Paleochannel groundwater discharge to the River Niger in the Iullemmeden Basin estimated by surface geophysics and piezometry

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Summary

In drylands groundwater is often the only perennial source of freshwater to sustain domestic water supplies and irrigation. Knowledge of the pathways and dynamics of groundwater discharge and recharge is therefore essential to inform sustainable and rational management of limited water resources. The lower valley of the Dallol Maouri in Niger represents a large fossil tributary (i.e.

paleochannel) of the River Niger and drains groundwater regionally from the Iullemmeden Basin through coarse-grained Quaternary sediments. The objective of this paper is to quantify groundwater discharge within this paleochannel using piezometry and surface geophysics (TDEM: Time Domain Electromagnetics, MRS: Magnetic Resonance Sounding). TDEM and MRS experiments, conducted at 21 sites along 3 transects, show the mean thickness of Quaternary alluvium varies from 11 m to 18 m with effective porosities ranging from 18% to 38% and a hydraulic conductivity of 2×10^{-3} m/s. Dense piezometric surveys along drainage channel reveal hydraulic gradients of 0.2‰ to 0.3‰ that generate Darcy fluxes of 1000 to 2000 m^3/day (dry season, i.e. minimum value). Paleochannel discharge, which currently provides baseflow to the River Niger, is the focus local demand to increase access to water for drinking, livestock watering, and supplementary irrigation.

Keywords: Semi-arid area, groundwater flow, alluvial aquifer

1 Introduction

Drylands are characterized by ephemeral rivers (D’Odorico and Bhattachan 2012; Tarnavsky et al. 2013; Koch and Missimer 2016 ; Davies et al. 2016). The Sahel of West Africa features strong seasonal variations in rainfall, causing intense runoff to topographic depressions that facilitate focused groundwater recharge (Favreau et al. 2009). Climate change intensifies precipitation, resulting in fewer but heavier rainfalls. This transition has been observed in the Sahel (Taylor et al. 2017) and is expected to amplify focused groundwater recharge (Cuthbert et al. 2016; 2019; Taylor et al. 2013a; Goni et al. 2021). Recent high-resolution modelling of Sahelian climate suggests further that the projected intensification of rainfall by climate change is even greater than that estimated previously by General Circulation Models (Berthou et al. 2019). Notwithstanding potential increases in groundwater recharge from the amplification of heavy rainfalls, growing demand for freshwater is placing increasing pressure on perennial groundwater resources (Taylor et al. 2013b; DeGraaf et al. 2019) whose discharges sustain dryland ecosystems.

In the drylands of Niger, groundwater is a vital source for supplying drinking water to most large cities and rural areas as well as for supplying livestock and irrigation (Nazoumou et al. 2016). Recent hydrogeological studies of the unconfined aquifer of Continental Terminal in the southwestern Iullemmeden Basin have shown a rise in the water table since the 1960s (Favreau et al. 1998; Favreau 2000; Leduc et al. 2001; Favreau et al. 2002; Leblanc et al. 2008, Favreau et al. 2009). Knowledge of the pathways and dynamics of groundwater discharge contained in Quaternary alluviums from valleys of fossil tributaries is essential for the sustainable and rational management of these vital resources. In the arid Heihe Basin of China for example, paleochannel groundwater discharges to the rivers are considered critical to regulating the hydrological cycle and ecosystem health (Yao et al. 2016; 2018; Zhao et al. 2016).

Several studies have demonstrated the efficacy of geophysical surveys for characterizing the geometry and lithology of paleochannels in drylands in order to assess the availability of groundwater. Oladunjoye et al. (2020) characterized the geometry of the Ilora Valley in southwestern Nigeria using vertical electric soundings. Similarly, Owen and Dahlin (2005) delineated the extent and thickness of the Quaternary infill of the Umzingwane Valley in Zimbabwe using Vertical Electric Soundings (VES). In drylands of Australia, Airborne Electromagnetic (AEM) geophysical surveys and piezometry have been used to define the dimensions of the Gallingarra Paleochannel and evaluate the groundwater discharge to the Moore River (Speed and Killen 2020).

Magnetic Resonance Sounding (MRS) is a non-invasive geophysical method (Legchenko and Valla 2002) which makes it possible to obtain hydrogeological parameters of an aquifer by directly measuring a signal emitted by the hydrogen protons of the water molecule (Vouillamoz et al. 2008). TDEM (Time Domain Electromagnetism) is an electromagnetic geophysical sounding method that allows determining the resistivity as a function of depth from the diffusion of a transient electromagnetic field (Fitterman and Stewart 1986; Goldman et al., 1991; Descloitres 1998). The combination of these two methods has already been successful applied in Niger in the study of the superficial aquifer of the Continental Terminal (Vouillamoz et al. 2008; Boucher et al. 2009a, Boucher et al. 2009b, Boucher et al. 2012) and on the unconfined Quaternary aquifer in the Komadugu Yobé valley of the Lake Chad basin (Descloitres et al. 2013).

The lower valley of Dallol Maouri (Fig. 1), is one of the fossils tributaries of the River Niger (paleochannel) which drains regional groundwater through Quaternary alluvium. This area is one of the most suitable regions of Niger for irrigation (Cochand 2007; Dambo 2007) and has been the subject of several hydrogeological studies since the 1970s. Early studies carried out by FAO (1970), exploited deep boreholes and constructed several piezometers to characterize the hydrodynamic parameters of aquifers in the area through pumping tests; the overall direction of groundwater flow and recharge areas were also mapped (FAO 1970). Gaoh (1993) characterized the aquifers of the Continental Terminal through a geophysical investigation and (Guéro 2003) through a hydrogeochemical and hydrodynamic approach. Recently, (Abdou Ali (2018) characterized aquifers through electric soundings, increasing hydrogeological knowledge of the Dallol Maouri valley. These previous studies examined the whole basin of Dallol Maouri whereas here we focus on the Quaternary formations of the lower valley of the Dallol Maouri.

Applying MRS and TDEM, the objective of this paper is to quantify groundwater discharge in the lower valley of the Dallol Maouri valley in the Iullemmeden Basin. TDEM (Time Domain Electromagnetism) and MRS (Magnetic Resonance Sounding) geophysical surveys were carried out on three transverse transects and a longitudinal transect of the study area. In the paleochannel of the lower Dallol Maouri, twenty-one TDEM and MRS soundings were conducted in order to characterize the geometry of aquifers and their hydrodynamic parameters including aquifer transmissivity. Piezometric variations at leveled piezometers along the paleochannel were used for to assess prevailing hydraulic gradients and quantify groundwater flow.

2 Presentation of the study area

2.1 General context

Niger has a hydrographic network consisting essentially of temporary rivers with the exception of the main channel of the River Niger. The hydrographic basin of River Niger in Niger is considered to host substantial groundwater resources, contained in the geological formations of the Iullemmeden basin and in the alluvial deposits of the valleys of the fossil tributaries of the River Niger (Favreau et al. 2012; MH/A 2017). The valley of the Dallol Maouri is a fossil tributary on the eastern bank of the River Niger in Niger and has a drainage area of ~45,000 km² (Fig. 1). It is the southernmost area of Niger and the most humid. Mean annual rainfall recorded at Gaya (Fig. 2) varies from 600 to over 1000 mm occurs over seven months of the year from April to October with the most intense months of rainfall from June to September. This region is classified as semi-arid within the Sudanese hydro-climatic zone. Diurnal temperatures vary considerably by values that can exceed 14°C. Potential evapotranspiration, estimated by the Penman method, is 2360 mm per year.

