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Contribution of geophysical surveys to groundwater modelling of a porous aquifer in semiarid Niger: An overview

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Abstract

Subsurface geophysical surveys were carried out using a large range of methods in an unconfined sandstone aquifer in semiarid south-western Niger for improving both the conceptual model of water flow through the unsaturated zone and the parameterization of numerical a groundwater model of the aquifer. Methods included: electromagnetic mapping, electrical resistivity tomography (ERT), resistivity logging, time domain electromagnetic sounding (TDEM), and magnetic resonance sounding (MRS). Analyses of electrical conductivities, complemented by geochemical measurements, allowed us to identify preferential pathways for infiltration and drainage beneath gullies and alluvial fans. The mean water content estimated by MRS (13%) was used for computing the regional groundwater recharge from long-term change in the water table. The ranges in permeability and water content obtained with MRS allowed a reduction of the degree of freedom of aquifer parameters used in groundwater modelling. ***To cite this article: M. Boucher et al., C. R. Geoscience 341 (2009).***

Résumé

Contribution de la géophysique à la modélisation hydrogéologique d'un aquifère poreux dans une région semi-aride du Niger : une revue. Des prospections géophysiques utilisant différentes méthodes ont été menées dans un aquifère gréseux libre au sud-ouest semi-aride du Niger, afin d'améliorer le modèle conceptuel des flux d'eau à travers la zone non saturée ainsi que la paramétrisation d'un modèle numérique des flux hydriques de l'aquifère. Les méthodes mises en œuvre sont : la cartographie électromagnétique, la tomographie de résistivité électrique (TRE), la diagraphie électrique, le sondage électromagnétique en domaine temporel (TDEM), et le sondage par résonance magnétique des protons (RMP). L'analyse des conductivités électriques, complétée par des mesures géochimiques a permis d'identifier des chemins préférentiels pour l'infiltration et le drainage sous les

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ravines et les zones d'épandage sableuses. La teneur en eau moyenne estimée par RMP (13 %) a été utilisée pour calculer la recharge régionale de l'aquifère à partir des variations piézométriques à long terme. Les gammes de perméabilité et teneur en eau obtenues par RMP ont permis de réduire le degré de liberté des paramètres de l'aquifère utilisés dans la modélisation hydrogéologique. ***Pour citer cet article : M. Boucher et al., C. R. Geoscience 341 (2009).***

Keywords: Porous aquifer; Groundwater recharge; Infiltration; Electromagnetic methods (EM); Electrical resistivity tomography (ERT); Magnetic Resonance Sounding (MRS); Niger

Mots clés : Aquifère poreux ; Recharge ; Infiltration ; Méthodes électromagnétiques (EM) ; Tomographie de résistivité électrique (TRE) ; Sondage par résonance magnétique des protons (RMP) ; Niger

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1. Introduction

In most semiarid areas at a global scale, unconfined aquifers provide the only permanent fresh water resource for most of the population. In south-western Niger, the unconfined aquifer has been intensively studied in order to estimate impacts of climate changes and land clearing on groundwater resources. Since the 1960s, a continuous rise of about 4 m (1963–2007) in the water table of the Continental Terminal (CT) unconfined aquifer has been observed [12], whereas rainfall has decreased by about 25–40% compared to the 1930–1960 period [17,23]. This paradoxical observation was mainly explained by a tenfold increase in the groundwater recharge due to land clearing, while groundwater pumping remained low (< 1 mm/yr, no irrigation).

In porous and/or semiarid aquifers, sub-surface, non-invasive geophysical methods have been successfully applied to determine:

- the degree to which discrete measurements in the vadose zone are spatially representative (e.g. [5,16,24]);
- to provide independent estimates on groundwater reserves characteristics (e.g. [9,14,26]).

Hydrodynamic monitoring, environmental tracers, remote sensing and hydrological modelling approaches were applied in SW Niger in order to constraint the water balance [12]. In this well-known aquifer, electromagnetic mapping, electrical resistivity tomography (ERT) and resistivity loggings (down to 25 m) were carried out at a local scale ($\sim$1.9 km^2) on the representative Wankama catchment [22]. At a larger scale ($\sim$3000 km^2), 22 sites were investigated by magnetic resonance soundings (MRS) north-east of Niger River [1,27]. Time domain electromagnetic (TDEM) soundings were also used on the same sites to delineate the conductive substratum and constrain MRS inversion. To the best of our knowledge, this represents one of the most significant hydrogeophysical data sets for an unconfined sedimentary aquifer in Africa.

