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ANALYSIS OF TERRESTIAL WATER STORAGE VARIATION OVER WEST AFRICA USING GRACE SATELLITE DATA

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ABSTRACT

GRACE-gridded monthly data for 2006 and 2015 was acquired to carry out spatial-temporal analysis of Terrestrial Water Storage (TWS). This analysis was carried out with a view to estimating and assessing the total water storage change between the two dates. The data was post-processed for north-south trending errors, glacial isostatic adjustments and other non-hydrological effects; the time-variable gravity fields were then converted to TWS variations. Multiband raster data for 2006 and 2015 were created by using composite bands function in ArcGIS 10.5 and re-projected to World Geodetic System (WGS) 1984. Water storage trends were generated by fitting a time series using least squares methods to determine the slope at each grid value and re-sampled to bilinear interpolation. The TWS for 2006 varies from – 10.58 mm to 47.14 mm with the mean and standard deviation of 9.86 mm and 10.10 mm respectively. While the spatial variability in TWS for 2015 ranges between - 27.51 mm and 64.03 mm, with 17.54 mm and 20.73 mm as the mean and standard deviation. The water thickness change between 2006 and 2015 over West Africa varies between -43.36 mm and 56.29 mm, having 7.66 and 22.18 as the mean and standard deviation respectively.
The study concluded that variable water storage change in terms of gain occurred across the central portion of West Africa trending east-west direction and to the south, while mutable storage deficit took place at north-east, south-east, south-west and north-west between 2006 and 2015.

1.0 INTRODUCTION

The time variable nature of the Earth system is of utmost importance to the study of the climate and land surface processes. One area of note is the variation of the water cycle; especially its seasonal and long term evolution. However, climate variability and climate change exert a considerable impact on water storage variability particularly with a distinct trend s over West Africa. Satellite gravimetry remains the only technique that provides information on the total water storage change at continental scales. Terrestrial water storage (TWS) is defined as vertically integrated water of all forms above and below the Earth's surface (e.g. surface water, soil moisture, groundwater, and snow and ice) (Famiglietti, 2004). It is not only a key control of global water, energy, and biogeochemical cycles but also provides an integrated indicator of water availability and uses (Lettenmaier and Famiglietti, 2006; Houborg et al., 2012; Long et al., 2013; Voss et al., 2013; Thomas and Famiglietti, 2015). The ability to estimate TWS is useful for understanding past events and predicting future changes in the hydrological cycle, stream-flow and water availability, as well as their impact on the occurrence of droughts, heat waves, and floods (Hirschi et al., 2007).

In spite of its manifold importance, water storage has not been adequately measured at continental scale (Lettenmaier and Famiglietti, 2006). The dearth of direct observations of large scale water storage estimates was resolved by the launch of Gravity Recovery and Climate Experiment (GRACE) in March 2002, as a joint project between the National Aeronautics and Space Administration (NASA) and the German Aerospace Center (DLR) and it collects unprecedented information about the earth from space. The mission consisted of twin satellites, launched into the polar orbit and separated along track by a distance of 220 km at an altitude of 500km. Electromagnetic Spectrum components include a K-band microwave ranging system, accuracy within 10um, accelerometers, and various positioning systems (NASA, 2002). Analysis of data provided by these systems makes it possible to determine variations in the earth's gravitational field. Of the total mass of the earth, water makes up 0.02%, and as the water moves about the planet, this mass variation is picked up by GRACE satellites, making it possible to determine variations in the equivalent water thickness on a gridded map of the earth. The fields of equivalent water heights (EWH) are estimated following the method used by Wahr et al. (1998). EWH derived from GRACE products represent TWS changes which account s for all state of the storage compartments. GRACE satellite provides new gravity data that can be used to monitor terrestrial water storage changes (TWSC), which is vertically divided into five parts: groundwater, soil moisture, surface water, snow/ice water and biological water storage (Strassberg et al., 2009).

Therefore the aim of this study is to use GRACE data to estimate and evaluate total water storage dynamics spatially and temporally, characterizing its variability across West Africa. The results of the study was used to augment the existing knowledge on water storage and can help to allocate water use, prepare regions for floods and drought, assess the rate of glacial melt, and monitor the global climate.