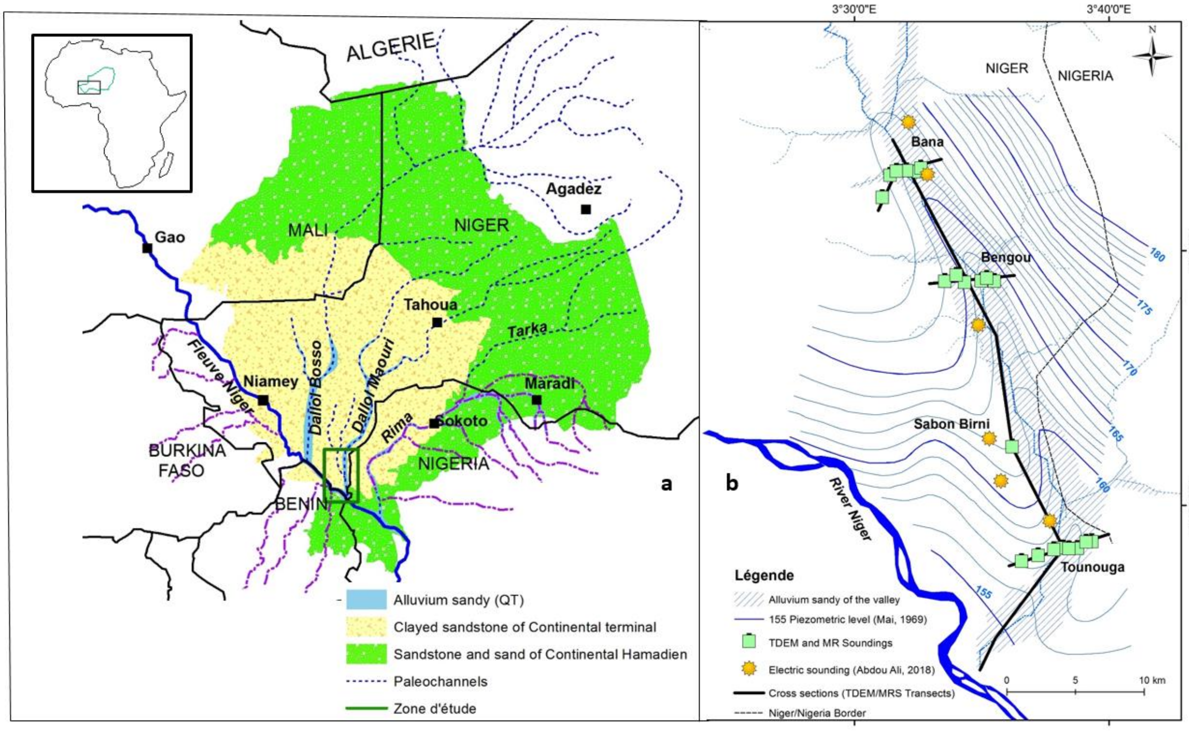


Fig. 1 Maps of the Dallol Maouri: (a) regional drainage and surface geology with inset map of Africa showing its continental context; and (b) location in the lower valley of the Dallol Maouri of TDEM and MRS drilling sites as well as historic piezometric contours from the 1960s (FAO, 1969).

The valley of the Dallol Maouri is characterized by tropical ferruginous soils with little or no leaching of clays and ferralitic soils on the plateaux and terraces of the River Niger. Hydromorphic soils are found in the valleys of the Dallol and the River Niger (Gavaud 1977). Discharges of the regional aquifer in the lowlands of the valley form a string of ponds that become interconnected during the rainy season and flow towards the River Niger. Due to its favorable climatic conditions for agriculture and livestock, this area is experiencing strong demographic pressures. The Gaya locality has an area of 4044km^2 (Dambo 2007). The population of the Gaya area has increased from 164 000 inhabitants in 1988 to over 261 000 inhabitants in 2012, representing a density of 65 inhabitants/km^2 and annual growth rate of 3.4% (INS 2012); these changes are increasing freshwater demand for domestic and agricultural purposes.

2.2 Geological context

In the lower valley of the Dallol Maouri, the surface geology comprises Quaternary alluvium. On the plateau, geological formations comprise a detrital complex of Oligocene age, siderolithic series of Ader Doutchi consisting of fine to medium clayey oolitic sands (CT1), clayey sandstones of CT3, and sandstones of CH, (BGR/ABN 2019) (Fig. 2).

