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Local and global hydrological contributions to time-variable gravity in Southwest Niger

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GJI Gravity, geodesy and tides

SUMMARY

Advances in methods of observation are essential to ensure a better understanding of changes in water resources considering climate variability and human activities. The GHYRAF (Gravity and Hydrology in Africa) experiments aim to combine gravimetric measurements with dense hydrological surveys to better characterize the annual water storage variability in tropical West Africa. The first absolute gravimetric measurements were performed in Southwest Niger, near a temporary pond where rapid infiltration to an unconfined aquifer occurs. As gravity is sensitive both to local and global variations of water mass distribution, the large-scale hydrological contribution to time-variable gravity has been removed using either GRACE satellite data or global hydrology models. The effect of the local water storage changes was modelled using *in situ* measurements of the water table, soil moisture and pond water level. The adjustment of these simulations to residual ground gravity observations helped to constrain the specific yield to a value ranging between 1.8 and 6.2 per cent. This range of value is consistent, albeit on the low side, with the aquifer water content (6–12 per cent) estimated by magnetic resonance soundings, which are known to slightly overestimate the specific yield in this geological context. The comparison of these two independent geophysical methods shows their potential to constrain the local hydrogeological parameters. Besides, this study evidences the worth of correcting the gravity signal for large-scale hydrology before recovering local water storage parameters.

Key words: Satellite geodesy; Time variable gravity; Hydrology; Permeability and porosity; Africa.

1 INTRODUCTION

The evaluation of water storage variations is a critical concern for resource assessment in semiarid areas. This issue is particularly acute in Southwest Niger, where both population growth (+3 per cent yr^{-1}) and climatic changes impinge on groundwater resources. Different approaches including hydrodynamic surveys, environmental tracer analysis, subsurface geophysical surveys and remote sensing were carried out to constrain the water balance in this region (Favreau *et al*. 2009). The quality of groundwater models predictions can still be improved by additional observations used as forcing data. In this perspective, geodetic observations constitute a valuable tool to calibrate and validate water storage models.

Water storage changes affect geodetic measurements in three ways (Zerbini *et al.* 2001; Jacob *et al.* 2008): (1) the water saturation and desaturation of soils modify pore volume and can lead to a soil displacement of several centimetres (Hoffmann *et al*. 2001); (2) the water acts as a load and induces a deformation of the Earth's crust due to its elastic behaviour (e.g. Blewitt *et al.* 2001; Bevis *et al.* 2005) and (3) the water mass distributions generate gravity changes by the combination of Newtonian attraction and elasticity effects (e.g. Amalvict *et al.* 2004; de Linage *et al.* 2007; de Linage *et al.* 2009). Llubes *et al.* (2004) quantified the influence of aquifers on gravity variations and evidenced that mass effects are dominant at local scale (<10 km), whereas elastic effects, related to the vertical displacement of the crust and the mass redistribution inside the Earth, are dominant at scales larger than several hundreds of kilometres.

Water storage variations generate such changes in gravity acceleration measured at the ground in the μGal range, which corresponds to 10 nm s^{-2} (e.g. Lambert & Beaumont 1977; Bower & Courtier 1998; Kroner 2001). Absolute gravimeters measure the exact value of gravity at a specific point in space and time with accuracy around 10–20 nm s^{-2} in case of low seismic noise conditions (Niebauer *et al.* 1995; Niebauer 2007). Superconducting gravimeters have a sensitivity (better than 10 nm s^{-2}) and a long term stability (a few tens of nm s^{-2} per year) which are adequate to investigate time-variable gravity changes caused by water storage changes (e.g. Kroner & Jahr 2006; Van Camp *et al.* 2006; Krause *et al*. 2009; Creutzfeldt *et al*. 2010). Relative, spring based gravimeters are sensitive to gravity differences either in space or time of several 10 nm s^{-2}. The accuracy achieved with such metres (usually 50–100 nm s^{-2}) depends on the quality of the instruments, on the measurement procedure, and on the means of transportation used (Hasan *et al*. 2008; Gehman *et al*. 2009; Jacob 2009). This accuracy can strongly be improved for short (a few tens of m) distances between measurements points (Naujoks *et al.* 2008). The efficiency in using gravity metres to measure water storage changes was tested among others in central Arizona, where the aquifer storage coefficient has been estimated using coincident monitoring of gravity and water levels (Pool & Eychaner 1995; Pool 2008). In karst systems, the water storage changes have been evaluated with repeated gravimetric measurements and mass balance modelling (Jacob *et al.* 2008, 2009). So far, very few ground based gravimetric measurements were performed to estimate water storage changes in semi-arid areas, especially in the African continent; in the Okavango basin (Botswana), Christiansen *et al.* (2009) managed relative gravimetric measurements to constrain hydrological modelling, retrieving signals of several tens of microGals.

The GHYRAF project (Gravity and Hydrology in Africa, see Hinderer *et al.* 2009 for a detailed description) aims to combine multidisciplinary observations to constrain water storage variability in Africa from the Sahara to the monsoon region. Therefore repeated ground gravimetric measurements are compared to *in situ* measurements of water balance components on four sites (Fig. 1a). Additional GPS measurements and subsurface geophysical measurements, including magnetic resonance soundings (MRS) and electrical resistivity surveys, complete ground observations. Hydrological effects are estimated at larger scale (several hundreds of kilometres) with satellite observations derived from the Gravity Recovery and Climate Experiment (GRACE, Tapley *et al.* 2004), and global hydrological models. According to these forecasts, the seasonal water storage variation is strong enough in southwestern Niger to generate a gravity change of about 100 nm s^{-2}, easily detectable with a free-fall absolute gravimeter of FG5 type (Hinderer *et al.* 2009).

This paper describes in detail how absolute gravimetric measurements help to recover water storage changes of the Continental Terminal aquifer, for a specific catchment in southwestern Niger. The effect of water redistribution on gravity changes is confirmed with amplitudes of about 100 nm s^{-2} at annual scale. It will be shown in the following that the effect of large-scale hydrology can be investigated using GRACE observations and/or simulations using global hydrological models. The analysis of residual ground gravity observations allows then improving the estimate of specific yield at local scale, which is found to be consistent according to independent MRS geophysical measurements. The hydrological context of Southwest Niger and Wankama catchment is depicted in Section 2. Section 3 describes the hydrological monitoring and the

