Quantifying changes in groundwater storage using water table fluctuation and *GRACE* Satellite data, Mali, Africa

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ABSTRACT
Water level data in three different regions of southern Mali in two major aquifer systems spanning various time periods throughout the 1980s and 1990s were analyzed along with climate data to establish the relationship between groundwater storage and precipitation input. The West African Monsoon influencing southern Mali cycled on decadal timescales in the latter part of the twentieth century, and the country experienced a long period of relative drought over the groundwater monitoring records. Mean annual hydrographs indicate that the magnitudes of annual water table fluctuations are similar (3m) between all three regions. The fractured crystalline basement rock aquifer responds more quickly to recharge in comparison to the sedimentary rocks of the Continental Terminal formations. Annual timing of estimated groundwater storage fluctuations in the three regions correlate strongly to GRACE satellite total water storage variability spatially averaged over a larger area; however, the magnitude of groundwater storage flux using a specific yield characteristic of weathered crystalline formations in Uganda (0.23) was too high. Based on these analyses, a specific yield of 0.075 is more representative for the regional aquifers.

RÉSUMÉ
Des données de niveau des eaux souterraines dans trois régions différentes du Mali méridional dans deux systèmes principaux d'aquifère pour diverses périodes de temps durant les années 80 et les années 90 ont été analysées avec des données de climat pour établir le rapport entre le stockage d'eaux souterraines et l'entrée des précipitations. La mousson africaine occidentale influençant le Mali méridional a fait un cycle d'une décennie dans la dernière partie du vingtième siècle, et le pays a connu une longue période de relative sécheresse qui s'est manifestée au niveau des historiques de surveillance des eaux souterraines. Les hydrographes annuels moyens indiquent que les fluctuations annuelles de la nappe sont semblables (3 m) entre chacune des trois régions. L'aquifère roc fracturé cristallin répond plus rapidement à la recharge par rapport aux roches sédimentaires des formations continentales terminales. La synchronisation annuelle des fluctuations estimées du stockage des eaux souterraines dans les trois régions se corrèle fortement à la variabilité totale des stockages d'eau moyennée sur une surface plus grande observée par le satellite GRACE. Cependant, l'importance du flux de stockage d'eaux souterraines en utilisant une porosité efficace caractéristique des formations cristallines érodées en Ouganda (0.23) était trop forte. Basé sur ces analyses, une porosité efficace de 0.075 est plus représentative pour les aquifères régionaux.

1 INTRODUCTION

Groundwater demand in many African nations is greatly increasing due to a number of factors. Inadequate sanitation has led waterborne diarrheal and other enteric illnesses to become the leading cause of death on the continent, accounting for over 40% of all child deaths in the Sub-Saharan region (McMurray, 2007). Many African nations are experiencing rapid population growth as well, as 28 of the continent's countries do not have much needed family planning policies to address this (Rosen and Conly, 1998). The increasing price of oil, loss of arable land to development, and conversion of food crops to biofuel production crops are causing food prices to soar on a global basis (United Nations World Food Programme, 2008), creating a desperation for countries to become self-sufficient with respect to food supply. However, in Africa's drought prone regions, crops are not dependable, which increases reliance on groundwater for irrigation where agriculture already accounts for (by far) the highest groundwater usage (Rosegrant and Perez, 1997).

Climate change is predicted to exacerbate demands placed on groundwater by increasing drought frequency and altering precipitation and temperature patterns (Calow et al., 1997; Intergovernmental Panel on Climate Change (IPCC), 2007). In West Africa, where the study region is situated, temperatures are expected to rise by 3-4ºC from 1900-1950 normals by the end of the century (Figure 1), which is 1.5 times the predicted global mean response to climate change (Christensen et al., 2007). The IPCC expresses less confidence for precipitation models of this region compared to other regions of Africa; however, six downscaled Global Climate Model's predict a reduction of mean monthly precipitation in the 0-80mm range (Christensen et al., 2007).

The need for aquifer characterization and resource assessment is obvious under the increasing pressure placed on groundwater resources; however, many developing regions, and particularly arid and semi-arid ones (de Vries and Simmers, 2002), suffer from inadequate monitoring. Hydrogeologic research tends to be highly localized and discontinuous (de Vries and Simmers, 2002) due to the fact that internationally sponsored studies are often funded for short time periods.