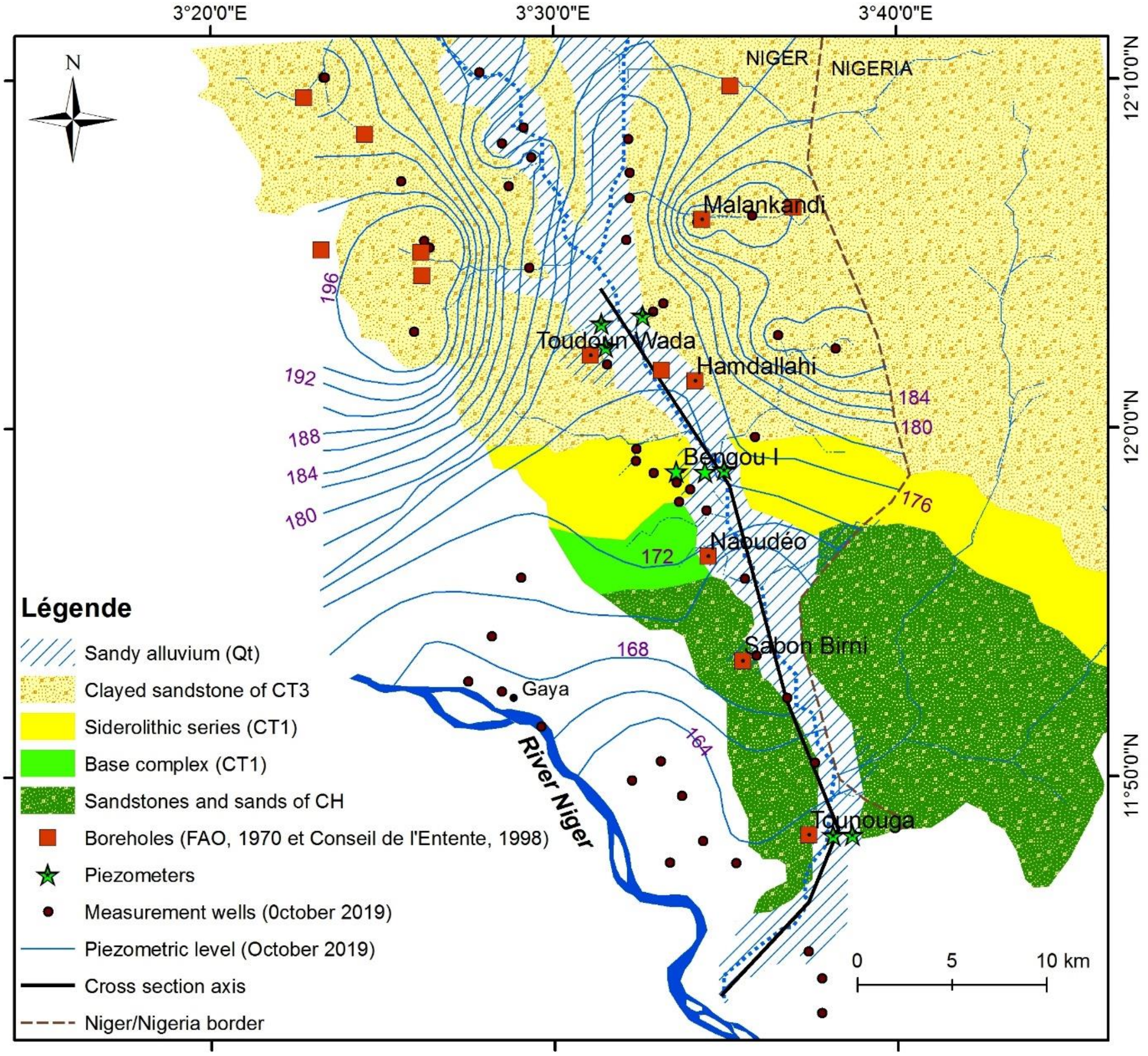


Fig. 2 Surface geology and contemporary (2019) piezometric contours of the unconfined aquifer in the Dallol Maouri valley and interfluves of southwestern Niger (BGR/ABN, 2019).

A geological section along the longitudinal axis of the Dallol Maouri valley, presented in Fig. 3, is based on a synthesis of borehole logs with depths varying between 55 and 346 m, electrical soundings from previous work (CGG 1968; Abdou Ali 2018), and geological sections found in the literature (FAO 1970; Guéro 2003; BGR/ABN 2019). This cross-section presents a succession of four (4) geological formations:

Precambrian basement rocks are reached by Bengou I borehole at a depth of 342 m (FAO 1970). This lithological surface is found depths of 11 m at Talambou (Northwest of Gaya), 375 m in Dosso (north of the study area), and sub-outcrops on the banks of the Niger River between Koulou and Sia (Guéro 2003), west of the study area.

The Lower Cretaceous Continental Hamadien is equivalent to the continental deposits of the Illo Formation of the Nigerian part of the Iullemmeden Basin (BGR/ABN 2019). This formation outcrops in the southern part of the study area between Sabon Birni and the Niger River. Its thickness is estimated at 323 m at the borehole of Bengou I (FAO 1970). This geological formation comprises alternating fine to coarse sands and mostlyclayey sandstones. Weathered sandstone formations of the Bengou sector are succeeded by more clayey sandstone formations at the village of Sabon Birni (Fig. 3). In places, there are traces of lignite and pyrite strewn in the sandstone formations.

Marine deposits of the Paleocene-Eocene (Tertiary) are of low thickness consisting mainly of marl, marl-limestone, gray to whitish clays and attapulgites in the western part of the Dallol Fogha (Guéro 2003). These mark the upper boundary of the sandstone formations of the Continental Hamadien. Its thickness is estimated at 3 m at the Toudoun Wada borehole and is absent under the alluvium between Bana and Hamdallahi (Fig. 3).

The Continental Terminal (CT), equivalent to the Gwandu formation in Nigeria (Greigert 1966), outcrops on all plateaux of the Bana and Bengou sectors but is not found in the valley of the study area. The CT is traditionally subdivided into three main lithological units: the siderolithic series of Ader Doutchi (CT1), the sandy clay series with lignites (CT2), and the clayey sandstones of Middle Niger (CT3) (Greigert 1966). The siderolithic series is characterized by alternating loose sands and oolites. The thickness of this formation is estimated at 20 m from the borehole log of Malankadi, 5 km north of Bana (Conseil de l'Entente 1998) and 75 m in Dogondoutchi (Guéro 2003), 170 km north of the study area. CT2 does not appear in the study area. It is a formation characterized by the intercalation of fine to coarse sands and gray clay to lignite. The thickness of this formation is estimated at 60 m at Dogondoutchi (Guéro 2003). The Middle Niger clayey sandstone series (CT3) constitutes the most extensive outcrop formation in the study area. CT3 is essentially made up of alternating ferruginous sandstone and yellow and reddish clays. In the study area, its thickness is estimated to be 15 m from the borehole log at Toudoun Wada and 175 m at Dogondoutchi (Guéro 2003), north of the study area.

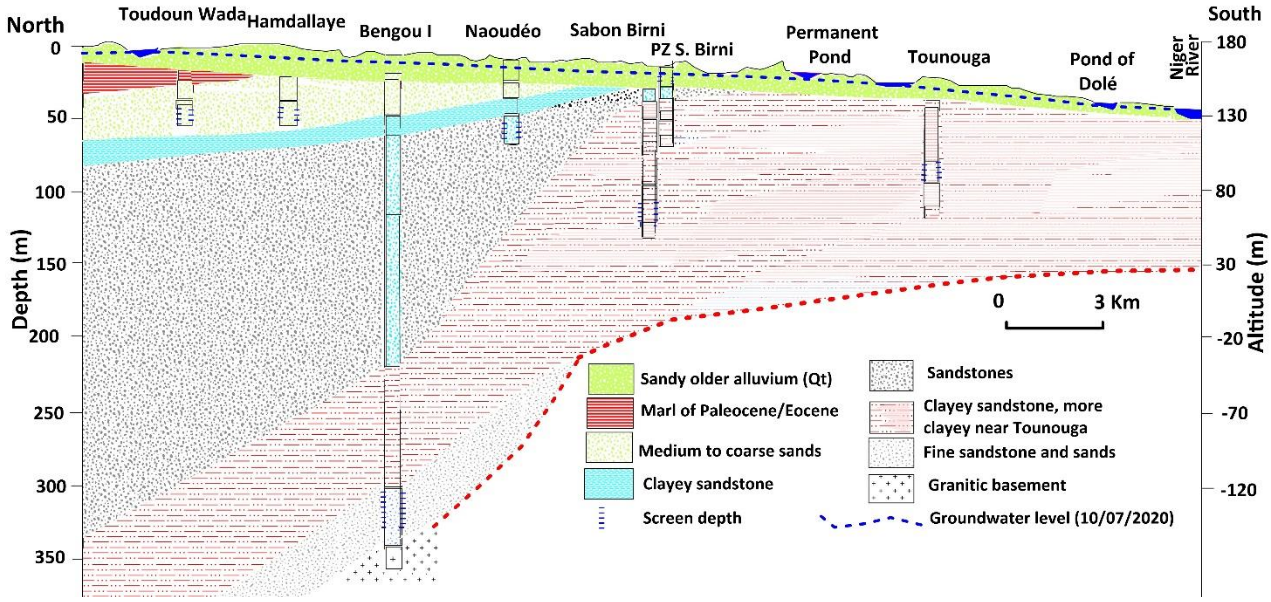


Fig. 3 Geological cross section along the longitudinal axis of the lower Dallol Maouri valley (cross section is presented by a line on the Fig. 2)

2.3 Hydrogeological context

Previous hydrogeological studies (Greigert 1957; FAO 1970; Greigert 1978; Armand 1987; Gaoh 1993; Guero 2003; Abdou Ali 2018) have described the general characteristics of the aquifers of the Dallol Maouri valley. Most groundwater is considered to flow in detrital terrigenous sedimentary formations of the Cretaceous (Continental Intercalaire/Hamadien) and the Tertiary-Quaternary formations (Continental Terminal and alluvium valleys). In the lower valley of the Dallo Maouri, groundwater is located in alluvial formations and terrigenous detrital formations of the Continental Hamadien (FAO 1970); these two formations form an unconfined aquifer in the valley with a thickness of 220 m in the Bengou sector (Guéro 2003). The Continental Hamadien formations present a confined aquifer between 300 and 342 m deep. In the northern part of the study area where the formation of Continental Hamadien is overlain by Paleocene-Eocene marine formations.