1.1 STUDY AREA

West Africa lies between latitudes 4°N and 28°N and longitudes 16°W and 15°E. It includes 16 countries (Figure 1): Benin, Cape Verde, Gambia, Ghana, Guinea, Guinea-Bissau, Ivory Coast, Liberia, Mali, Mauritania, Niger, Nigeria, Senegal, Sierra Leone, Togo and Upper Volta. It has an area of 6 million km2 covering one fifth of Africa. The study area is bounded in the south by Gulf of Guinea, while to the north is the northern boundary of Mauritania, Mali and Niger. The Mount Cameroon/Adamawa Highlands and the Atlantic Ocean form the eastern and western limits.

West Africa has wet and dry seasons resulting from the interaction of two migrating air masses. The first is the hot, dry tropical continental air mass of the northern high pressure system, which gives rise to the dry, dusty, harmattan winds that blow from the Sahara over most of West Africa from November to February. The maximum southern extension of this air mass occurs in January between latitudes 5^0 and 7^0 N. The second is the moisture-laden tropical maritime or equatorial air mass, which produces southwest winds (Nicholson, 2000). The maximum northern penetration of this wet air mass is in July between latitudes 18^0N and 21^0 N. The region where these two air masses meet is a belt of variable width and stability called the Intertropical Convergence Zone (ITCZ). The north and south migration of this ITCZ, which follows the apparent movement of the Sun controls the climate.

2.0 MATERIALS AND METHODS

2.1 DETERMINATION OF WATER BUDGET

The GRACE satellites provide monthly estimates of the Earth's gravity field at a 400 km spatial resolution at the equator (Wahr et al., 1998; 2004; Tapley et al., 2004) and was used to compute the estimates of total water storage anomalies (TWSA). It has a major advantage in that it senses water stored at all levels. Hence, the total water storage (TWS) is a vertical sum of all water storage. TWS variations observed by GRACE include the combined contributions of changes in snow water equivalent anomalies (SWEA), surface water anomalies (SWA) from lakes, reservoirs and rivers, soil moisture anomalies (SMA), vegetation canopy anomalies (VWA) and groundwater anomalies (GWA). As an integrated measure of surface and groundwater availability, total water storage anomalies (TWSA) can also be expressed as terrestrial water storage anomalies (TWSA). Therefore, it has significant implications for water resources management (Syed et al., 2005). Unlike radars and radiometers, it is not limited to measurement of near-surface phenomena.

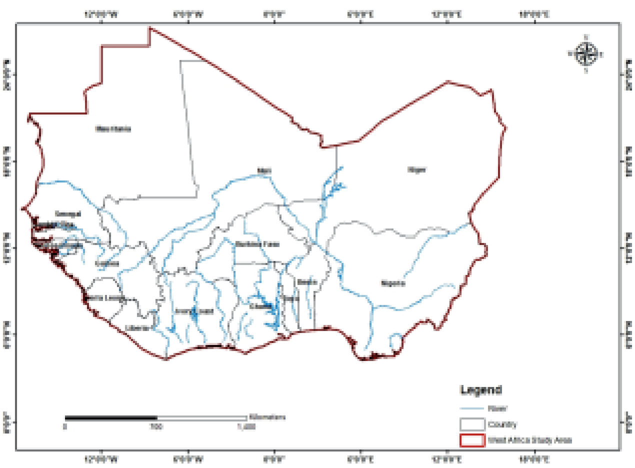

Figure 1: Map of West Africa showing Countries and Major Rivers

$$TWSA_t = SWEA_t + SWA_t + SMA_t + VCA_t + GWA_t \quad (1)$$

Where t = time of data acquisition.
Storage anomaly is the residual storage content at a given time with respect to the content at a reference epoch. Then storage change is the difference between storage anomalies of any two successive time steps (Moiwo et al., 2011).

2.2 GRACE DATA

In order to investigate the terrestrial water storage change (TWSC) between January 2006 and December 2015, this study utilized gridded terrestrial water storage (TWS) monthly estimates derived from temporal gravity field variations observed by the GRACE satellites; data was provided by the Centre for Space Research (CSR) at the University of Texas, Austin. The GRACE data was post-processed for north-south trending errors, glacial isostatic adjustments and non-hydrological effects. Hence, combination of constraint and truncation were applied to stabilize the attenuation of real geophysical signals as a result of post-processed methods. The post-processed time-variable gravity fields were then converted to equivalent water heights also referred to as terrestrial water storage (TWS) variations. Monthly GRACE solutions for 2006 and 2015 were stored in ArcGIS database. The composite bands function was used to compile and create global multiband rasters for 2006 and 2015 GRACE data. To reduce the computation processing time, shapefile representing West Africa study area was used to subset the global data. The multiband raster was re-projected to World Geodetic System (WGS) 1984. Gridded water storage trends were generated by fitting a time series using least squares methods to produce TWSA for 2006 and 2015. The general least square process was broken down as shown in equation 2:

$$\frac{1}{t_1^2 + t_2^2 + ... + t_n^2} (t_1 y_1 + t_2 y_2 + ... + t_n) \quad (2)$$