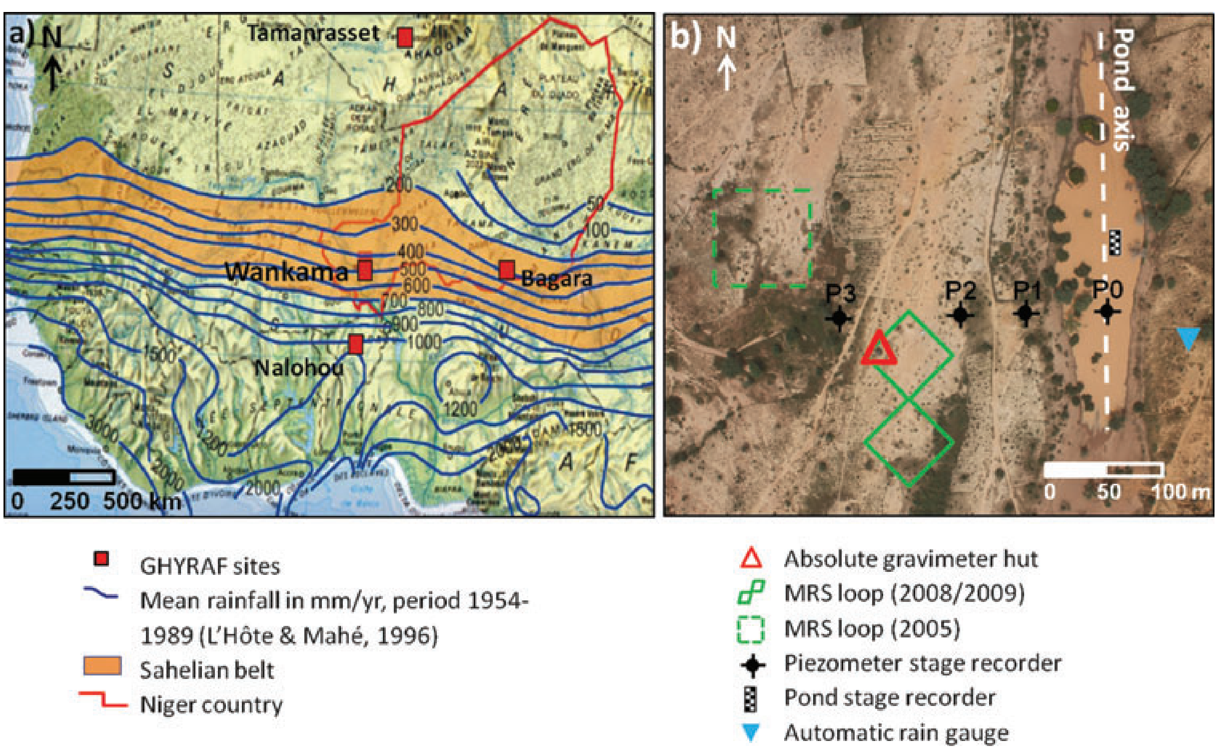

Figure 1. Description of the study area. (a) Location of the GHYRAF sites in western Africa. (b) The gravimetric measurement site. (Background aerial photograph by J.L Rajot, IRD, 2008 October 14; at this date, the pond water level was 1.15 m.).

acquisition of geophysical measurements, including MRS and ground gravity. The results of the hydrological and gravity observations are given in Section 4. The local and large-scale hydrological contributions to the gravity signal are analysed in Section 5. In Section 6, the specific yield of the aquifer is recovered from ground gravity observations. The effects of soil moisture and possible sources of uncertainty are discussed. The specific yield derived from ground gravity observations is then compared with the aquifer water content independently retrieved from MRS. Conclusions and perspectives are given in Section 7.

2 DESCRIPTION OF THE STUDY CATCHMENT IN SOUTHWEST NIGER

The study area is a part of the Wankama catchment situated in the Niamey region of southwestern Niger (Fig. 1a). The catchment is one of the four GHYRAF sites and belongs to the AMMA-CATCH observatory (Cappelaere *et al.* 2009; Lebel et *al.* 2009; http://www.amma-catch.org). The climate is tropical semi-arid, driven by the West African monsoon. About 90 per cent of precipitations occur in a wet season between June and September during short and intense events of convective origin. The annual precipitation is about 560 mm in Niamey (airport data) for the years 1950–2007, the annual average temperature is around 29°C and the potential evapotranspiration reaches 2500 mm (Favreau *et al.* 2009). Besides seasonal variation, the Sahelian belt (Fig. 1a) experienced a severe drought lasting since the 1960s (Lebel *et al.* 2009). In spite of the monsoonal rainfall deficit, the level of the water table has been continuously rising with 0.02 m yr^{-1} in the 1960s, up to 0.2 m yr^{-1} in 1990s–2000s (Favreau *et al.* 2009). This phenomenon is explained by the massive land use changes encountered in this region, due both to the extensive development of rain-fed agriculture and to severe drought conditions. The devastation of the savannah vegetation led among others to an increase of temporary ponds constituting preferential spots of groundwater recharge (Desconnets *et al.* 1997). Actually, there is no evidence of deep infiltration elsewhere in the landscape, with a possible exception for ravines and alluvial fans (Massuel *et al.* 2006; Boucher *et al.* 2009a). Previous groundwater modelling (Massuel 2005) has shown that independent information about hydrodynamic properties of the aquifer would be useful for constraining the parametrization of the model and for improving the numerical representation of hydrologic processes in such areas. A motivation for this study is to provide new quantitative observations of water storage changes to improve hydrological modelling at the local (<1 km) scale.

Wankama, located at longitude 2.65°E and latitude 13.64°N, is a small (~2.5 km^2) endorheic catchment typical of the cultivated Sahel (Peugeot *et al.* 2003). The watershed extends from west to east, reaching an altitude of 260 m at the lateritic plateau and falling to 203 m at the hillslope pond. The hill flank is gently sloped (≤2 per cent), separated at mid trail by an alluvial fan disconnecting the drainage network into two main ravine reaches. A fraction of the catchment drains directly to the pond. The catchment is intensively cultivated with numerous small millet fields. Fallow savanna and uncultivated bare soil constitute the remaining surface (Cappelaere *et al.* 2009). The unconfined aquifer belongs to the Continental Terminal 3 (CT3), mainly composed of loosely cemented clays, silts and sands of continental origin (Lang *et al.* 1990). The substratum consists in a continuous and impermeable grey clayed layer, thick of several ten metres. The water table displays hydraulic gradients ≤0.1 per cent, except near ponds where they can reach 1 per cent at the peak of the rainy season. This aquifer has been largely investigated with hydrodynamic monitoring and subsurface geophysical measurements (Leduc *et al.* 1997; Leduc *et al.* 2001; Massuel *et al*. 2006; Boucher *et al.* 2009b).

3 INSTRUMENTAL SETUP

A dense network of hydrological monitoring and geophysical measurements is devoted to document hydrological processes of the water cycle at catchment scale (Cappelaere *et al.* 2009). The hydrological, gravimetric and subsurface geophysical measurements sites considered in this study are mapped in Fig. 1(b). The topography is evaluated, with a centimetric resolution in height, from 2900 differential GPS measurements (DGPS) distributed on the 2.541 km^2 of the Wankama catchment (Gendre 2010). A higher (1470 points on 0.5 km^2) density of DGPS points have been taken in the pond surroundings.

