwater storage variability and its association with climate teleconnections in Northern Africa (1982-2011): **a** Northern Atlantic Oscillation (NAO) and Atlantic Multi-Decadal Oscillation (AMO) indices, **b** simulated changes in total water storage ($\Delta TWS_{\text{MODEL}}$), and **c** $\Delta TWS_{\text{MODEL}}$ -NAO wavelet coherence plot (see text for description of boxes 1, 2 and 3) (Note: x-axis is date (year) and y-axis in c is period in years)

Figure 6 – Groundwater storage variability and its association with climate teleconnections in the Sahel (1982-2011): **a** Atlantic Multi-Decadal Oscillation (AMO) index and **b** simulated changes in total water storage (ΔTWS_{MODEL})

Figure 7 – Groundwater storage variability and its association with climate teleconnections in Equatorial Africa (1982-2011): **a** Atlantic Multi-Decadal Oscillation (AMO) index and **b** simulated changes in total water storage ($\Delta TWS_{\text{MODEL}}$)

Figure 8 – Groundwater storage variability and its association with climate teleconnections in Southern Africa (1982-2011): **a** El Niño Southern Oscillation (ENSO) index, **b** simulated changes in total water storage (ΔTWS_{MODEL}); and ΔTWS_{MODEL} -ENSO wavelet coherence plots for the **c** Karoo Sedimentary Aquifer and **d** Stampriet Transboundary Aquifer System (Note: x-axis is date (year) and y-axis in **c** and **d** is period in years)

Figure 9 - Groundwater storage variability and its association with climate teleconnections in the Sahel (1982-2011): **a** El Niño Southern Oscillation (ENSO) index, **b** simulated changes in total water storage (ΔTWS_{MODEL}); and ΔTWS_{MODEL} -ENSO wavelet coherence plots for the **c** Nubian Sandstone Aquifer System and **d** Senegalo-Mauritanian Basin Aquifer (Note: x-axis is date (year) and y-axis in **c** and **d** is period in years)

Figure 10 – Groundwater storage variability and its association with climate teleconnections in Equatorial Africa (1982-2011): **a** El Niño Southern Oscillation (ENSO) index, **b** simulated changes in total water storage (ΔTWS_{MODEL}); and ΔTWS_{MODEL} -ENSO wavelet coherence plots for the **c** Volta Basin Aquifer and **d** Karoo Carbonate Aquifer
(Note: x-axis is date (year) and y-axis in **c** and **d** is period in years)

Figure 11 – Groundwater storage variability and its association with the Indian Ocean Dipole (IOD) index in Eastern Africa (1982-2011): **a** Indian Ocean Dipole (IOD) index, **b** simulated changes in total water storage (ΔTWS_{MODEL}); and ΔTWS_{MODEL} -IOD wavelet coherence plots for the **c** Nubian Sandstone Aquifer System, **d** Karoo Carbonate Aquifer and **e** Karoo Sedimentary Aquifer
(Note: x-axis is date (year) and y-axis in **c**, **d** and **e** is period in years)