Where, t is a time value (in this case each month), y is the data value (the value of equivalent water height in each cell), and the subscript shows the associated raster band. These computations were performed cell by cell to determine the slope at each grid value and re-sampled to bilinear interpolation. Zonal statistics tool in ArcGIS 10.5 was then used to estimate the mean and standard deviation.

3.0 RESULTS AND DISCUSSION

The TWS for 2006 varies from – 10.58 mm to 47.14 mm (Figure 2) with the mean and standard deviation of 9.86 mm and 10.10 mm respectively. It shows the time and spatial variation of the gravity force of the earth measured in equivalent (mm) of water depth on the earth's surface, termed the total water storage or terrestrial water storage (TWS) (Andersen et al., 2005) i.e. changing pattern of TWS anomalies over West Africa. It demarcates the gain and loss of water on the earth's surface and subsurface as the result of endless dynamic force of global water redistribution across the globe between the land and the oceans.

Therefore, Figure 2 delineates increasing trends in water storage at the southeastern and southwestern of the study area (4.42 mm to 47.14 mm). The southeastern water storage gain of West Africa for 2006 consists of north-central, north-east, south and south-east of Nigeria while the southwestern encapsulate Guinea-Bissau, major part of Guinea and Sierra Leone. The decreasing water storage depletion (4.42 mm to -10.58 mm) in the northern, southern, northeastern and northwestern zones consist of Mali in the north, east of Ivory Coast, Ghana, Togo and southern of Benin and Burkina Faso in the south and central, Niger in the north-east, and Mauritania in the north-west of the study area.

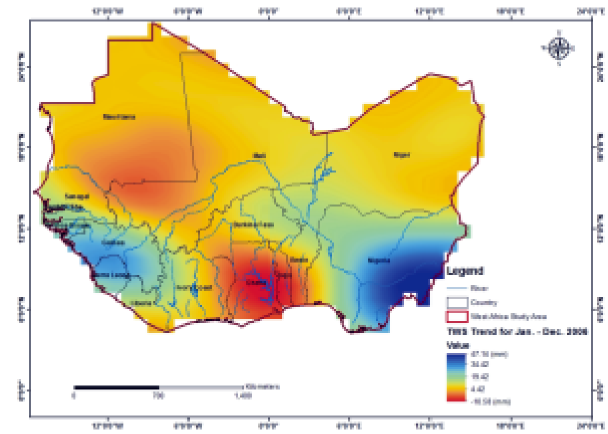

Figure 2: Spatial Variability of TWS Linear Trend for 2006

The spatial variability in TWS for 2015 (Figure 3) ranges between - 27.51 mm and 64.03 mm with 17.54 mm and 20.73 mm as the mean and standard deviation. Figure 3 shows increase in water storage (-2.51 mm to 64.03 mm) across the central portion of West Africa, trending east to west which covers north-east and North central of Nigeria. Other countries it traverses along this orientation are Burkina Faso, south-west of Mali, Guinea, Guinea-Bissau, Senegal and southern parts of Ivory Coast and Ghana. While storage water depletion (-2.51 mm to -27.51 mm) (Figure 3) begins from northern parts of Mauritania, Mali and Niger to Sierra Leone, Liberia, central part of Ghana, south of Togo, north of Benin and south-west, south, south-east and extreme north-east of Nigeria.

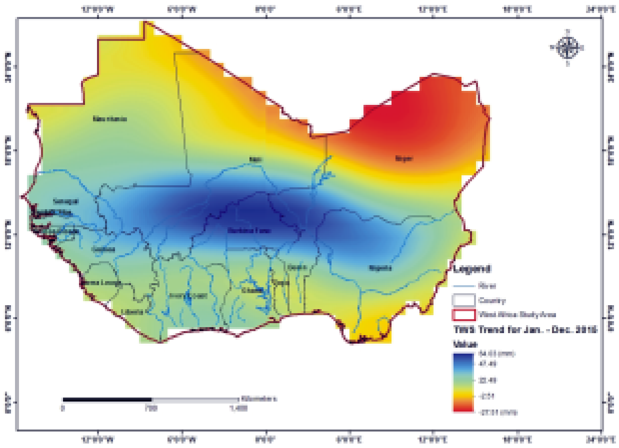

Figure 3: Spatial Variability of TWS Linear Trend for 2015

Therefore, the gain and loss in water storage variation observed in Figures 2 and 3 is attributed to the complex dynamic force of global water redistribution across the globe under the influence of gravitational force as measured by GRACE satellite (Swenson and Wahr, 2006).