3.1 Hydrological monitoring

Two automatic rain gauges, located on the plateaus and in the vicinity of the pond, allow recording rainfall every minute. In 2008–2009, a pressure sensor (manufactured by STS©) and a float (OTT Thalimede©) measured the pond water level every 20 and 5 min, respectively. The water table level was recorded every 20 min with pressure sensors on four piezometers located at 0, 64, 110 and 210 m of the pond axis. Direct measurements using luminous probe (OTT KL010©) were used to correct the drift of automatic sensors. In addition, every minute, 6 capacity probes (Time – Domain type CS616 of Campbell Scientific) buried from 0.1 to 2.5 m below the surface measured the soil volumetric water content at two typical sites of millet and fallow located at 1.5 and 2 km upstream from the pond (Cappelaere *et al.* 2009; Ramier *et al.* 2009).

3.2 Magnetic resonance soundings

MRS is a geophysical technique specially adapted for groundwater investigation (Legchenko *et al.* 2002). This method allows measuring the magnetic field generated by the precession of the nuclei of hydrogen atoms present in groundwater molecules after an electromagnetic excitation at a specific frequency (resonance frequency). The amplitude of the measured signal (in nV) is directly related to the volume of water contained in the subsurface layers of soil. The depth of investigation (up to ~100 m) is controlled by the moment of the excitation pulse (in A ms). The inversion of MRS data provides a vertical distribution of the water content in the aquifer (Legchenko *et al.* 2004). The MRS water content is generally assumed to be close to the effective porosity, which is the portion of water that contributes to flow through the sediment (Vouillamoz *et al.* 2008). For unconfined aquifers, the effective porosity is slightly higher than the part of water that can be drained by gravity forces, identified as the specific yield (Lubczynski & Roy 2005).

Many MR soundings were performed in the Continental Terminal aquifer (Vouillamoz *et al.* 2008; Boucher *et al.* 2009a, 2009b) for better characterizing the hydrogeological properties (porosity and permeability) of the aquifer. A new MRS survey has been performed during the 2008–2009 rainy season close to the gravity measurements (Fig. 1b). This sounding was repeated 10 times to improve its accuracy. Measurements were performed with the Numis^{Plus} device. For MRS inversion, the geometry was fixed according to available hydrogeological information in order to decrease ambiguities in the

Table 1. FG5 absolute gravity values at Wankama site (in nm s^{-2}).

Date	Gravity value (nm s^{-2})	Standard deviation	Gravity changes (nm s^{-2})	Standard deviation
17/07/2008	9782506027.0	19.8		
			87.3	26.2
04/09/2008	9782506114.3	17.1		
			–48.7	22.1
05/02/2009	9782506065.6	14.0		
			–31.4	21.3
05/04/2009	9782506034.2	16.1		

interpretation and improve the estimate of water content. The water table depth and the bottom of aquifer were fixed using respectively measurements in piezometers (P2 and P3), and depth of the clayed aquiclude estimated by Time Domain Electromagnetic (TDEM) soundings and available geological data (Boucher *et al.* 2009a).

3.3 Absolute gravity data acquisition

Absolute gravimeters of FG5 type measure the exact acceleration of gravity due to the Earth along the direction of a freely falling body. This gravity measurement has the advantage to be calibrated, drift-free, and accurate (Niebauer *et al.* 1995; Niebauer 2007). The lack of drift is particularly useful for monitoring gravity changes over long periods of time. FG5 measurements were performed at the Wankama site four times between 2008 July and 2009 April. Measurements were done on a concrete pillar (1 m^3) protected from wind with a traditional hut constructed at 190 m of the pond axis (Hinderer *et al*. 2009). FG5 measurements were performed during nighttime to avoid heating effects. The mean value of gravity is estimated by averaging many series of sets (usually one set every hour or half an hour) consisting of 100 drops (a drop every 10 s) of a corner cube in a vacuum chamber. Gravity values are corrected for temporal effects, including solid earth tides (tidal parameters from EGTAB software; Wenzel 1996), ocean loading (Schwiderski 1980), air pressure effects (*in situ*-measurements, regression coefficient of -0.3 μGal hPa^{-1}) and polar motion contribution (correction of the international earth rotation service, IERS – http://www.iers.org). Final gravity values (Table 1) are transferred from the instrumental height to the ground. This correction has no influence on the investigation of the gravity changes in time, since the same free air gradient is always used. The very small standard deviation (ranging from 14 to 20 nm s^{-2}) of the final absolute gravimetric measurements resulted from very low seismic noise and well-suited corrections of temporal effects.

4 OBSERVATION OF A MONSOONAL CYCLE

4.1 Local hydrology

The hydrological signal of the 2008–2009 monsoon period recorded in Wankama is depicted in Fig. 2. Daily precipitation records indicate intense events between 2008 June and October, resulting in rapid rises of the pond water level (Fig. 2b) and seasonal water storage in the first metres of soil, essentially at the end of the rainy period (Fig. 2c). The water table recharge is focused below the pond: a plurimetric piezometric dome is generated in September, when the pond water level reaches its peak (Fig. 2a). The infiltration is enhanced by the sandy texture of the soils at the shore of the pond (Desconnets *et al.* 1997; Martin-Rosales & Leduc 2003), leading to a dome higher by 0.44 m at P1 than at P0 (Figs 2a and d). Time variations of the water table at P0, P1, P2 and P3 are shown in Fig. 2(d). Seasonal changes of the water table are significant near the pond (P0, P1), but their amplitudes decrease with distance (P2, P3) and become negligible at a distance of a few hundreds of metres from the pond (Desconnets *et al.* 1997). The level reached by the water table in September 2008 is the highest recorded since the beginning of the piezometric monitoring in 1993. This event results both from strong consecutive rainfall events (annual rainfall = 637 mm at the plateaus rain gauge in 2008) and from the long-term rise of the water table (+0.25 m yr^{-1} in Wankama, 1993–2009). Fig. 2(c) shows the time variations of the water storage in the first 3m of soil, separately for the fallow and millet sites. The difference in the soil water stocks reached at the end of the rainy season for the fallow (115 mm) and millet (164 mm) sites illustrates the large spatial variability of infiltration of rainwater in the soil.