This paper presents a case study of Mali, West Africa, which is rated as the fourth poorest nation in the world (United Nations, 2008) and suffers from the monitoring challenges mentioned above. Water level data spanning several Malian regions and time-periods are compared with available climate data to characterize the relationship between water table response and precipitation input. Estimated storage variabilities from the in situ observations are also compared with total water storage variation obtained from the **G**ravity **R**ecovery and **C**limate **E**xperiment (GRACE) satellites in an attempt to quantify annual and long term trends in groundwater storage. The GRACE satellites have been successfully correlated to groundwater storage estimates - and have been used to estimate groundwater storage changes themselves - in several large basins in recent years, including the High Plains Aquifer, the Mississippi River basin, and the Amazon River Basin (Strassberg et al., 2007; Rodell et al., 2007; Zeng et al., 2008). GRACE measures anomalies in the Earth's gravitational field that are primarily attributed to changes in terrestrial water storage, including snow, ground, soil, and surface water. Satellite based monitoring methods may be more feasible in developing regions where there is often a lack of capacity at the country level to initiate and maintain groundwater information systems due to economic and/or other constraints.

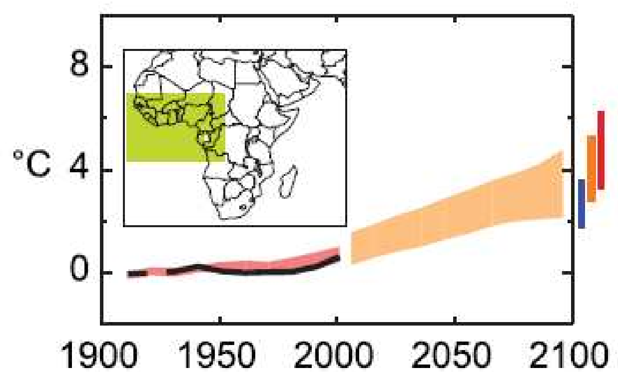

Figure 1. Predicted temperature anomalies in West Africa with respect to 1901-1950 values: observed temperatures (black line), and simulated 20th (red envelope) and 21st (orange envelope) century temperatures (IPCC, 2007). Bars on right y-axis indicate range of three different simulations. (From: reference, date)

2 STUDY AREA

2.1 Mali

Mali is a large land-locked country in Western Africa, sharing borders with Mauritania, Algeria, Niger, Burkina-Faso, Cote D'Ivoire, Guinea, and Senegal (Figure 2). Climate varies greatly from sub-tropical conditions in the south to desert conditions in the north. Climate in the north is characterized by a hot and dry tropical continental air mass, while climate in the rest of the country is determined by the interaction between this hot and dry air mass with a humid maritime mass originating from the Atlantic and associated with south-westerly winds (United Nations, 1988). The latter is referred to as the West African monsoon, which determines Malian precipitation; the zone of discontinuity between the two air masses is the Inter Tropical Convergence Zone (United Nations, 1988). Mean annual cumulative precipitation ranges from less than 50mm in the extreme north to over 1500mm in the southwest (Coulibaly, 2004), though the 100mm isohyets have been migrating south since 1960 (UNESCO, 2006). The rainy season can last up to 7 months (April to October) in the south or less than two in the north, with July, August, and September having the heaviest precipitation in most regions (Coulibaly, 2004). Mean annual air temperatures range from 26.4ºC in Sikasso to 29.2ºC in Tomboctou. From south to north four principle ecological zones can be identified: i) the West Sudanian Savanna consisting of tropical and sub-topical grasslands, savannas, and shrublands; ii) the Sudano-Sahelian Savanna consisting of tropical and subtropical grasslands; iii) the Southern Saharan Steppe and Woodlands consisting of desert and xeric shrublands; and iv) the Saharan Desert to the extreme north (United States Geological Survey, 2003).