The historic piezometric map (Fig. 1b) of the water table of the lower Dallol Maouri from 1969 shows a north-south flow along the axis of the valley with a hydraulic gradient of 0.3 ‰ (FAO, 1970). On the left bank plateau, the contours are rectilinear and there is an absence of evidence of human withdrawals from the unconfined aquifer during this period. The contemporary (2019) piezometric map (Fig. 2) also shows a north-south flow along the axis of the valley, with a very low gradient of 0.4 ‰. On the plateau, the flow converges towards the Dallol Maouri valley with a hydraulic gradient of 3 ‰ on both banks of the Dallol Maouri. The disappearance of contours 160 m and 155 m towards the outlet also highlights a rise in the unconfined aquifer of 4 to 6 m, the high values of the hydraulic head on either bank suggest that the plateaux may constitute recharge areas to the unconfined aquifer.

3 Materials and Methods

3.1 Surface geophysics: combined use of Time Domain Electromagnetism (TDEM) and Magnetic Resonance Sounding (MRS)

TDEM makes it possible to determine the vertical distribution of soil resistivity with depth (Descloitres 1998). Detailed descriptions of the method can be found in Fitterman and Stewart (1984), Descloitres (1998), and Reynolds (2011). Magnetic Resonance Sounding (MRS) is a non-invasive geophysical method (Legchenko and Valla 2002). This method makes it possible to obtain hydrogeological parameters of an aquifer by directly measuring a signal emitted by the hydrogen protons of the water molecule (Vouillamoz et al. 2008). Details of the method can be found in (Legchencko and Valla 2002). This method has the advantage of having information that is directly related to the mobile water content in the subsoil and a relaxation time related to the size of the pores (Schirov et al. 1991).

The hydrogeophysical parameters from MRS are the water content, which represents the part of the investigated volume occupied by mobile water (Legchenko et al. 2004; Lubczynski and Roy 2005), and the proton relaxation time constants T_1 and T_2, which provide information on the average pore size (Legchenko et al. 2002; Vouillamoz et al. 2007). Water content (θ_{MRS}), given by MRS, is comparable to the effective porosity (Lubczynski and Roy 2005). The hydraulic conductivity (K_{MRS}) and transmissivity (T_{MRS}) of the aquifer are deduced from these parameters using equations 1 and 2 (Kenyon 1997):

$$\boldsymbol{K_{MRS} = C_p \times \theta_{MRS}^{a} \times T_1^{b}} \quad \text{(eq. 1)}$$

$$\boldsymbol{T_{MRS} = K_{MRS} \times \Delta Z} \quad \text{(eq. 2)}$$

where *Cp*, *a*, and *b* are the parametric factors, dependent on the geology of the area, $\boldsymbol{\Delta Z}$ the thickness of aquifer. The factors *a* and *b* can take values 1 and 2 or 4 and 2 respective (Plata and Rubio 2008). The couple 1 and 2 is the most used and which gives satisfactory results (Plata and Rubio 2008; Lubczynski and Roy 2005; Boucher et al. 2009a; Vouillamoz et al. 2008; Chalikakis et al. 2008; Descloitres et al. 2013; Legchenko et al. 2017; Kemgang et al. 2019). The parametric factor *Cp* depending on the geology of the area, requires calibration with data from pumping tests (Chalikakis et al. 2008; Boucher et al. 2009a). The geological formations of the study area are similar to the geological formations of the intensely studied Continental Terminal (CT3) (Favreau 2000; Favreau et al. 2009; Boucher et al. 2009a). All the hydrodynamic parameters (K_{MRS} and T_{MRS}) were estimated on all the points of the soundings using the parametric factor ($C_P = 1.4 \times 10^{-8}$) determined on the unconfined aquifer of the Continental Terminal (Boucher et al. 2009a).

3.2 Field implementation

TDEM soundings employed Temfast 48, developed by Applied Electro Magnetism Research (AEMR Technology). This very light device, ~2 kg, enabled relatively deep soundings ranging from 50 to 200 m, recorded by a “nomad” mini-computer. For MRS soundings, NUMIS$^{\text{PLUS}}$ (which has an investigation depth of approximately 100 m) and NUMIS$^{\text{LITE}}$ (which has an investigation depth of approximately 50 m), developed by IRIS Instruments were used. Two campaigns of geophysical sounding (TDEM and MRS) were executed in December-January 2019 and April 2020. A total of twenty one (21) experiments were conducted, 20 sites on 3 transects perpendicular to the valley and one site at Sabon Birni. The first campaign was conducted at 13 sites. At each site, a series of 3 TDEM soundings were carried out with loops of 50 and 150 m, in coincident mode, and 150 × 50 in central mode. During the second campaign, only one TDEM sounding per site was carried out with a 100 m side loop at 8 sites. The characteristics of all MRS experiments are summarised in Table 1. Eight-square loops were used to minimize the effect of electromagnetic noise on sounding (Trushkin et al. 1994; Plata and Rubio, 2002).

3.3 Data inversion and assessment of the quality of sounding

TDEM soundings were inverted with TEM-RES software (AEMR Technology). The interpretation method adopted for the data follows that of Décloitres et al. (2013). For the inversion of the MRS, SAMOVAR_V11.6 software was used. The inversion is made by assuming a horizontally stratified tabular field (Vouillamouz 2003). The geological logs constrain the interpretation of the MR Soundings. The strategy adopted involved inverting the data into a "block" following a model of two (2) to three (3) layers consistent to the geology revealed by the geological logs and the TDEM results. To assess the quality of the data collected, two parameters were used. The first parameter is the signal-to-noise (S/N) ratio which must be greater than 4 (Descloitres et al. 2013), for a sounding to be considered of good quality. The second parameter is the difference between the average frequency of the MRS signal (Larmor frequency) and the average excitation frequency of the hydrogen protons which must be less than or equal to 1 Hz in absolute value, (Chalikakis et al. 2008). Each experiment showed a good signal to noise ratio (S/N) ranging from 6 to 77; differences between the average frequency of the MRS signal (Larmor frequency) and average excitation frequency of the hydrogen proton varied from -1.41 to 1.56 Hz.

3.4 Hydrogeological method

Darcy's Law is applied to estimate groundwater discharge in the Bana, Bengou and Tounouga areas and the average linear velocity of groundwater through equations 3 and 4, respectively.

$$\boldsymbol{Q} = -\boldsymbol{K} \times \boldsymbol{A} \times \boldsymbol{i} \qquad \text{(eq. 3)}$$

$$\boldsymbol{v} = (-\boldsymbol{K} \times \boldsymbol{i})/\boldsymbol{\phi} \qquad \text{(eq. 4)}$$

where $\boldsymbol{Q}$ is groundwater discharge (m^3/day) ;

$\boldsymbol{K}$ is the hydraulic conductivity of Quaternary alluvium (m/day);

$\boldsymbol{A}$ is cross-sectional area (m^2);

$\boldsymbol{i}$ is the hydraulic gradient (unitless);

$\boldsymbol{v}$ is the average linear groundwater velocity (m/day);

and $\boldsymbol{\phi}$ effective porosity $\boldsymbol{\approx\theta_{MRS}}$ (unitless).