4.2 Gravity signal

Time-lapse gravity observations listed in Table 1 are in phase with the monsoonal rainfall at local and regional scales (Fig. 1). The 87 nm s^{-2} gravity rise observed between the 17th of July and the 4th September can be explained by the water storage recharge observed in Wankama and by the large scale recharge due to the West African monsoon derived from global hydrological models and indeed observed with GRACE satellites (Hinderer *et al.* 2009). Also the gravity decline observed from September to April is consistent with the end of the wet season occurring approximately at the same time at the scale of Wankama catchment and at the scale of the Sahelian belt (Fig. 1a). To explain the gravity signal, independent estimates of the gravity variations generated by local water storage changes and large scale hydrological effects are required (Longuevergne *et al.* 2009).

5 ANALYSIS OF THE MONSOONAL GRAVITY SIGNAL

5.1 Local water storage model

To first order, the local variations of superficial (pond, soil moisture) and deeper (aquifer) water storage generate a gravity change caused by the Newtonian attraction of masses. The vertical component of the Newtonian attraction Δg (m s^{-2}) caused by the sum of elementary volumes of water storage changes dV in a total volume V (m^3) is given by:

$$\Delta g = G\rho \int_V \frac{\mathrm{d}V}{r^2} \cos \propto, \tag{1}$$

where G (6.67×10^{-11} N m^2 kg^{-2}) is the gravitational constant, ρ (kg m^{-3}) the density of water storage (e.g. the mass of water per volume unit), r (m) the distance between the observation point and the water storage change and $\propto$ the angle enclosed by r and the vertical axis. The geometry of the water storage changes can be represented by a configuration of prisms of various densities and dimensions. Then, integration is carried out for any specific prism and the contributions are added (Nagy 1966; Leirião *et al.* 2009).

Time gravity variations due to the Newtonian attraction of water storage changes are computed at the FG5 measurement point from 2008 April to 2009 April. The water storage in Wankama site is split among three water storage components, as follows.

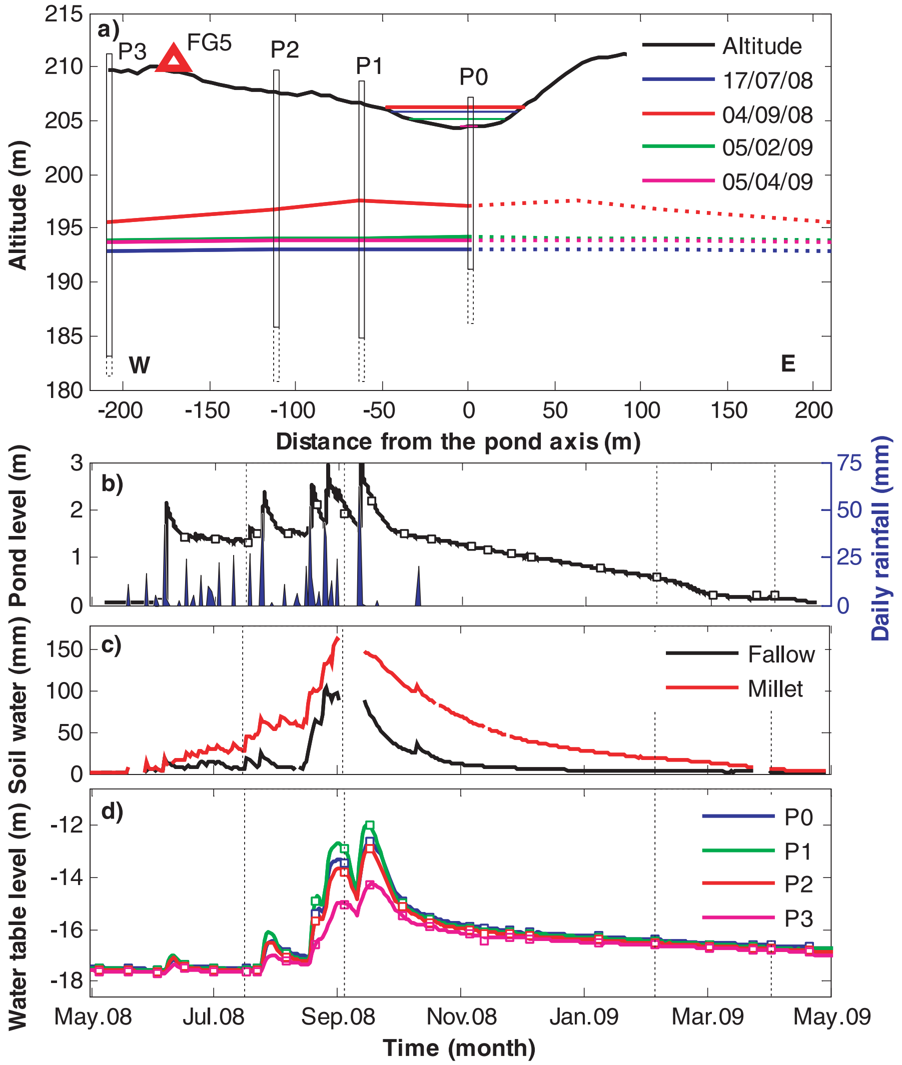

Figure 2. Hydrological processes for 1 yr on a 400 m profile. (a) Cross section of the piezometric profile showing the pond water level and the water table level at FG5 measurement dates. The water table shape is assumed to be linear between each of the four piezometers (solid lines) and symmetric with respect to the pond axis (dashed lines). The term FG5 refers to the absolute gravimeter. (b) Time variations of pond water level (black) associated with automatic recordings of rainfall events (blue) at the plateaus rain gauge. The vertical dashed lines represent FG5 measurement dates. The squares represent manual measurement of the water level. (c) Time variations of the soil water stocks between 0 and 3m at the fallow and millet sites. (d) Time variations of the water table level at four piezometers. The water level corresponds to the depth of the water table from the FG5 sensor.

(1) The unconfined aquifer is the most important storage entity in terms of volume. The water table shape is constrained in time and space with the four piezometric measurements points: the water table is assumed linear between each of the four piezometers, symmetric with respect to the pond axis and infinite in the pond axis direction. Each prism is centimetric in height, metric in the piezometric axis direction and infinite in the pond axis direction. In this case the integration over the volume is 2-D. For an unconfined aquifer, the density ρ is equal to the density of water (10^3 kg m^{-3}) multiplied by the specific yield *Sy* (non-dimensional number). The specific yield is assumed to be constant and defined as the volume of water that can be extracted by gravity per the total volume of drained rock. The gravity variations caused by the water table fluctuations are computed for values of the specific yield ranging from 1 to 15 per cent. About 80 per cent of the gravimetric signal generated by the aquifer fluctuations is comprised within a radius of 70 m around the FG5.

(2) The pond is simplified by a rectangular shape, which results in negligible effects on gravity considering the weakness of the slope (∼2 per cent) between the FG5 point and the pond surface. The volume of the pond is calculated using a relationship between the level and the volume of water in the pond derived from the topography (Peugeot *et al.* 2003). The density ρ is equal to the density of water. The resulting contribution of the pond on gravity changes is below 3 nm s^{-2} between FG5 measurement dates, which is one order of magnitude below the instrumental detection limit.