Figure 4 shows the GRACE-derived water thickness change between 2006 and 2015 over West Africa. It varies between -43.36 mm and 56.29 mm having 7.66 mm and 22.18 as the mean and standard deviation respectively. Increasing proportion of water storage change (-13.36 mm to 56.29 mm), as being the integrated vertical sum of waters below and above the earth surface in terms of gain, occurred at Senegal, southern end of Mauritania, south-west of Mali, Burkina Faso, east of Ivory Coast, Ghana, Togo, Benin, and north-west of Nigeria. While changes in water storage loss (-13.86 mm to -43.86 mm) between 2006 and 2015 occurred in the following countries: Guinea-Bissau, major part of Guinea, Sierra Leone, north of Liberia, extreme west of Ivory Coast, northern parts of Mauritania, Mali and Niger, and south and south-east region of Nigeria. Similar experience have been reported by Papa et al. (2008), Grippa et al. (2011), Nahmani et al. (2012) and Ramillien et al. (2014). The depicted gain in water storage change could be indicative of agricultural water saving, soil-pore/aquifer compaction or recharge, and probably flooding in areas of medium to high precipitation. While, storage depletion in the region could have negative implications for the fragile wetland ecosystem, agriculture, people's livelihood, and at times drought or heat wave in a region of low precipitation. There is possible soil-pore collapse, and land subsidence due to storage depletion in the study area. This implies that decision-makers/stake-holders of water resources in the region should focus on water-saving measures on the seasons with storage loss and use the trends to gauge the success of adopted policies/strategies.

CONCLUSIONS

This study investigates the spatiotemporal monitoring of total water storage (TWS) using the Gravity Recovery and Climate Experiment (GRACE) satellite. GRACE-derived TWS for 2006 and 2015 varied between – 10.58 mm to 47.14 mm and -27.51 mm to 64.03 mm respectively. The total water storage surplus and deficit were calculated from the GRACE satellite-measured total water storage change (TWSC) between 2006 and 2015. The surplus varies from – 13.86 mm to 56.29 mm while the deficit varies between -13.86 mm and -43.86 mm.

Therefore, GRACE-derived TWS is the only sensor ever known to mankind that measures the vertical integration of water columns from below and above surface, soil, vegetation canopy and snow across the globe. For the area under study, snow water column is not present. In combination with in situ data, radar altimetry data and land surface models, TWS can be used for global or regional groundwater storage change, drought monitoring, flood characterization and decomposition of hydrological components particularly for poorly gauged region where hydrological data is sparsely available.

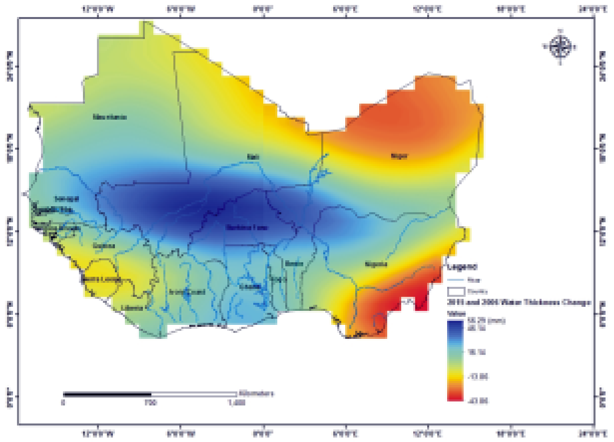

Figure 4: Water Storage Change between 2006 and 2015

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REFERENCES

Andersen, O.B.; Seneviratne, S.I.; Hinderer, J.; Viterbo, P. (2005). GRACE-derived terrestrial water storage depletion associated with the 2003 European heat wave. Geophys. Res. Lett. 2005, doi:10.1029/2005GL023574.

Famiglietti, J. S. (2004). Remote sensing of terrestrial water storage, soil moisture and surface waters, Geophys. Monogr. Ser., 19, 197–207, doi: 10.1029/150GM16.