Hydraulic conductivity $\boldsymbol{K}$ and aquifer thickness $(\Delta \boldsymbol{Z})$ were determined from surface geophysical soundings using TDEM and MRS. The hydraulic gradient was determined using observed variations in hydraulic head at levelled piezometers along the lower valley of Dallol Maouri

Table 1. Characteristics and results of MRS soundings in the lower valley of the Dallol Maouri

Site	Location		Formation	Loop Sharpe/size	Signal/Noise		Alluvium (Quaternary)				MARL (Paleocene-Eocene)			Sandstone (CH)	
	Longitude	Latitude			S/N	Δf (Hz)	θ_{MRS} (%)	K_{MRS} (10^{-3} m/s)	Δz (m)	T_{MRS} (10^{-2} m^2/s)	θ_{MRS} (%)	K_{MRS} (m/s)	Δz (m)	θ_{MRS} (%)	K_{MRS} (10^{-3} m/s)
Toudou Wada	3.518183	12.034861	CH	E 125 m	42	-0.06	-	-	-	-	-	-	-	26	0.8
Baro GF01	3.523093	12.049319	Q/P/CH	E 50 m	24	0.21	32	2	11	2	2	$\leq 10^{-6}$	4	32	0.4
Baro_Q1	3.527482	12.052118	Q/P/CH	E 100 m	21	-0.4	30	2	11	2	2	$\leq 10^{-6}$	6	35	0.4
Baro_Q2	3.533831	12.053284	Q/P/CH	E 100 m	20	-0.51	23	1.5	9	1.4	2	$\leq 10^{-6}$	6	30	0.3
Baro_Q3	3.541253	12.052517	Q/P/CH	E 100 m	10	-1.41	18	0.9	8	0.7	2	$\leq 10^{-6}$	6	32	0.5
Bana_GF02	3.544254	12.054242	Q/P/CH	E 100 m	10	-0.9	19	1	7	0.7	3	$\leq 10^{-6}$	7	29	0.4
Bengou P26	3.559065	11.980012	Q/CH	E 50 m	22	0.47	30	1.5	7	1	-	-	-	26	1
Bengou_Q1	3.565937	11.983333	Q/CH	E 100 m	19	0.46	34	0.7	16	1	-	-	-	20	0.2
Bengou P23	3.572120	11.979304	Q/CH	E 50 m	14	-0.07	38	2	18	3.6	-	-	-	20	2
Bengou GF01	3.582884	11.980524	Q/CH	S 75 m	10	-0.67	35	0.8	19	1.5	-	-	-	22	0.8
Bengou_Q2	3.587077	11.982084	Q/CH	E 75 m	8	-1.2	34	0.7	17	1	-	-	-	19	0.2
Bengou_CEG	3.591489	11.980006	CH	E 100 m	9	1.56	-	-	-	-	-	-	-	23	0.1
Sabon Birni	3.604858	11.87207	Q/CH	E 50 m	7	-0.36	34	0.8	10	0.8	-	-	-	9	0.01
Toun_CT_CH-1	3.610111	11.797124	CH	S 150 m	33	0.12	-	-	-	-	-	-	-	10	0.08
Toun_CT/CH-2	3.651577	11.809453	CH	S 150 m	10	0.43	-	-	-	-	-	-	-	11	0.08
Toun_Q1	3.631106	11.805919	Q/CH	E 100 m	10	0.02	23	3	7	2	-	-	-	3	0.01
Toun_GF01	3.636271	11.805167	Q/CH	S 75 m	9	0.27	18	2	10	2	-	-	-	4	0.06
Toun_Q2	3.645356	11.805219	Q/CH	S 75 m	6	0.48	19	0.6	9	0.5	-	-	-	7	0.06
Toun_GF02	3.645874	11.804921	Q/CH	S 75 m	8	0.29	33	2	11	2	-	-	-	14	0.05
Toun_Q3	3.620080	11.800585	Q/CH	E 50 m	16	-0.59	26	2	10	2	-	-	-	15	0.3
Toun_CT_CH-3	3.654995	11.809747	CH	E 50 m	10	-0.35	-	-	-	-	-	-	-	9	0.02

CH Continental Hamadien; Q Quaternary ; P Paleocene ; E Eight ; S Square ; S/N signal/noise ; θ_{MRS} MRS water content ; K_{MRS} MRS hydraulic conductivity ; Δz thickness of the saturated aquifer ; T_{MRS} MRS transmissivity. K_{MRS} and T_{MRS} were estimated using the parametric factor ($C_P = 1.4 \times 10^{-8}$) (Boucher et al., 2009a)

4 Results

4.1 Interpretation procedure for TDEM and MRS soundings

Figures 4 and 5 show detailed descriptions of lithological logs with evidence from MRS and TDEM experiments for Bengou I borehole and Sabon Birni piezometer, respectively. Evidence from Bengou I borehole (Fig. 4) shows a succession of four layers of varying resistivity that include two aquifer formations. The first (shallowest) layer (ρ (real resistivity) = 60 to 70 Ω·m) with a thickness of 15 m and effective porosity of 30% corresponds to unconsolidated Quaternary sediments in the lithological log. The second, more resistant layer (ρ =200 to 240 Ω·m) with a thickness of 30 m and effective porosity of 25%, corresponds on the lithological log to fine to coarse sands of CH. The third, more conductive layer (ρ = 13 to 20 Ω·m) over a thickness of 14 m, corresponds to fine clayey sandstones of the CH. The fourth layer (ρ = 150 to 200 Ω·m) encountered beyond a depth of 60 m, corresponds to the alternating hard and soft sandstones of the CH as suggested by the lithological the log. At Sabon Birni (Fig. 5), soundings reveal a succession of three layers of variable resistivity. The first (shallowest) layer (ρ = 90 to 137 Ω·m) with a thickness of 10 m and effective porosity of 34% corresponds to Quaternary sands. The second layer (ρ = 30 to 50 Ω·m) has a thickness of 20 m below a depth of 10 m and corresponds to fine to medium clayey sands of the CH. The third layer (ρ = 2 to 3 Ω·m) strating at a depth of 30 m is associated with clayey sandstones of CH.

The interpretation of soundings from these two sites enabled the calibration of inversion of the TDEM and MRS soundings of the lower valley of the Dallol Maouri. It emerges from this interpretation that Quaternary sands have a resistivity that varies between 60 and 130 Ω·m from Bengou to Tounouga. Predominantly hard sandstones of CH exhibit a resistivity greater than 200 Ω·m whereas clayey sandstone formations of the Bana-Bengou sector have a resistivity close to 15 Ω·m. The very fine clayey sandstones of the Sabon Birni-Tounouga sector reveal a very low resistivity around 3 Ω·m.