(3) The contribution of the soil water storage is the most difficult to estimate as no measurements were available in the near vicinity of the FG5 measurement point for the rainy season 2008. While neutron probes were settled at the beginning of the rainy season 2009, the data are not yet available, as they require calibration with soil samples at each measurement site. Nevertheless the soil water infiltration recorded at the fallow site can be considered as an upper bound for the infiltration at FG5 point for the following reasons:

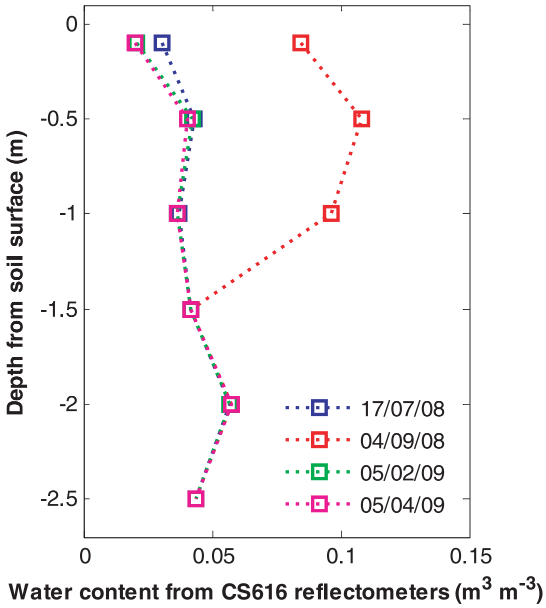

Figure 3. Time variation of the volumetric water content in the 2.5 first metres of soil as recorded by the six capacity probes at the fallow station.

(i) the FG5 measurement point is situated in a degraded area with very sparse vegetation of fallow type (Fig. 1b),

(ii) soil crusting and subsequent Hortonian runoff were mapped to be higher in the FG5 surroundings than at the fallow site (Seguis *et al.* 2004),

(iii) the surface slopes are comparable at the FG5 (1.47°) and fallow sites (1.43°; Gendre 2010), and

(iv) the non-calibrated neutron measurements in the vicinity of the FG5 site show no variation of the volumetric water content below 1.5 m deep in accord with the limit of infiltration observed at the fallow site (Fig. 3).

The soil moisture contribution is then computed for four soil layers centred on the capacity probes' depth (0.1, 0.5, 1 and 1.5 m) and following the topography. Their volumetric water content can vary from 0 to the soil water content measured at the fallow station. 96 per cent of the resulting gravity signal is generated within a radius of 50 m around the FG5.

5.2 Large scale hydrological effects

In addition to the Newtonian attraction of local water masses, large scale hydrological distributions generate an elastic deformation of Earth's crust along with a mass redistribution inside the Earth, resulting in non-negligible effects on gravity (Farrell 1972). The sum of these two effects of the crust deformation is known as surface loading. Furthermore distant water masses generate Newtonian attraction, enhanced by the sphericity of the Earth (e.g. de Linage *et al.* 2007; de Linage *et al.* 2009). For a better interpretation of our gravimetric measurements, we attempt to correct them for these large-scale effects using either global hydrological models, or GRACE satellite data.

The content of water in the first metres of soil can be described for the whole continental surface excluding Antarctica by the global land data assimilation system (GLDAS; Rodell *et al.* 2004) with temporal and spatial resolutions of 3 hr and 0.25° (~25 km). The European Centre for Medium-range Weather Forecasts (ECMWF on http://www.ecmwf.int; Uppala *et al.* 2005) provides another estimate of soil water content at global scale with a 6 hr temporal resolution, and a spatial resolution of about 0.25°. The soil water mass distribution simulated by GLDAS or ECMWF is convolved with the Green's functions associated to Newtonian and deformation effects, assuming a spherical non-rotating, elastic and isotropic (SNREI) Earth model (standard procedure for the calculation of global atmospheric or ocean loading effects, e.g. Boy & Hinderer 2006). This convolution gives the total gravity variations including the following.

(1) *Local mass effects.* The Newtonian attraction of the water stored in the pixel of observation. The attraction of a uniform layer of water is a Dirac function centred on the site (here Wankama) and equal to the attraction of an infinite Bouguer plate. Its vertical component Δg is given by

$$\Delta g = 2\pi G \rho H, \tag{2}$$

where H is the water elevation predicted by GLDAS or ECMWF in the Wankama pixel and ρ the density of water. This equation leads to an attraction of 0.42 nm s^{-2} per millimetre of water thickness. The spatial resolution is given by the highest resolution of the model output (here 25 × 25 km^2), related to the resolution of forcing data (precipitation, wind and temperature), without any considerations of geological or geomorphologic criteria.

(2) *Surface loading effects.* The vertical deformation of the Earth crust and the change in gravitational potential generated by the global continental water storage variations.

(3) *Remote mass effects.* The Newtonian attraction of the water stored (equivalent to the global continental water storage) outside the pixel of observation, which is enhanced by the sphericity of the Earth.

To obtain solely the large-scale contribution (2 and 3), local mass effects (1) have hence to be removed.

The GRACE mission is recovering the Earth's time variable gravity field with spatial and temporal resolutions of a few hundreds of kilometres and 10–30 d, respectively (Tapley *et al*. 2004). In numerous studies, the continental water mass variations have been successfully related to the GRACE data (e.g. Ramillien *et al.* 2005; Schmidt *et al.* 2006; Hinderer *et al.* 2006; Crowley *et al.* 2006). Over Africa, the GRACE solutions from different processing centres reveal similar estimates of the continental water storage at seasonal timescales, both on continental and river basin scales (Boy *et al.* 2010). In this study, the solutions of the Centre National d'Etudes Spatiales / Groupe de Recherche en Géodésie Spatiale (CNES/GRGS) are used to reckon the time variable gravity field with temporal and effective spatial resolutions of respectively 10 d and about 400 km (Bruinsma *et al.* 2010). The effects of elastic surface loading and attraction of remote masses are obtained as previously by removing local mass effects from the total gravity variations. This local contribution is calculated as the attraction of a Bouguer plate whose thickness is equal to GRACE water equivalent height in the 400 × 400 km^2 pixel including the Wankama site. GRACE, GLDAS and ECMWF estimates of gravity changes are shown on Fig. 4.