Grippa, M.; Kergoat, L.; Frappart, F.; Araud, Q.; Boone, A.; de Rosnay, P.; Lemoine, J.-M.;

Gascoin, S.; Balsamo, G.; Ottlé, C. (2011). Land water storage over West Africa estimated by GRACE and land surface model. Water Resour. Res., doi:10.1029/2009WR008856.

Hirschi, M.; Seneviratne, S. I.; Hagemann, S.; and Schär, C.(2007). Analysis of seasonal

terrestrial water storage variations in regional climate simulations over Europe, J. Geophys. Res., 112, D22109, doi: 10.1029/2006JD008338.

Houborg, R.; Rodell, M.; Li, B.; Reichle, R. and Zaitchik, B. F. (2012). Drought indicators based on model-assimilated Gravity Recovery and Climate Experiment (GRACE) terrestrial water storage observations, Water Resour. Res., 48, W07525, doi: 10.1029/2011wr011291

Lettenmaier, D. P. and Famiglietti, J. S. (2006). Hydrology: water from on high, Nature, 444, 562–563.

Long, D.; Scanlon, B. R.; Longuevergne, L.; Sun, A. Y.; Fernando, D. N.; and Himanshu, S. (2013). GRACE satellites monitor large depletion in water storage in response to the 2011 drought in Texas, Geophys. Res. Lett., 40, 3395–3401, doi:10.1002/grl.50655.

Moiwo, J. P.; Yang, Y.; Tao, F.; Lu, W. and Han, S. (2011). Water storage change in the

Himalayas from the Gravity Recovery and Climate Experiment (GRACE) and an empirical climate model. Water Resour. Res. 47, W07521.

Nahmani, S.; Bock, O.; Bouin, M.-N.; Santamaría-Gómez, A.; Boy, J.-P.; Collilieux, X.;

Métivier, L.; Panet, I.; Genthon, G.; de Linage, C. (2012). Hydrological deformation induced by the West African Monsoon. Comparison of GPS, GRACE and loading models. J. Geophys. Res.: Solid Earth, doi:10.1029/2011JB009102.

NASA (2002) GRACE: Gravity Recovery and Climate Experiment. NP-2002-2-427-GSFC.

http://www.csr.utexas.edu/grace/publications/brochure/GRACE_Brochure.pdf.

Nicholson, S.E. (2000). The nature of rainfall variability over Africa on time scales of decades to millenia. Global and Planetary Change, 26:137-158.

Papa, F.; Güntner, A.; Frappart, F.; Prigent, C.; Rossow, W.B. (2008). Variations of surface water extent and water storage in large river basins: A comparison of different global data sources. Geophys. Res. Lett., doi:10.1029/2008GL033857.

Paulson, A.; Zhong, S. and Wahr, J. (2007). Inference of mantle viscosity from GRACE and relative sea level data. Geophys. J. Int. 171, 497–508.

Ramillien, G.; Frappart, F. and Seoane, L. (2014). Application of the Regional Water Mass Variations from GRACE Satellite Gravimetry to Large-Scale Water Management in Africa. Remote Sens. 6, 7379-7405; doi:10.3390/rs6087379

Strassberg, G.; Scanlon, B.R.; Chambers, D. (2009). Evaluation of groundwater storage monitoring with the GRACE satellite: Case study of the High Plains aquifer, central United States. Water Resour. Res., 45, W05410.

Syed, T. H.; Famiglietti, J. S.; Chen, J.; Rodell, M.; Seneviratne, S.I.; Viterbo, P. and Wilson,

C.R. (2005). Total basin discharge for the Amazon and Mississippi river basins from GRACE and a land-atmosphere water balance, Geophys. Res. Lett., 32, L24404, doi:10.1029/2005GL024851.

Swenson, S.C.; Wahr, J. (2006). Post-processing removal of correlated errors in GRACE data.

Geophys. J. Int., doi:10.1029/2005GL025285.

Tapley, B. D.; Bettadpur, S.; Watkins, M.; andReigber, C. (2004). The gravity recovery and climate experiment: Mission overview and early results. Geophysical Research Letters, 31(9). http://doi.org/10.1029/2004GL019920

Voss, K.A.; Famiglietti, J.S.; Lo, M.; de Linage, C.; Rodell, M.; and Swenson, S.C. (2013).

Groundwater depletion in the Middle East from GRACE with implications for transboundary water management in the Tigris-Euphrates-Western Iran region. Water Resour. Res. 2013, 49, 904–914.