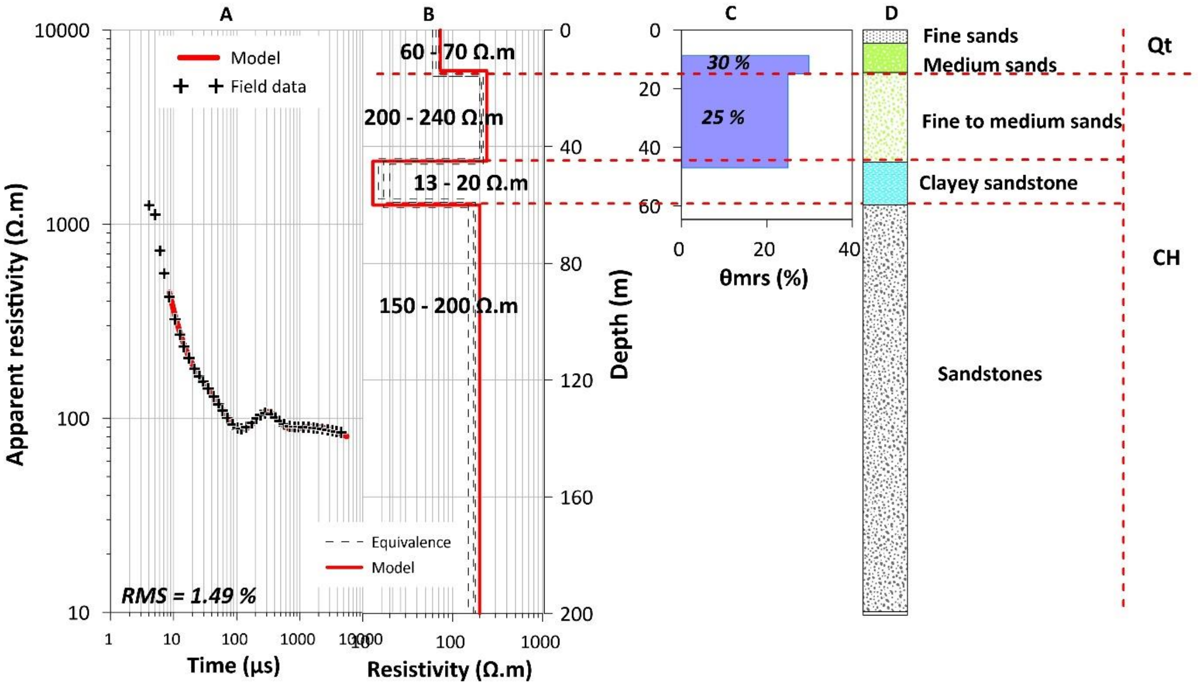


Fig. 4 Interpretation procedure for TDEM and MRS soundings, example of soundings around Bengou I borehole, Bengou cross-section. A: TDEM raw data and the inversion model, B: TDEM results best model and equivalences, C: MRS results, D: geological log of Bengou I borehole.

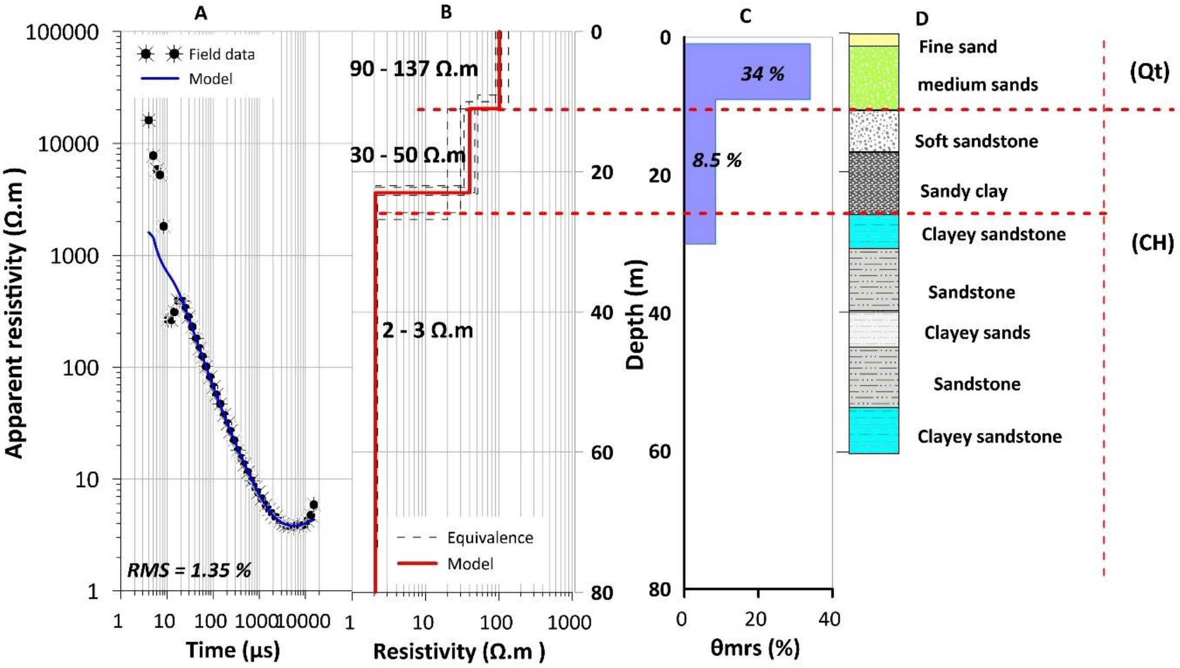
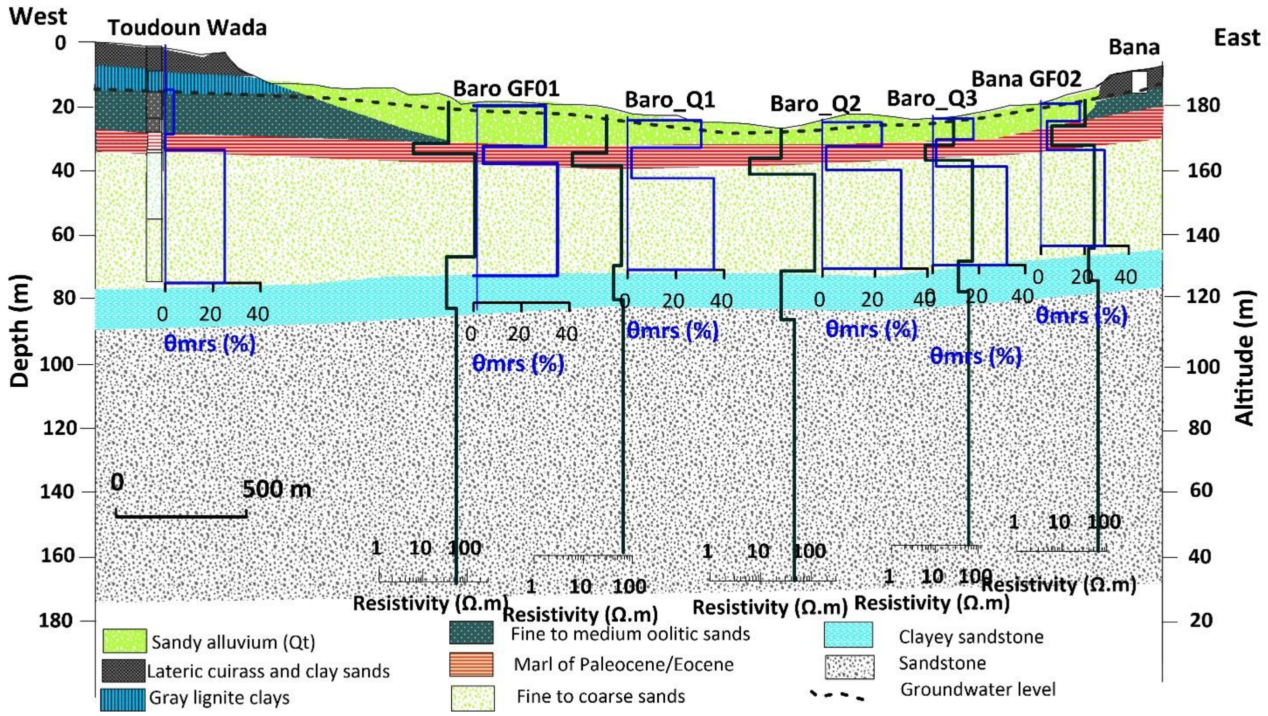


Fig. 5 Interpretation procedure for TDEM and MRS soundings, example of soundings around Sabon Birni piezometer. A: TDEM raw data and inversion model, B: TDEM results, best model and equivalences, C: MRS results, D: geological log of Sabon Birni piezometer.