The first aim of this article is to synthesize results illustrating how complementary subsurface geophysical measurements can shed light on the hydrogeological functioning of aquifers in a semiarid context. The second aim is to show how to use this geophysical information to improve the reliability of groundwater modelling.

2. Study area

The study site is located in Sahelian SW Niger, at a few tens of kilometres east of Niamey (Fig. 1) [3]. In this area, the main unconfined aquifer belongs to the Continental Terminal 3 (CT3) formation, and consists of loosely cemented sandstones of Tertiary origin [18]. Eastward, the Dallol Bosso valley is a large paleo-river filled with coarse Quaternary sands. The water table exhibits a continuous, smooth surface, with hydraulic gradients lower than 0.1%, and little seasonal changes, except near infiltrating ponds [10,11]. The water table depth (average of 50 m) displays a large variability, with depths of more than 70 m below the plateaus, and less than 10 m below sandy valleys. The substratum of the unconfined CT3 aquifer consists of a continuous grey clayey layer several tens of meters in thickness.

The climate is semiarid with an average temperature of 29 °C, a potential evapotranspiration near 2500 mm.yr^{-1} and a yearly rainfall of about 560 mm (1950–2007). The rainy season consists of intense rainfall events, typically lasting a few hours. In this area, the groundwater recharge is indirect and occurs mainly through temporary ponds, outlets of watersheds of a few square kilometers [20]. The natural vegetation of the region is wooded savannah but, with increasing clearing, much of the area is now a patchwork of fallow and millet fields.

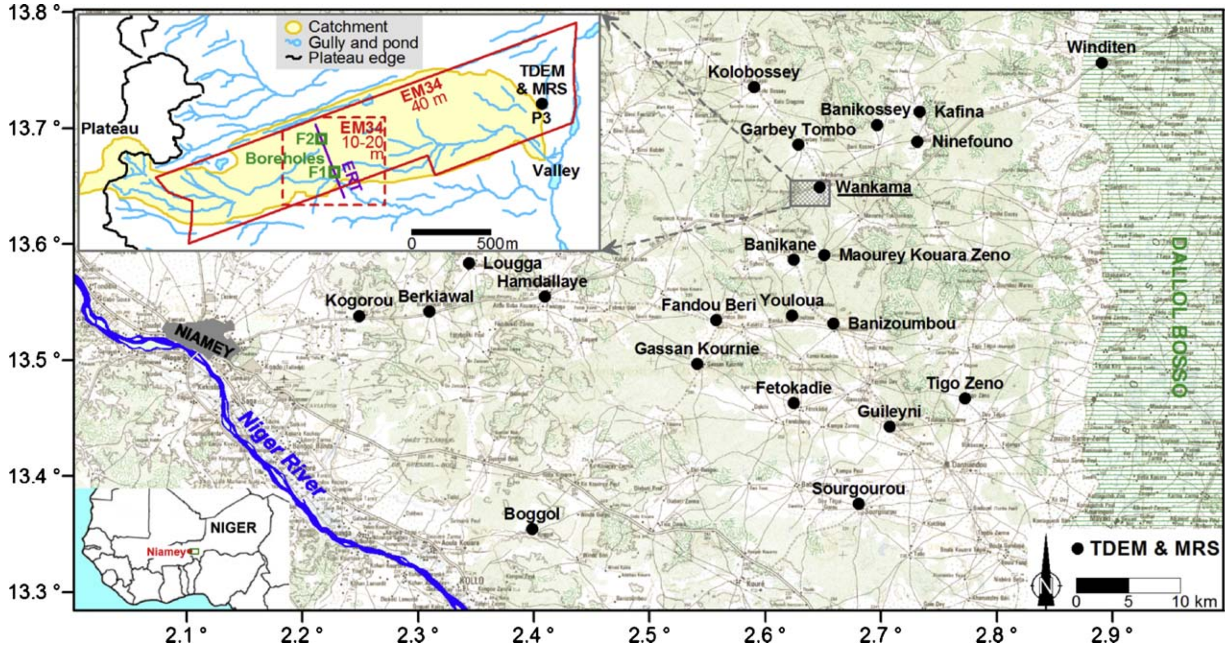

Fig. 1. Location of the study area. Small insert top-left: Zoom-in on the Wankama catchment (modified after [3]).

Fig. 1. Localisation du site d'étude. Petit encart en haut à gauche : zoom sur le basin versant de Wankama (modifié d'après [3]).