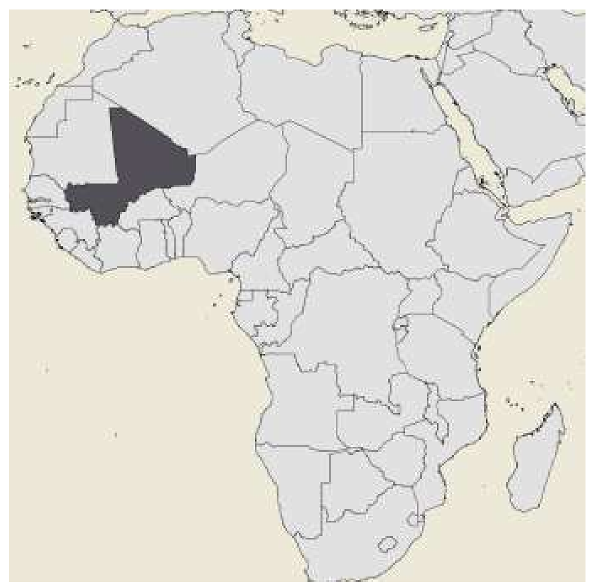

Figure 2. Location map showing Mali in darkened grey.

The vast majority of Mali falls within the Taoudeni Basin geologic province, with only the extreme southern tip occupying the West African Shield. There is little topographic relief over most of the country. Lows occur in the Sahara to the north and Bafing valley along the Senegalese border; outside these two regions elevation ranges only between 250-500m above sea level (Coulibaly, 2004). Much of Mali is located within two major drainage basins – those of the Niger and Senegal Rivers (Coulibaly, 2004). These basins encompass 570 000km^2 and 155 000km^2 respectively, and together drain 70 billion m^3 of water in an average year (UNESCO, 2006; Coulibaly, 2004).

2.2 Southern Mali

The water level data obtained from the Direction Nationale de l'Hydraulique consist of 27 well records scattered throughout the country; however, the most complete records are for wells clustered around three regions in southern Mali.

These three regions are north of Bamako, Bougouni to the south of Bamako, and San to the east (Figure 3). The geological setting of the San and north of Bamako regions is that of the Continental Terminal formation. These are weakly cemented sands and sandy-clays of Tertiary (Neogene) age with some lateritised horizons, and may include sandstone, shales and marls (United Nations, 1988; British Geological Survey, 2002). Pyrite and lignite are common in this sequence. Generally the deposits are quite shallow (several tens of metres thick), though in the Iullemeden Basin of south east Mali they exceed 1000m (United Nations, 1988; British Geological Survey, 2002). The Continental Terminal is in good hydraulic contact with overlying Quaternary alluvial deposits, creating unconfined or semi-confined aquifers depending on the clay content of the sediments (United Nations, 1988; British Geological Survey, 2002).

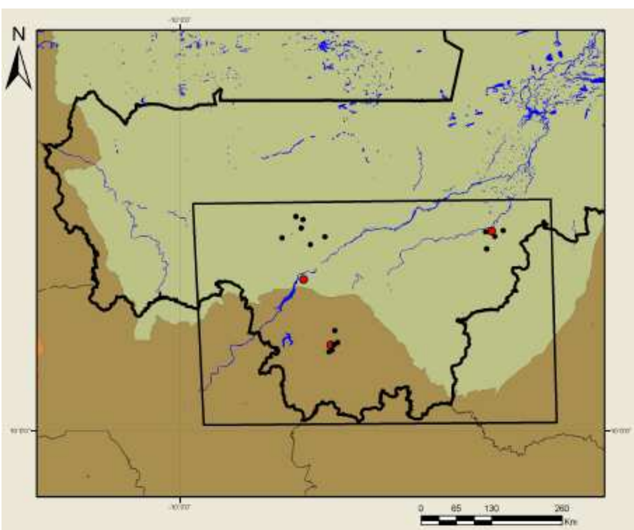

Figure 3. Southern Mali showing the cities (red) of Bamako (center), Bougouni (south), and San (east) with the corresponding clusters of wells (black). The box outlines the region for which GRACE satellite data were obtained.

Groundwater of the Bougouni region is present in the weathered fractured crystalline Precambrian (Birrimean) basement and regolith (United Nations, 1988; British Geological Survey, 2002). Dominant rock types include granites, schists, micaschists, and graywackes. Groundwater is more abundant where overburden is thickest and water level variations are large (United Nations, 1988; British Geological Survey, 2002). Productivity in the basement rocks is highly variable, and they are also either unconfined or semi-confined depending on the overlying Quaternary deposits (United Nations, 1988; British Geological Survey, 2002).