The annual amplitude (2008–2009 May) of the total gravity changes differ largely from GRACE to GLDAS (+65 nm s^{-2}) or ECMWF (+28 nm s^{-2}), even if the signals are in phase. The discrepancy observed between GLDAS and ECMWF simulations can be explained by the differences in forcing data (especially precipitation) and by the differences in land surface models. The difference in spatial resolution between GRACE (400 × 400 km^2) and global hydrological models (25 × 25 km^2) accounts for a large part

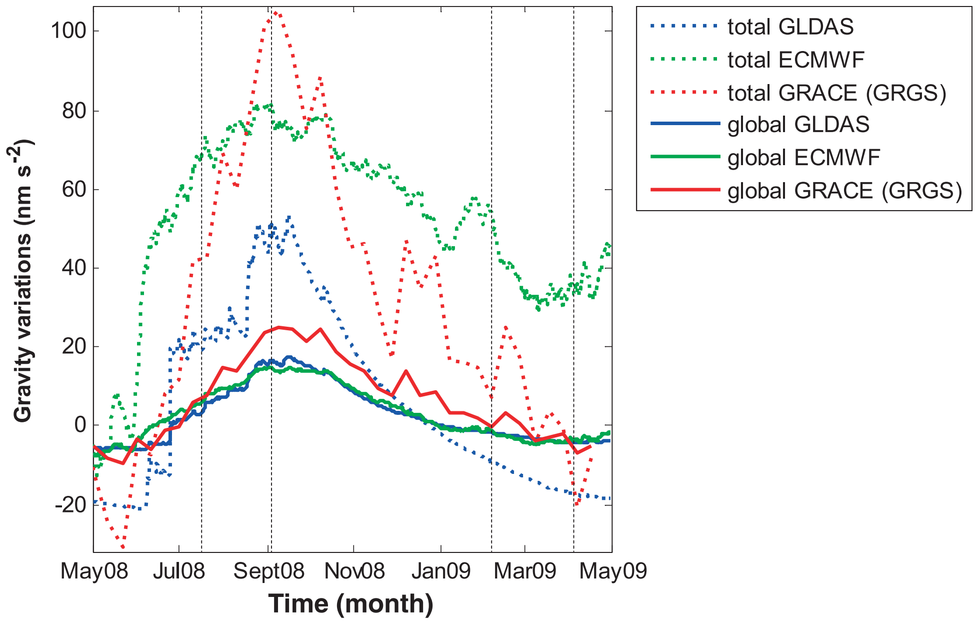

Figure 4. Total and global hydrological contributions to gravity variations estimated in a pixel area centred on Wankama. The term total refers to the sum of Newtonian attraction and surface loading effects of water masses. The term global refers to the large-scale contribution computed as the total gravity changes induced by hydrology minus the attraction of a Bouguer plate whose thickness is the predicted water elevation change for the Wankama pixel. The dashed vertical lines correspond to FG5 measurement dates.

of the differences observed between the total gravity variations. Besides, GLDAS and ECMWF models do not include any surface water or groundwater which, when not negligible, can lead to a disagreement with GRACE water storage estimates (e.g. Leblanc *et al.* 2009; Han *et al.* 2009). Nevertheless, if global hydrological forecasts and GRACE derived data are not expected to fully explain the ground gravity variations, they provide a useful tool for the estimate of large-scale (several hundreds of km) gravity variations related to continental hydrology. This global component accounts for approximately 20 per cent of the total gravity changes (Fig. 4). Such an effect can clearly not be ignored in interpreting absolute gravity measurements. The mean standard deviation of the differences between GRACE, GLDAS and ECMWF estimates of the global contribution is only 5 nm s^{-2}, indicating a high consistency between independent estimates of large-scale hydrological effects on gravity field. The annual amplitude (2008–2009 May) of this global component is however found to be slightly larger for GRACE data than for the GLDAS (+11 nm s^{-2}) and ECMWF (+8 nm s^{-2}) simulations.

6 DISCUSSION

6.1 Estimate of the specific yield

The simulated gravity changes due to local water storage (Section 5.1) are compared with the FG5 measurements corrected or not corrected for large-scale hydrological effects (Fig. 5). Uncorrected ground gravity observations are in phase, but of higher amplitude than observations corrected for large-scale hydrological effects. The gravity simulations can be expressed as the sum of the water table and soil moisture effects. The soil moisture contribution can vary from 0 (Fig. 5a) to the soil water content measured at the fallow site (Fig. 5b). The amplitude of this contribution is controlled with a scale factor ranging from 0 to 1 identified as the soil moisture index (Fig. 6). The water table contribution is proportional to the specific yield (*Sy*) of the aquifer (Fig. 5a): this parameter can hence be constrained by an adjustment of gravity simulations to gravity observations. The resulting *Sy* values depend both on the soil moisture index and on the correction of large-scale effects (Fig. 6). For GRACE correction of large-scale effects, *Sy* values range from 1 to 6 per cent, regarding the whole range of the soil humidity index. If we do not consider any corrections of large-scale hydrological effects, *Sy* will be overestimated to values ranging from 3 to 9 per cent.

6.2 Uncertainty analysis

Several sources of uncertainty may affect the estimate of the specific yield, as follows.

(1) The soil moisture contribution could be underestimated by the fallow measurements. This possibility has been investigated by computing the gravity variations induced by the soil water content changes measured at the millet site. The resulting gravity variations become higher than the ground measurements corrected or not for the large-scale hydrological effects. This soil moisture contribution is then added to the water table contribution. The adjustment of these updated simulations to ground gravity measurements leads to a minimal *Sy* value of 0.5 per cent, when considering GRACE correction of large scale hydrological effects and 70 per cent of the soil water content measured at the millet site. The upper limit of *Sy* range is unaffected as it is obtained for a null soil moisture contribution. These results show that (i) the soil moisture contribution in the FG5 surroundings is likely lower than what could be measured at the millet site and (ii) considering higher soil moisture contributions than what could be measured at the fallow site does not change significantly the *Sy* estimate.