3. Geophysical implementation

Two major scales were studied. At the local scale, a typical watershed (Wankama catchment, 1.9 km^2) was studied to estimate drainage and aquifer recharge through a sandy alluvial fan of $\sim$0.6 km^2 [22]. Electromagnetic mapping and ERT were used to evaluate the electrical resistivity in three dimensions. Electrical resistivity is linked to the porosity, the water content and electrical conductivity of the water, and is thus adapted to investigations of the unsaturated zone: infiltration zones are characterized by variations of resistivity because they produce changes in porosity, water content or water salinity. For electromagnetic mappings, a Geonics EM-34 electromagnetic device was used in horizontal dipole mode with three intercoil spacings (10, 20 and 40 m), which provided maps for three different depths of investigation. The 40-m-spacing array was used to investigate the whole catchment (1.9 km^2), while 10-m-spacing and 20-m-spacing were implemented on the alluvial fan area (Fig. 1, small insert). ERT was carried out using a Syscal R2 resistivity meter along a profile to investigate down to 38 m deep below the soil surface. The acquisition and the interpretation were performed combining 2 arrays, the Wenner and Dipole–Dipole, taking advantage of their different sensitivity to 2D distribution of the ground resistivity. Electrical resistivity loggings were used to calibrate ERT in unlined bores (F1 and F2, Fig. 1 small insert) down to 25 m. Hydrological and chemical analyses on borehole cuttings were used for water and solutes contents analyses [22].

At a larger scale, MRS were performed on 22 sites in December 2005 and November 2006 in order to better constrain the aquifer characteristics [1,27]. The MRS method allows estimates of the effective porosity and the permeability of the aquifer [19]. Measurements were performed with the Numis$^{\text{Plus}}$ device with an eight-square-shape loop of 50 or 75 m side. MRS data were inverted firstly by automatic smooth inversion and secondly with a fixed aquifer geometry in order to avoid problems of equivalence and to estimate the mean water content of the aquifer (Fig. 2). The geometry was fixed according to available hydrogeological information: water table depth measured in neighbouring wells, and depth of the clayey aquiclude estimated by a dense network of deep boreholes. In addition, TDEM soundings were performed on each site surveyed by MRS and at logging boreholes (F1 and F2) in the Wankama catchment. TDEM soundings are sensitive to electrically conductive layers down to a few hundred meters [6,13]. The main objectives were to accurately determine the depth of the conductive clayey aquiclude (Fig. 2) and to improve MRS inversion. A Tem-Fast 48 device from AEMR Technology, the Netherlands was used with three loop configurations (a small coincident loop of

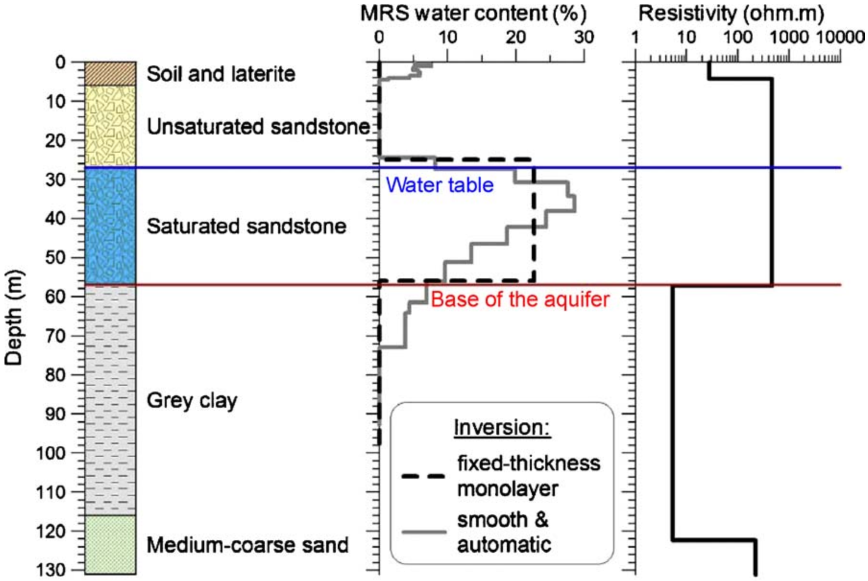

Fig. 2. Typical example of MRS and TDEM results compared with simplified geological description (Kolobossey borehole).

Fig. 2. Exemple typique de résultats RMP et TDEM, en comparaison avec une description géologique simplifiée (forage de Kolobossey).

25 × 25 m^2; a larger coincident loop of 100 × 100 m^2; and a central loop with a 100 × 100 m^2 transmitter loop and a 25 × 25 m^2 receiver loop at the centre of the transmitter). TDEM soundings for each site were jointly inverted taking into account magnetic viscosity and induced polarisation effects, in order to increase the reliability of the interpretation [8].