3 DATA AND METHODOLOGY

Climate data (mean monthly temperature and precipitation) were obtained from the Royal Netherlands Meteorological Institute (KMNI) for 10 climate stations throughout Mali. Only the three nearest stations to the wells of interest for this study are considered here. Cumulative annual rainfall standardized to the means i) over the entire length of the record; and ii) over the length of the relevant well records were calculated to characterize long term precipitation trends and shorter term water level response. Mean monthly accumulations were used only over the length of the corresponding well record to generate the mean annual hydrographs. A summary of the climate stations used in this study is presented in Table 1.

Table 1. Summary of climatic records.

Station	Record	Mean Annual Rainfall (mm)
Bamako	1919-1996	1009
Bougouni	1921-1996	1210
San	1922-1993	725

The periods of record for the water level data for the 27 vary both between and within regions (Table 2), because monitoring was carried out as part of localized studies sponsored by various international organizations. They also vary significantly in completeness. Some wells were measured up to 20 times a month, while other wells were sporadically monitored (there may be several months without a measurement). Due to this lack of consistency in the periods of record, the wells selected for this study are those that are most representative of each region and have the most complete records.

Mean annual hydrographs were generated by determining the average water level for each month of a specific year on record, and then averaging these average monthly values for all years to establish a mean level over the period of record for that well. Water storage anomalies were computed as the difference between the measured water level and a weighted mean water level for that location, and multiplied by an estimated specific yield according to the method by Rodell et al., 2007. Mean water levels at each location were weighted according to the mean annual hydrographs for the period of record, as in some months far more measurements were taken (in most instances measurement frequency was higher in the rainy season than the dry season). The estimated specific yield was 0.23 $\pm$ 0.05, which was determined from pumping test analyses in weathered crystalline basement rocks in Uganda (R. Taylor, personal communication).

Storage anomalies were plotted as monthly averages for the period of record, and the magnitude of variability compared to the total water storage variation shown by GRACE. It is important to note that the time series for the hydrographs do not coincide with the GRACE data and that this is a limitation of the study. The implications of the mis-matched times series is discussed later. Finally, Sy values were adjusted to provide a better calibration to observed GRACE data for the entire region.

GRACE satellite data were obtained for an area of -3 to -10ºW and 10 to 14ºN as shown in Figure 3 from April 2002 to January 2008. The data show the variation in total water storage (including ground, soil, and surface water) spatially averaged over the grid from the mean total water storage over the time period. The GRACE data were obtained from Natural Resources Canada.

Table 2. Summary table of wells in the three regions including period of record, elevation, water level range, and geological setting. CT Continental Terminal; BIR Birrimean Crystalline Basement.

Well ID	Region	Record	Elevation (masl)	Range (masl)	Geologic Setting
2125841	N. Bamako	Sep 84 - Sep 87	390	378.3 - 382.2	CT
2149415	N. Bamako	Jan 84 - Dec 94	340	319.7 - 326.3	CT
2537166	N. Bamako	Jul 89 - Jul 94	395	380.1 - 385.6	CT
2601388	N. Bamako	Mar 87 - Aug 92	405	388.5 - 390.7	CT
2601793	N. Bamako	Jun 85 - Aug 95	405	384.1 - 389.0	CT
2601829	N. Bamako	Jan 83 - Jul 95	444	419.9 - 427.6	CT
3201097	Bougouni	Oct 84 - Dec 95	340	324.0 - 328.4	BIR
3201133	Bougouni	Oct 84 - Dec 91	340	322.4 - 329.9	BIR
3201325	Bougouni	Mar 84 - Dec 95	355	345.0 - 351.8	BIR
3201457	Bougouni	Aug 81 - Mar 91	365	354.2 - 361.3	BIR
3201469	Bougouni	Aug 81 - Mar 91	325	314.1 - 323.3	BIR
4601000	San	Apr 86 - Oct 88	248	239.5 - 244.9	CT
4601794	San	Jan 89 - Jan 91	277	264.9 - 265.4	CT
4649324	San	Jul 85 - Jan 91	280	270.2 - 277.0	CT
4673622	San	Oct 85 - Jan 91	280	270.2 - 276.2	CT

4 RESULTS

4.1 Long Term Climate Trends

Standardized cumulative annual rainfall at Bamako, Bougouni, and San records are shown in Figure 4. Early in the 20th century (pre-1940) the three regions do not correlate well. In Bamako, rainfall cycles between relatively wet and dry periods on a 5 year basis (Figure 4a), while rainfall in San alternates between wet and dry almost yearly (Figure 4c). During this time, in Bougouni the majority of years experienced heavy accumulation (Figure 4b).