(2) A hysteresis effect may occur as the water table rises in fields that have dried for approximately 8 months. In addition, the upper level reached by the water table in September 2008 had not been saturated since the beginning of the piezometric monitoring

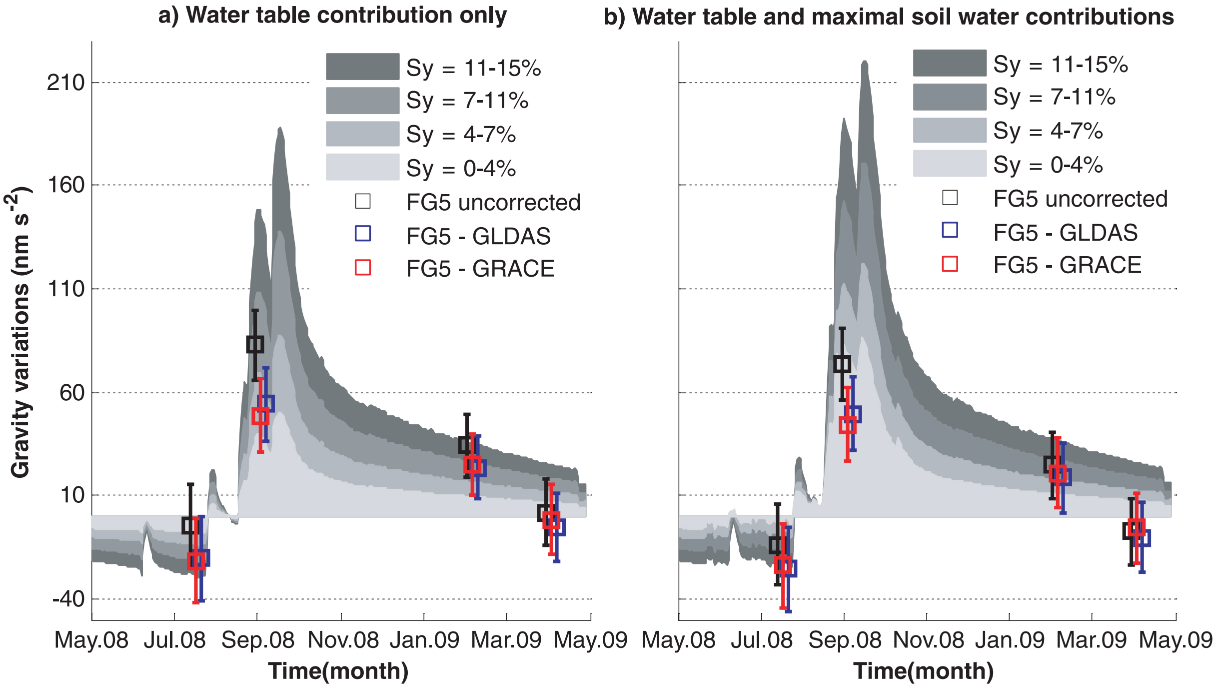

Figure 5. Comparison of the simulated and observed gravity variations at Wankama site. The specific yield of the aquifer is indicated by *Sy*. The squares are the FG5 observations either uncorrected (black) or corrected for the large-scale hydrological contribution using GRGS solutions of GRACE satellite data (red), or GLDAS hydrological model (blue). For visibility purpose, the different values for each FG5 measurement are slightly shifted in time when considering GRACE, GLDAS or no large-scale correction. (a) considers only the water table contribution and (b) the sum of the water table and maximal soil moisture contributions (using the soil water content measured at the fallow site).

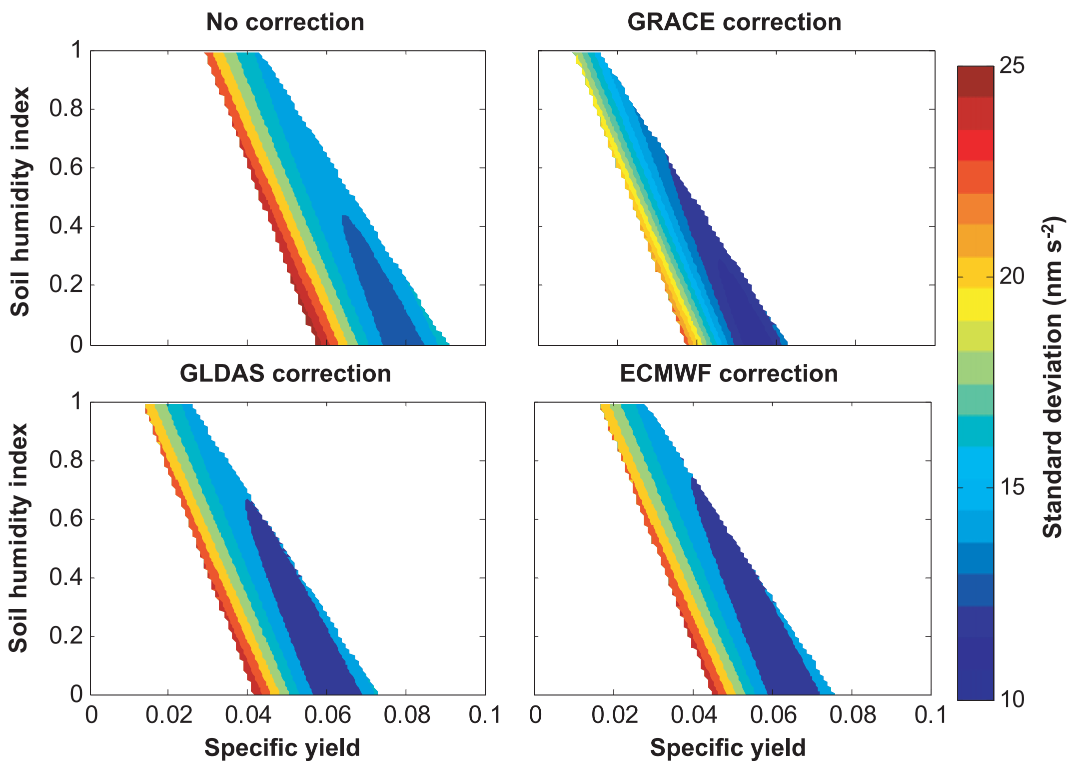

Figure 6. Range of parameters for which the local water storage simulations are comprised within FG5 measurements error bars. The soil humidity index is a scale factor applied to the soil water contribution measured at the fallow site. The standard deviation of the difference between the gravity measurements and simulations is indicated for each couple of parameters. Four different corrections of large scale hydrological effects are considered, the term *no correction* referring to FG5 observations uncorrected for large scale hydrological effects, but corrected as usual for temporal effects (solid earth tides, ocean loading, air pressure, polar motion).

in 1993 at least. During the first month of the dry season, the water table rapidly decreases (Fig. 2c) but some water remains in the unsaturated zone due to capillarity effects. During the end of the dry season, the drop of the water table is slower but the water stored in the fluctuation zone by capillarity continuously decreases. This retention and release of water in the unsaturated part of the fluctuation zone could explain why the gravity decrease measured from February to April is higher than the modelled gravity decrease (Fig. 5).

(3) The local water storage modelling assumes uniform aquifer porosity, a simplified aquifer geometry, and homogeneous layers of soil moisture (details in Section 5.1).

(4) The correction of large-scale hydrological effects depends on the reliability of GRACE satellite data and global hydrological models to recover water storage at scales of several hundreds of kilometres (details section 5.2).

(5) The uncertainty of time lapse gravimetric measurements ranges from 21 to 26 nm s^{-2}, which represents a quarter to a third of the signal induced by local hydrology.