4. Results

4.1. Unsaturated zone

At the scale of the whole Wankama catchment (1.9 km^2), EM mapping (intercoil spacing of 40 m) showed high apparent resistivity (50 to 1000 ς.m) with lower values located downslope (Fig. 3). In the sandy fan area (0.6 km^2), the results of EM mappings (intercoil spacing of 10 and 20 m) showed a distinctly higher apparent resistivity below the alluvial fan (Fig. 3). The ERT shows a discontinuous conductive layer (∼50 ς.m) between ∼3 and ∼8 m deep (Fig. 4). Above and below this layer, the resistivity is higher and corresponds to typical values of dry sand. Where discontinuities appear in the intermediate conductive layer, the resistivity at depth is lower (∼1000 ς.m) than below the conductive layer (∼5000 ς.m). These results were confirmed by two deep resistivity loggings (20 and 25 m), one crossing the conductive layer, and the other in a discontinuity (Fig. 4).

Geochemical analyses showed that the decrease of electrical resistivity in the unsaturated zone is linked to higher solute contents of the pore water [22]. The conductive layer was thus interpreted as a discontinuous mineralized layer between ∼3 and ∼8 m deep. Increased salinity of the pore water may have been caused by high evapotranspiration which does not allow the water to infiltrate deeper than 3–8 m and which concentrates atmospheric solute. MR soundings, which were performed just after the rainy season, show low water content ($< 8\%$) in the unsaturated zone down to 12 m with no water detected below 12 m (ex. Fig. 2, automatic smooth inversion). This result is consistent with weak or non-existent drainage down to 12 m.

4.2. Saturated zone

The MRS water content was shown to be positively correlated with the specific yield estimated on six sites by pumping tests (Fig. 5A). The MRS water content always displayed higher values than the specific yield. This was explained by the fact that part of the water detected by MRS cannot be extracted by pumping tests because of capillary forces [1]. After calibration using an empirical conversion equation [19,27], the permeability values estimated by MRS showed uncertainties close to those obtained by pumping tests (Fig. 5B).

The water table depth estimated by MRS was shown to be in good agreement with direct measurements in

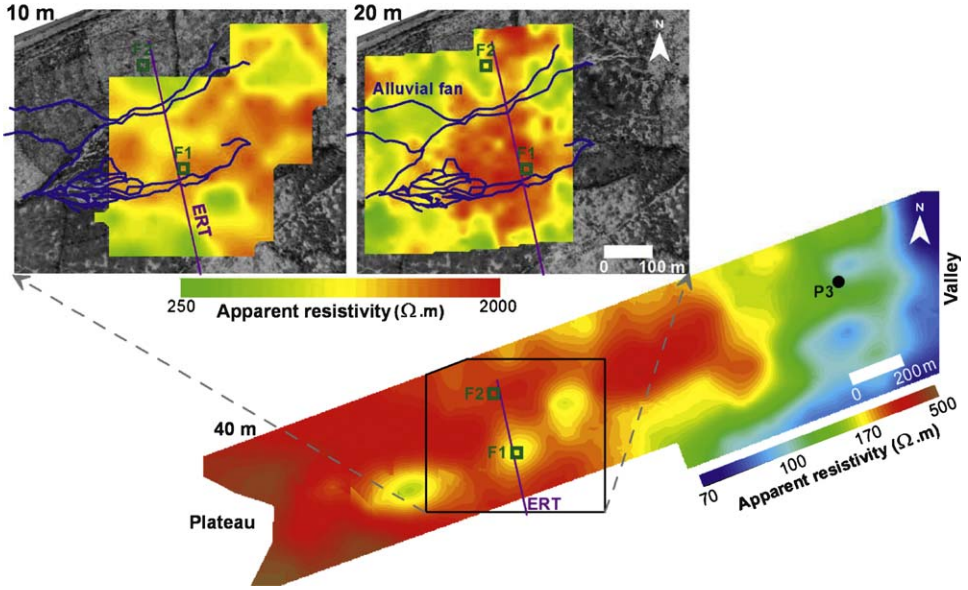

Fig. 3. EM34 mapping. Intercoil spacing is reported on the top-left of each map. (New interpretation after [22]).

Fig. 3. Cartographie EM34. L'espacement entre bobines est indiqué en haut à gauche de chaque carte. (Nouvelle interprétation d'après [22]).