However, in the latter half of the 20th century similar long term patterns can be observed in all three regions. Throughout the 1950's and early 1960's most years are quite wet, while in the 1970's through the early 1990's (the period of groundwater monitoring) all three regions experienced drought (Figure 4). Such long term cycling is characteristic of the West African Monsoon, though the mechanism which causes it is poorly understood (Le Barbe et al., 2002). The Asian Monsoon is generally much more resilient to drought than West Africa, as India has never experienced more than two consecutive years of drought; conversely, the 20 year drought shown in Figure 4 was observed over much of the Sahel and Sub-Sahel (Le Barbe et al., 2002).

Data for the most recent time period (spanning 1995 to 2008) were not reported for these stations, however more recent data suggests precipitation over West Africa has been alternating between relative wet and dry years since 1997 (Rowell, 2003).

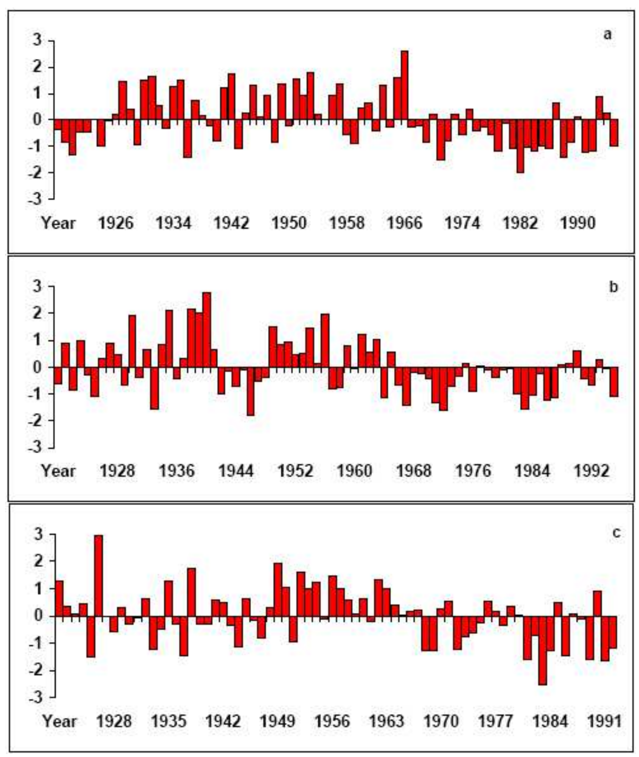

Figure 4. Standardized cumulative precipitation for Bamako (a), Bougouni (b), and San (c).

4.2 Annual Water Level Response

Mean annual hydrographs were compared with mean monthly rainfall over the corresponding monitoring periods for each of the three regions (Figure 5). The magnitude of annual water level fluctuation is similar for each of the three regions (3m); however, there are notable differences in water level response. The region north of Bamako reaches a groundwater level low in June (Figure 5a), while east near San the low occurs one month earlier - in May (Figure 5c).