The quality of the adjustment between the local water storage model simulations and the ground gravity measurements is estimated by the standard deviation of their differences. The minimal standard deviation (11 nm s^{-2}) is achieved for *Sy* values and soil moisture index ranging in intervals of [5.0–6.0 per cent] and [0.0–0.3], respectively, when considering GRACE correction for large-scale hydrological effects. Slightly higher *Sy* values ([5.6–6.8 per cent] or [6.0–7.0 per cent], respectively) are reached for a standard deviation of 12 nm s^{-2} when considering GLDAS or ECMWF corrections. One can see that the lowest standard deviations are obtained for a soil humidity index below 0.8 (Fig. 6), suggesting that the amplitude of the soil water storage variations is less than the one measured at the fallow site. When measurements stay uncorrected for large-scale hydrological effects, the minimal (14 nm s^{-2}) standard deviation is achieved for a specific yield ranging from 8.2 to 9.2 per cent. The average standard deviation is improved by 13 per cent, when correcting the ground gravity measurements for GRACE estimate of the large-scale hydrological effects (and by respectively 5 and 7 per cent for GLDAS and ECMWF corrections). The optimum (standard deviation $<$15 nm s^{-2}) *Sy* values range from 1.8 to 6.2 per cent for the assumptions of (i) a soil moisture contribution limited by the measurements at the fallow site and (ii) a reliable GRACE correction of large scale hydrological effects.

6.3 Independent estimate of the groundwater content with MRS

The measured MRS signal and its inversion are shown in Fig. 7 for a representative sounding. Each of the 10 soundings was inverted in the same way. The mean MRS water content is about 8–10 per cent and slightly differs from the soundings performed in 2005 December (12.0 per cent, Boucher *et al*. 2009b) suggesting slight lateral heterogeneities of aquifer porosity (MRS locations in Fig. 1b). The difficulty to fit all the data when assuming constant water content for the entire aquifer (Fig. 7) suggests the presence of vertical heterogeneities in the aquifer. When using a model with 8.5 per cent of water content, the amplitudes for high value of pulses are underestimated and when using a model with 9.5 per cent of water content, the amplitudes for low value of pulses are overestimated. The fit of data is greatly improved when considering that the water content is lower in the top of the aquifer than in the bottom. This difference of water content can be explained by the geological heterogeneity of the Continental Terminal aquifer, which consists in an alternation of more or less clayed beds of small extension (Greigert & Bernert 1979; Lang *et al*. 1990). The analysis of each of the 10 MR soundings reveals a water content in the top of the aquifer (where fluctuations occur) of 6.7 ± 1 per cent.

Pumping tests performed in the Continental Terminal aquifer show that the MRS water content was always higher than the measured specific yield (Boucher *et al.* 2009b). This information was interpreted as MRS being sensitive to capillary water unlike pumping tests. The same reason can explain that the specific yield ([1.8–6.2 per cent]) estimated from gravity variation is less than the MRS water content measured in the top of the aquifer (down to 30 m from the soil surface). It is worth noting, that the *Sy* values estimated from the repeated gravity surveys are representative of the upper part of the aquifer, seasonally saturated and desaturated. The deeper

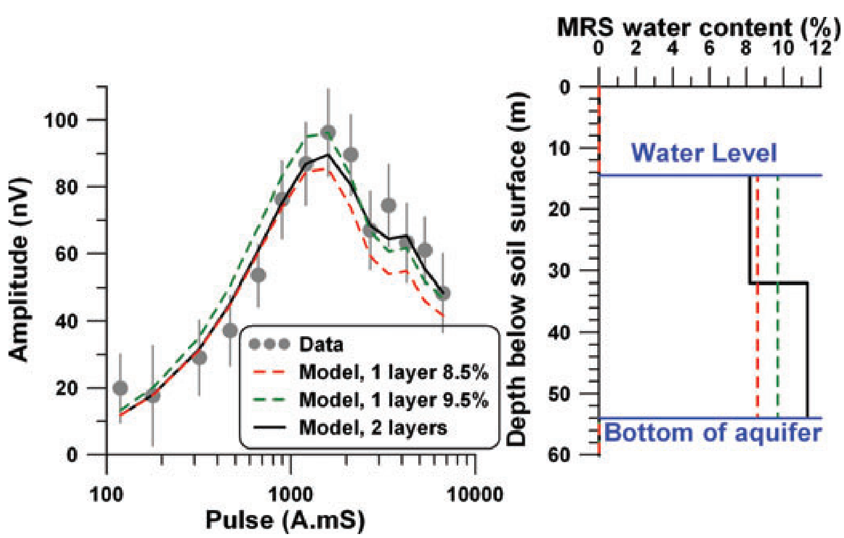

Figure 7. Typical MRS results (2009 February 5) showing the comparison of measured and modelled signals (in nV) for three different models of water content varying with depth in the aquifer.

part of the aquifer does not contribute to gravimetric changes as it remains saturated for the entire year.

7 CONCLUSIONS AND PERSPECTIVES

The GHYRAF experiment permitted to carry out the first absolute gravity monitoring in West Africa. Main results can be summarized as follows:

(1) Time lapse gravimetric measurements are significantly influenced both by local and large-scale signals of the West African monsoon. The large-scale contribution must hence be removed from the gravity measurements before investigating local water storage variations. GRACE satellite can effectively be used to estimate the gravity variations induced by large-scale hydrology and surface loading. This effect is found to be comparable and even slightly (about 10 nm s^{-2}) larger than the simulations of the GLDAS and ECMWF hydrological models.

(2) In spite of the small to medium amplitude of the recorded gravity signal, the specific yield of the unconfined aquifer can be retrieved to an optimum value ranging from 1.8 to 6.2 per cent. These values rely on a probable range of soil moisture distribution (estimated after measurements with capacity probes) and on GRACE assessment of the large-scale (several 100 km) water storage variability.

(3) The specific yield inferred from gravity surveys is consistent with the water content retrieved with MRS. The consistency between both geophysical methods shows their potential to validate and calibrate local hydrologeological models of water storage changes. Because resonance magnetic soundings integrates the whole saturated thickness of the aquifer, it is less sensitive than the gravity surveys to the water table fluctuations, and is usually mainly used to estimate spatial changes in the water content.

A refinement of the local hydrological modelling would be necessary to improve our knowledge of the water storage variability at the catchment scale. The neutron probes installed at the beginning of the rainy season in 2009 will help to quantify changes of the water content in the whole thickness of the unsaturated zone. A densification of gravimetric measurements was carried out with two microgravimeters during the 2009 monsoon period. The results from these two experiments will be concurrently analysed with the purposes of (i) better constraining the intraseasonal water balance, (ii) exploring spatial heterogeneities of the water storage and (iii) detecting processes governing focused recharge in semiarid SW Niger.

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