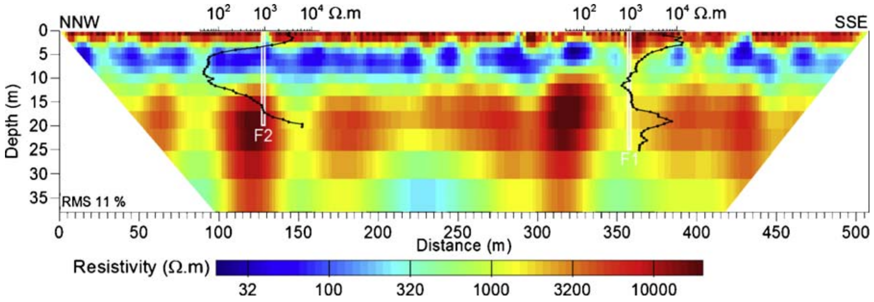

Fig. 4. Electrical resistivity tomography and boreholes logging, Wankama catchment. (New interpretation after [22]).

Fig. 4. Tomographie de résistivité électrique et diagraphie en forage, bassin versant de Wankama. (Nouvelle interprétation d'après [22]).

wells, but the uncertainty from the MRS result was much higher (13% and about one centimeter, respectively) [27]. The base of the aquifer (grey conductive clayey layer) was poorly defined with MRS but accurately estimated (mean uncertainty of ± 1 m) with TDEM (Fig. 5C).

5. Discussion

5.1. Combining geophysical methods

Combining results obtained from different geophysical surveys helped to validate methods and to reduce uncertainty on the interpretation. At the local scale (fan area of Wankama catchment, 0.6 km^2), the comparison of four electric-electromagnetic methods (Fig. 6) showed the consistency of all results. At borehole F1, both ERT and logging show mainly high resistivities with a slight decrease of resistivity between 5 and 15 m depth. This decrease of resistivity is not accurately seen by the TDEM interpretation because of the lack of sensitivity of TDEM method to resistive grounds. The increase of resistivity below 15 m can explain the higher apparent resistivity of the 20-m-spacing EM34 measurement compared to the 10-m-spacing one. At F2, the layer between 5 and 15 m depth is clearly conductive (80 ς.m) for ERT and for logging. For TDEM it appears as an 18-m-thick conductive layer (125 ς.m). This conductive layer is in agreement with the apparent resistivity of the 20-m-spacing EM34, which is lower (480 ς.m) than the nearby F1 (1000 ς.m). At depth, ERT suggests that the resistivity is higher below F2 than