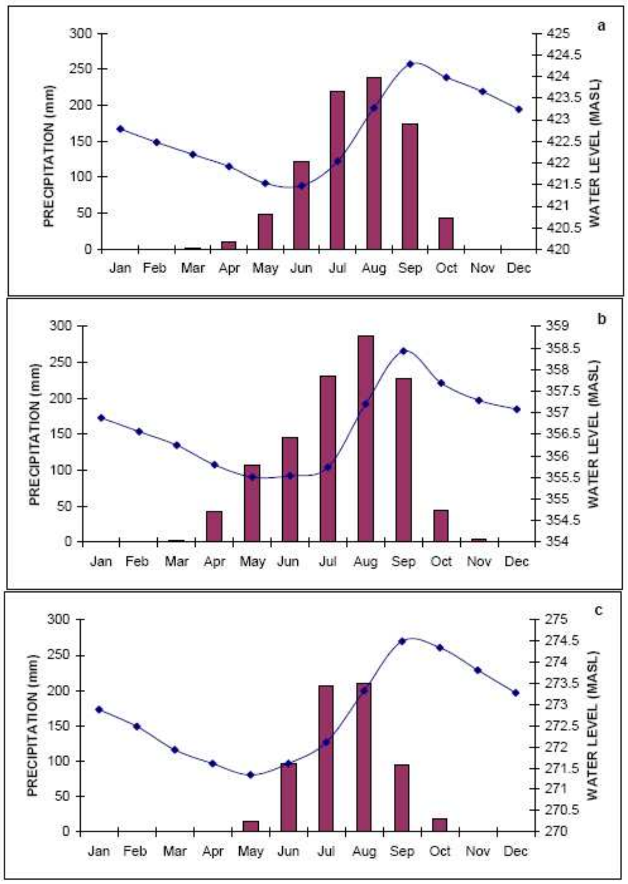

Figure 5. Mean monthly water levels and rainfall for well 2601829 (N. Bamako; a), 3201457 (Bougouni; b), and 4649324 (San; c). Climate records spanned 1983-1994 (a), 1981-1991 (b), and 1985-1990 (c).

All three regions reach their water level peak in September, though the lengths of time over which they are recharging or draining are different. North of Bamako and near San water levels start to rise in June and May, respectively (Figures 5a and 5c). Recharge occurs through September and the Continental Terminal aquifer drains gradually throughout the remainder of the year. The recharge period in the Bougouni region is much shorter, occurring as a steep water table rise from July to September (Figure 5b). Drainage (recession) starts rather quickly after water levels peak, and proceeds more slowly throughout the rest of the year. The hydrograph also indicates that the weathered crystalline basement aquifer sustains a longer period of water table lows; nearly 4 months long spanning April to July (Figure 5b).

These observations suggest a clear difference in the recharge characteristics of the two aquifer formations. In particular, the Birrimean crystalline basement aquifer exhibits a delayed recharge relative to the onset of the rainy season in comparison to the other two regions (situated in the Continental Terminal formation). However, the response is quite rapid when it does occur. This rapid response is much more pronounced in the full time series, and is particularly evident over the longer periods of record for Bougouni wells (see Table 2).

The reason for the differences in response time are likely associated with the different hydraulic properties of the formations; with the Birrimean crystalline basement likely having different fracture characteristics compared to those of the Continental Terminal formation. As well, the role of primary permeability cannot be ruled out as a contributing factor given that the Continental Terminal formation is comprised of weakly cemented sedimentary rocks. It is not uncommon for fractured aquifers to respond quickly to recharge and discharge cycles in comparison to porous aquifers. Field observations of outcrop and fracture mapping in combination with hydraulic testing of wells may provide an explanation.

4.3 Ground and Satellite Water Storage Anomalies

The estimated monthly groundwater storage anomalies using an assumed specific yield value for crystalline rock (Sy = 0.23) and total water storage variation determined by GRACE are shown in Figure 6.

Timing of yearly storage changes at each of the three local sites (Figure 6b) corresponds very well to the timing of total fluctuations spatially averaged over the whole region (i.e., from GRACE), with lowest storage values occurring in May-June and peak storage values in September-October in both datasets (Figure 6a). The magnitude of storage flux and yearly timing of anomalies between the three regions also correlates well, with a few differences attributed to local differences in precipitation inputs. When cumulative annual rainfall is standardized over well periods of record (rather than the climate station periods of record) the abnormally high or low storage anomalies are accounted for. The good correlation amongst the three regions in Figure 6b suggests recharge mechanisms are not all that dissimilar between the two major aquifer types.