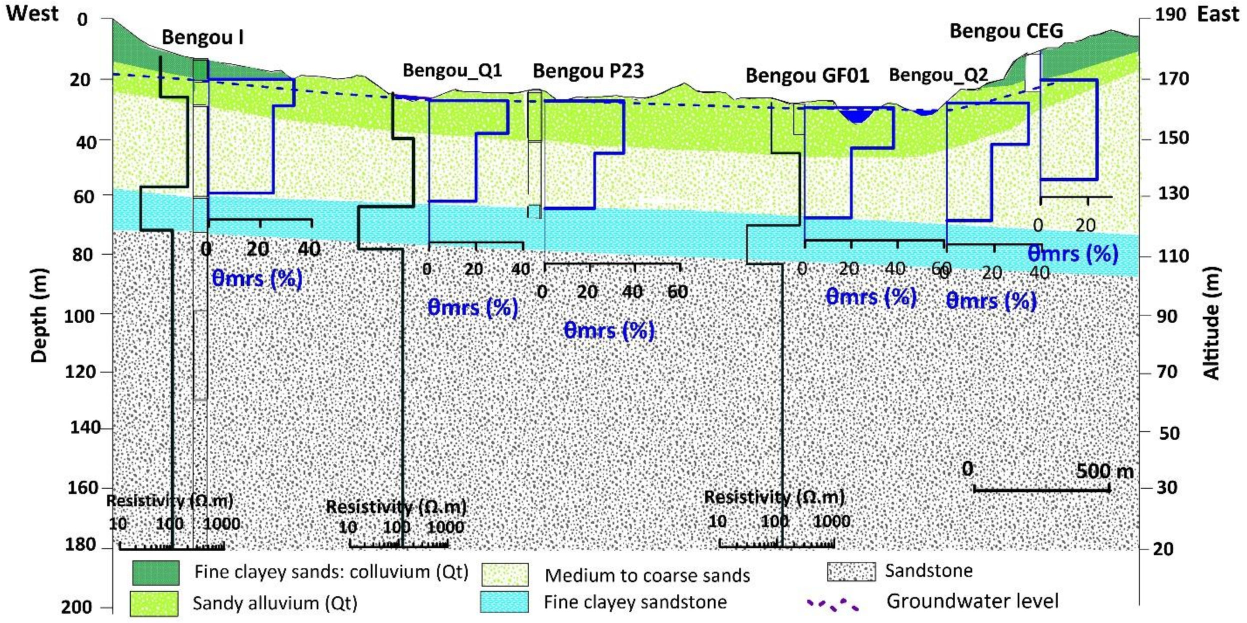
4.2 Characterization of the geometry of aquifers

The inversion results of TDEM and MRS soundings carried out in the lower valley of the Dallol Maouri show two aquifer layers with different characteristics depending on the transect. The first (shallowest) aquifer layer is generalized across the entire valley and characterized by resistivities ranging from 25 to 40 Ω·m at Bana (Fig. 6a), 60 to 70 Ω·m at Bengou (Fig. 6b), and 90 to 120 Ω·m at Tounouga (Fig. 6c). Average thicknesses over these three transects range from 11 to 18 m (Fig. 6d). The associated evidence from MRS reveals mean effective porosities that vary from 25% (range: 20 to 35%) at Bana to 33% (range: 30 to 38%) at Bengou, and 20% (range: 17 and 26%) at Tounouga transect (Table 1).

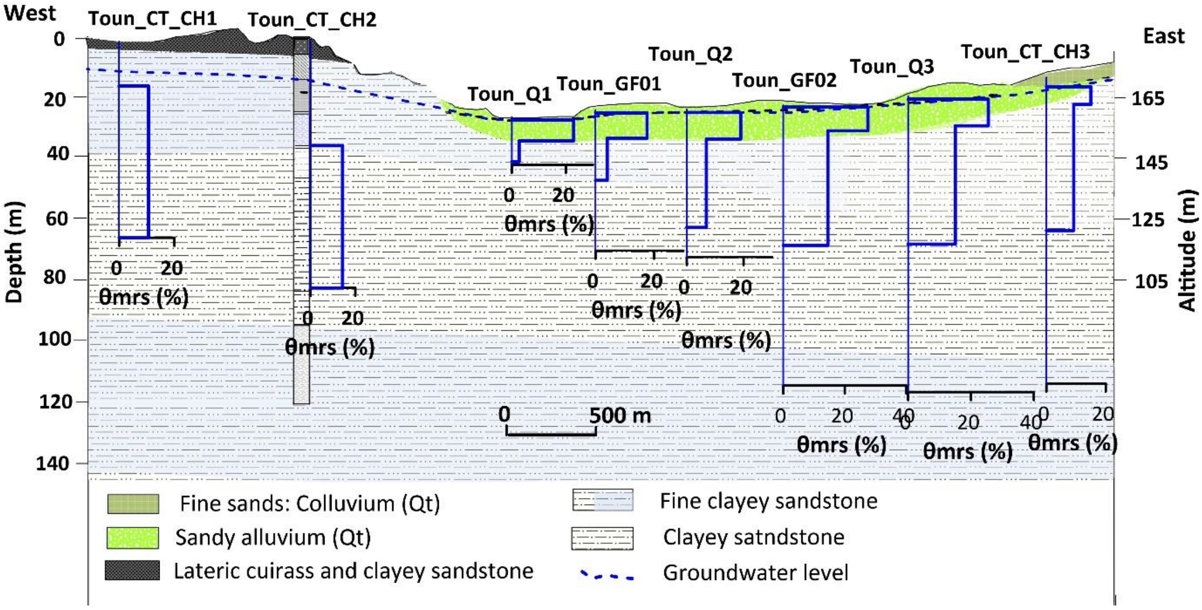
The second shallowest aquifer layer is better represented in the Bana to Bengou sectors relative to the Tounouga sector. It is characterized by resistivities ranging from 60 to 150 Ω·m at Bana (Fig. 6a) and 200 to 220 Ω·m at Bengou (Fig. 6b). Average thickness over these two transects is 30 m. From Sabon Birni village to Tounouga, this aquifer layer has a resistivity of 30 to 40 Ω·m, and an average thickness of 20 m. The associated evidence from MRS reveals means effective porosities ranging from 25 to 33 % in at Bana-Bengou sector, and from 3 to 15% from Sabon Birni village to Tounouga sector. A highly conductive formation (5 to 7 Ω·m), and very low effective porosity (2 to 3%), with an average thickness of 5 m, separates the first two shallowest aquifers layers along the Bana transect.