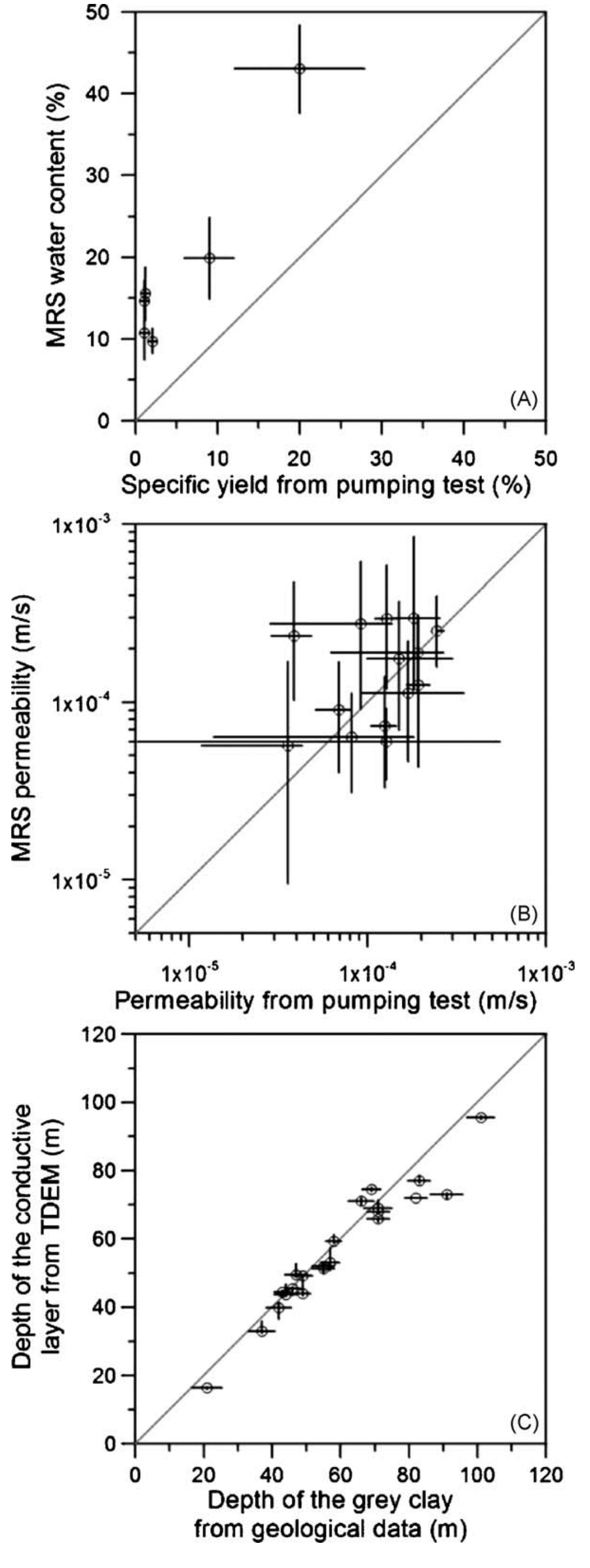

Fig. 5. Estimates of the hydrodynamic properties and geometry of the aquifer using MRS and TDEM. (A) Porosity. (B) Permeability. (C) Depth of the aquifer basement (clayey layer).

below F1, which is consistent with the 40-m-spacing EM34, which shows an apparent resistivity of 210 ς.m near F2 and 160 ς.m near F1.

At the catchment scale (1.9 km^2), the results of EM mapping showed a general decrease in apparent resistivity from upslope to downslope. This trend was previously explained by a decreasing thickness of the vadose zone with topography [22]. TDEM results revealed however that there is no significant electrical resistivity contrast between the vadose and the saturated zones whereas a strong contrast is observed between the saturated zone ($\geq$ 200 ς.m) and the clayey substratum ($\sim$5 ς.m) (Fig. 2). The trend observed at the catchment scale with EM mapping was thus reinterpreted as the result of a decreasing thickness of the whole aquifer (unsaturated and saturated) rather than to a shallower depth to the water table.

For the inversion of MRS data, the geometry of the aquifer was fixed according to geological information in order to better constrain the estimation of the water content. However, the geometry of aquifers is usually not as well documented as in SW Niger. In such a case, MRS can be complemented by TDEM, which may provide an accurate estimation of the depth of a clayey aquiclude. In SW Niger, when using TDEM results for fixing the bottom of the aquifer, the uncertainty on the MRS water content (29%) was close to that obtained using geological information (23%).

5.2. *Recharge process*

In semiarid areas, surface water–groundwater fluxes are often limited in time and space and direct measurements are difficult to obtain [24]. In the Wankama catchment, the higher resistivity measured below the fan area and decreases in resistivity beneath discontinuities in the mineralized layer (Fig. 4) suggest both a leaching of this mineralized layer and deep infiltration [22]. While deep infiltration and drainage were reported to occur only through endorheic ponds in SW Niger [20] geophysical results combined with geochemical analyses demonstrate that deep infiltration and groundwater recharge can also occur episodically through alluvial fans. This case study demonstrates that subsurface resistivity mapping can delineate areas where deep drainage occurs, which would be difficult using classical hydrological surveys.

Fig. 5. Estimation des propriétés hydrodynamiques et de la géométrie de l'aquifère par RMP et TDEM. (A) Porosités. (B) Perméabilités. (C) Profondeur du mur de l'aquifère (couche argileuse).

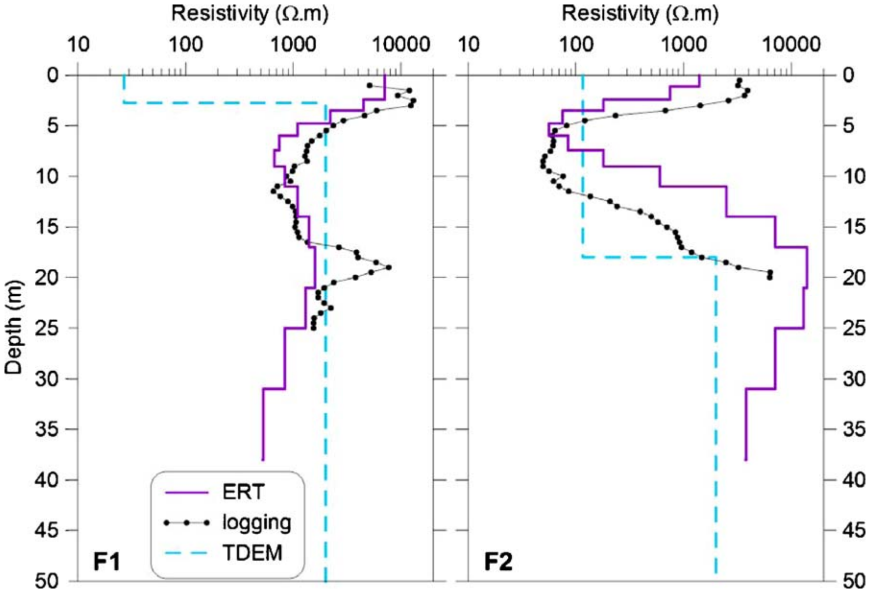

Fig. 6. Comparison of resistivities obtained with independent methods, Wankama catchment.