The GRACE satellite results yield an average annual fluctuation of total terrestrial water storage of 236 mm over the years 2002-2007 (Figure 6a), while the estimated average annual variation in groundwater storage in the north-of-Bamako, Bougouni, and San regions over the relevant time periods are 713 mm, 697 mm, and 770 mm, respectively using an estimate of Sy=0.32 (Figure 6b). This value of Sy is based on well testing in weathered crystalline basement aquifers in Uganda (R. Taylor, personal communication) and appears not to be representative for the Continental Terminal and Birrimean crystalline aquifers of southern Mali. If the mean storage anomalies of the three regions are averaged (727 mm), then using an estimated specific yield of 0.23 the mean annual variation of the water level between the three regions is 3159 mm (or 3.16m), which is in agreement with the average water level fluctuation of approximately 3m observed throughout the region (see Figure 5). Dividing the GRACE storage variability (236 mm) by this value (3159 mm), a specific yield of 0.075 is obtained, which is generally consistent with the range of values for bedrock (e.g., Woodard et al., 2002). This specific yield value, however, remains uncertain and would benefit from hydraulic testing of wells within the study region.

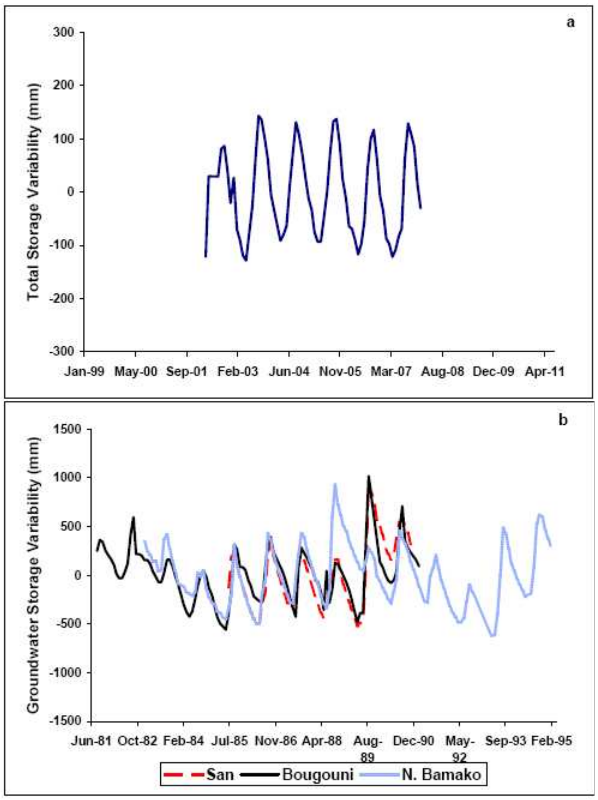

Figure 6. Monthly water storage variability determined by (a) GRACE satellite data and (b) estimated monthly groundwater storage anomalies for wells 2601829 (N. Bamako), 3201457 (Bougouni), and 4649324 (San).

Also, as noted earlier, the period of record for the well hydrographs does not coincide with that of the GRACE data. The periods of record for groundwater level monitoring span a period of drought, which appears to continue to present; therefore, it is likely that the GRACE data are reasonably representative. Nonetheless, we hope to obtain concurrent water level observations for the southern Mali region. It is our understanding that some wells have been monitored during the period for which GRACE data are available. These data are not held by the DNH of Mali, but rather with a Swiss research team. Our future work with the GRACE data will hopefully make use of these additional data.

Future work will also attempt to model recharge specifially to estimate the soil water storage, which is incorporated in the GRACE data. Discharge data for the Niger River and its major tributaries running through the GRACE grid will also need to be considered.

5 CONCLUSIONS

Cumulative rainfall recorded at three representative climate stations in southern Mali (Bamako, Bougouni, and San) show evidence of the West African Monsoon with cycles on decadal timescales in the latter part of the twentieth century. During the period of record for which groundwater level data are available, the country experienced a long period of relative drought that persists to the present day. Mean annual hydrographs indicate that the magnitudes of annual water table fluctuations are similar (3m) between all three regions. The fractured crystalline basement rock aquifer responds more quickly to recharge in comparison to the sedimentary rocks of the Continental Terminal formations, and point to differences in the hydraulic properties of these aquifers. Annual timing of estimated groundwater storage fluctuations in the three regions correlate strongly to GRACE satellite total water storage variability spatially averaged over a larger area. The magnitude of groundwater storage flux suggests that a specific yield on the order of 0.075 may be representative of these aquifers.

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