Fig. 6. Comparaison des résistivités obtenues avec des méthodes indépendantes, bassin versant de Wankama.

5.3. Estimate of groundwater recharge

In semiarid areas, low annual rainfall amounts combined with high evapotranspiration rates imply that recharge rates of unconfined aquifers are difficult to estimate. Various methods exist to estimate recharge, most of them requiring an accurate knowledge of the aquifer porosity [25]. In regions with significant water table fluctuations, recharge can be quantified using the water table fluctuation method [15]:

$$R = Sy \cdot \Delta h \qquad (1)$$

where R is the recharge rate ($L.T^{-1}$), Sy is the porosity that is affected by the variations in saturation (usually the specific yield, dimensionless) and Δh is the change in water level through time ($L.T^{-1}$). The history of the water table movement needs to be considered to choose a relevant value of Sy. In the study area, the specific yield (1–2%) measured by dewatering the aquifer (i.e. by pumping tests) underestimates the porosity parameter [12,27] because the long-term water table rise occurs mainly in the unsaturated zone with a residual water content lower than the amount of capillary water remaining after pumping. Capillary water is known to be at least partially detected by MRS, since the MRS water content shows higher values than the specific yield (Fig. 5A). Since no water was detected by MRS in the deep unsaturated zone ($>$ 12 m, e.g. Fig. 2), it can be expected that the porosity affected by the rise of the water level (i.e. total porosity minus residual water content in unsaturated zone) is close to the MRS water content. Using the average MRS water content (13%) and the average rise in the water table (0.18 m/yr, 1991–2007), net groundwater recharge was estimated at 23 ± 7 mm/yr [12,27].

5.4. Aid for groundwater modelling

Prior to MRS and TDEM surveys, a first joint surface-groundwater modelling was implemented for predicting the evolution of the groundwater resource considering changes in annual runoff and recharge through ponds depending on rainfall. First, a runoff model [2] allowed us to calculate the volume of water that is concentrated in endorheic ponds and contributes to groundwater recharge. Then a groundwater model was built considering the recharge simulated by the runoff model [21]. The aquifer matrix parameters (porosity and permeability) were tuned to fitting the observed water levels in transient mode for a period of 12 years (1992–2003). During the calibration process, a classical equivalence [4,7] between parameters occurred: various combinations of recharge rates, recharge point locations, porosity and permeability values can be used to represent piezometric levels. Independent estimates of the range of aquifer matrix parameters may improve cross-validation of the surface and groundwater models.

Because MRS results are more numerous (22 values) than pumping tests (14 values of permeability and 6 values of specific yield), the range of values estimated by MRS was considered more representative of the aquifer than the range obtained by pumping tests [1]. In addition, MRS water content (~ effective porosity [27]) is a more appropriate porosity parameter for modelling the long-term rise of the water table than the specific yield estimated by pumping tests.

The range of permeabilities (Fig. 7A) used in the first groundwater model (from 1.0×10^{-6} to 1.2×10^{-3} m/s) was larger than the range of permeabilities estimated by MRS (from 1.1×10^{-5} to 3.0×10^{-4} m/s). The porosity values used in the groundwater model were underestimated compared to MRS water content (Fig. 7B): 75% of porosity values used in the model are lower than 8% while the average MRS water content is 13%. Because of the equivalence between recharge and porosity (cf. Eq. (1)), underestimating the groundwater recharge rate causes an underestimation of the aquifer porosity. The recharge rate in the initial model was computed using the runoff model, which did not take into account recharge flows below alluvial fans shown by electrical mapping in the unsaturated zone. This can explain the underestimation of porosity in the initial model.

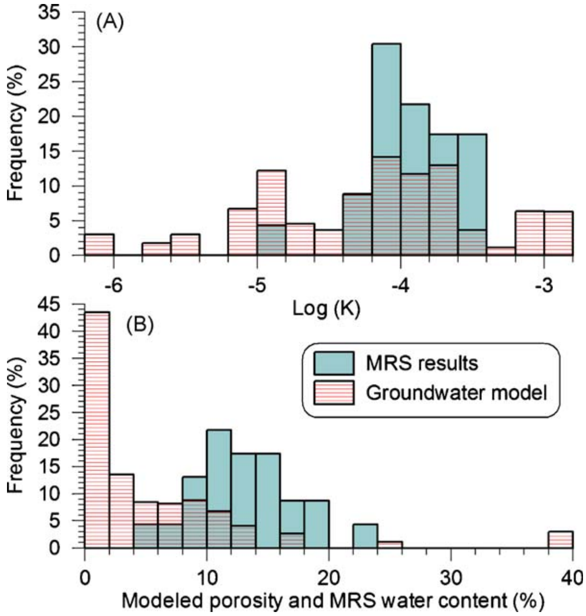

Fig. 7. Statistical distribution of MRS results and initial groundwater modelling parameters. (A) Permeability. (B) Porosity.

Fig. 7. Distribution statistique des résultats RMP et des paramètres de la modélisation hydrogéologique. (A) Perméabilité. (B) Porosité.

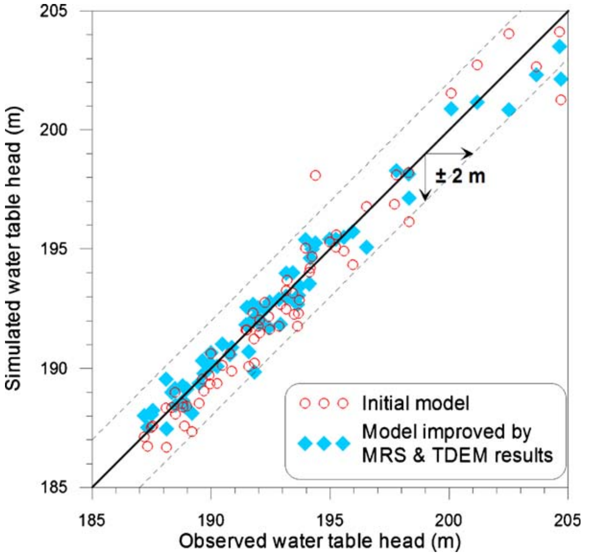

Fig. 8. Comparison of simulated water table heads with piezometric measurements in 67 wells (May 2003). In the initial model, permeability and porosity values were arbitrary chosen and the base of the aquifer was roughly defined. Improved model takes into account MRS water contents, MRS permeabilities and depths of the base of the aquifer obtained by TDEM results. The average aquifer recharge was 5.3 mm/yr in the initial model and is 23 mm/yr in the model taking into account geophysical results.

Fig. 8. Comparaison des niveaux piézométriques modélisés et mesurés sur 67 puits (mai 2003). Dans le modèle initial, les perméabilités et porosités ont été choisies arbitrairement et le mur de l'aquifère a été défini approximativement. Le modèle amélioré prend en compte les teneurs en eau RMP, les perméabilités RMP et les profondeurs du mur de l'aquifère obtenues par TDEM. La recharge moyenne de l'aquifère était 5,3 mm/an dans le modèle initial et est de 23 mm/an dans le modèle qui prend en compte les résultats géophysiques.

The groundwater model was modified using the range of MRS water content and permeability, and improving the geometry of the aquifer basement with TDEM results. The recharge rates were tuned for fitting the measured piezometric levels. The simulated heads fit observed water levels (absolute residual mean of 0.61 m) if a constant and homogeneous recharge of 18 mm/yr over the whole area is added to the local recharge computed by the runoff model (Fig. 8). This result suggests that deep infiltration below alluvial fans and/or rain-fed millet fields previously assumed as minor [20,21] is probably significant for the aquifer balance.

6. Conclusion and perspectives

This study of an unconfined aquifer in semiarid Niger represents a good example of the efficiency of using complementary geophysical methods for improving:

- understanding of recharge processes in a porous aquifer;
- estimate of the range of aquifer parameter values;
- density of measurements required for a better parameterization of hydrological models.

The main results can be summarized as follows:

- lateral and vertical mapping of electrical resistivity of the unsaturated zone (by EM mapping and ERT) allowed us to delineate preferential pathways for deep infiltrations through alluvial sandy fans;
- resistivity mapping is useful for characterizing the geometry of aquifers: the TDEM method allows a fast and accurate estimate of the conductive layer such as a clayey aquifer basement;
- the MRS method supplemented by piezometric water level fluctuations can be used to estimate the aquifer recharge rate;
- MRS results allowed a robust statistical analysis of the distribution of porosity and permeability within the saturated aquifer. The statistical distribution of MRS parameters can be used to better constrain numerical groundwater modelling.

The methodology used in our study could be applied to numerous unconfined aquifers in semiarid areas, even if the long-term hydrodynamics (stable or declining water table) may differ. Of particular interest is the use of MRS, which could improve groundwater modelling and prediction of changes in semiarid regions where groundwater reserves are increasingly pumped for irrigation and domestic uses.

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