West
East
Toudoun Wada
Baro GF01
Baro_Q1
Baro_Q2
Baro_Q3
Bana GF02
Bana
Depth (m)
Altitude (m)
θmrs (%)
Resistivity (Ω.m)
0
500 m
Sandy alluvium (Qt)
Lateric cuirass and clay sands
Gray lignite clays
Fine to medium oolitic sands
Marl of Paleocene/Eocene
Fine to coarse sands
Clayey sandstone
Sandstone
Groundwater level

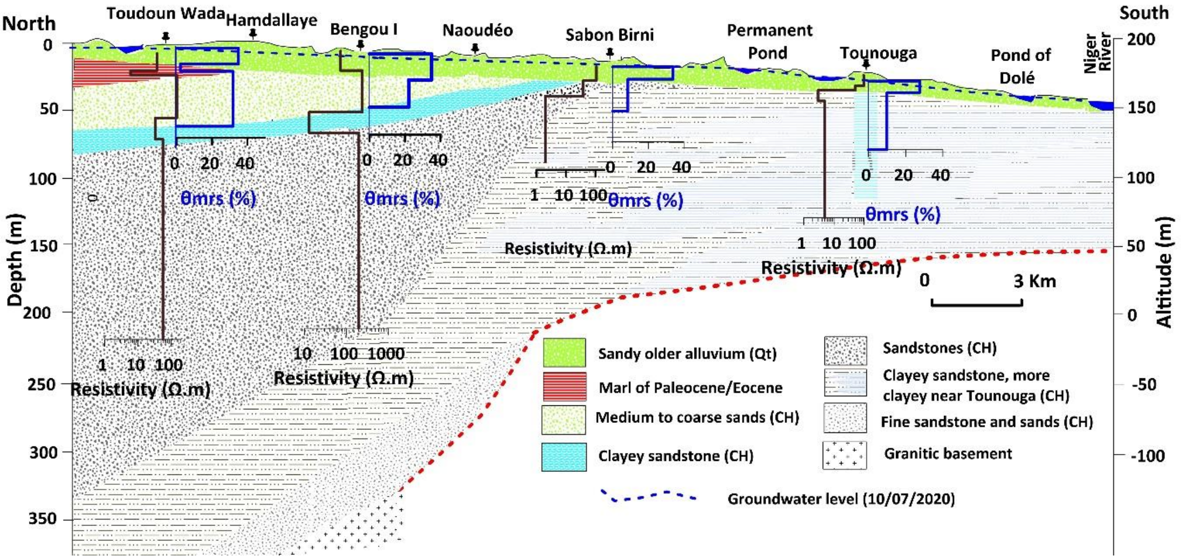
(a)


West
East
Bengou I
Bengou_Q1
Bengou P23
Bengou GF01
Bengou_Q2
Bengou CEG
Depth (m)
Altitude (m)
θmrs (%)
Resistivity (Ω.m)
0
500 m
Fine clayey sands: colluvium (Qt)
Sandy alluvium (Qt)
Medium to coarse sands
Fine clayey sandstone
Sandstone
Groundwater level

(b)



(c)



(d)

Fig. 6 Distribution of the water content and resistivity correlated to the geological formation **(a)** on the Bana transect, **(b)** on the Bengou transect, **(c)** on the Tounouga transect, **(d)** along the longitudinal axis of the valley.

4.3 Estimation of hydrodynamic parameters from MRS

The hydraulic conductivity (*K*) of Quaternary sands in the paleochannel ranges from 9×10^{-4} to 2×10^{-3} m/s with a geometric mean value of $1.4\pm0.1 \times 10^{-3}$ m/s at Bana transect, 7×10^{-4} to 2×10^{-3} m/s with a geometric mean value of $1.0\pm0.1 \times 10^{-3}$ m/s at Bengou transect, and 6×10^{-4} to 2×10^{-3} m/s with a geometric mean of $9.0\pm0.2 \times 10^{-4}$ m/s at Tounouga transect (Table 1). The value of transmissivity ranges from 2×10^{-3} to 4×10^{-2} m^2/s with a geometric mean of 1.5×10^{-2} m^2/s. In the medium to coarse sand and Continental Hamadien sandstone formations, hydraulic conductivities vary from 10^{-4} to 2×10^{-3} m/s with a geometric mean of 6×10^{-4} m/s in the Bana – Bengou sector. In the clayey sandstones from Sabon Birni to Tounouga sector, hydraulic conductivities vary from 3×10^{-5} to 10^{-4} m/s with a geometric mean of 5×10^{-5} m/s. Geometric mean transmissivity is 2×10^{-2} m^2/s in the Bana-Bengou sector and 2×10^{-3} m^2/s in the clayey sandstones encountered from Sabon Birni village to Tounouga secteor.

5 Discussions

5.1 Integration of geological and geophysical data to delineate paleochannel architecture

The shallowest aquifer layer with a high effective porosity (18 to 38%), identified across the entire valley, is correlated to Quaternary alluvial sands. The high effective porosities revealed by MRS in the lower valley of Dallol Maouri are comparable to those obtained in some similar studies in the world (table 2). The range of resistivity values given by the TDEM soundings (60 to 70 Ω·m) in the Bengou sector is comparable to that (88 Ω·m) found by Abdou Ali (2018) using Vertical Electrical Soundings (VES). The conductive layer with resistivity values of 5 to 7 Ω·m revealed by soundings of the Bana transect corresponds to the marl-limestone, a marine formation of the Paleocene-Eocene encountered in a borehole of Toudoun Wada (Conseil de l'Entente 1998) and located on the plateau 1.5 km from the sounding site. This formation has also been identified by VES with resistivity values of 5 Ω·m, (CGG 1968) and a range of values from 2 to 60 Ω·m (Abdou Ali 2018). The second shallowest aquifer layer with effective porosities ranging from 20 to 35% in the Bana-Bengou sector corresponds to the fine to coarse sands encountered by the Bengou I borehole (Fig. 4) between 19 and 45 m deep (FAO 1970). From Sabon Birni village to Tounouga sector, the more conductive layer revealed by the TDEM soundings corresponds to the soft clayey sandstone and sandstone clay formations (effective porosities ranging from 3 to 15%) encountered by the Sabon Birni piezometer (FAO 1970) and the Tounouga borehole (Conseil de l'Entente 1998).

Table 2 Comparaison of the effective porosity values in the similar studies in the world

Study area	**Geological formation**	**Effective porosity** ***($\phi \approx \theta(mrs)$)***
Lower valley of Dallol Maouri (this study)	Alluvial deposits	18 to 38%
Sedimentary aquifers in Danemark (Chalikakis et al. 2009)	Clayey to sandy deposits	5 to 33%
Sedimentary aquifers in Pays-Bas (Roy and Lubczynski 2003)	Clayey to sandy deposits	0.5 to 40%
Sedimentary aquifers in Canada (Legchenko et al. 2011)	Medium to coarse sandy	35 to 35%

Hydrodynamic parameters determined by MRS compare favourably with data obtained by pumping tests in the area (FAO 1970) and MRS soundings carried out in Niger (Boucher et al. 2009a; Descloitres et al. 2013; Vouillamoz et al. 2008), as well as the results of hydrogeological modeling (Guéro 2003). Values of hydraulic conductivity that vary from 3 × 10^{-4} to 2 × 10^{-3} m/s (geometric mean: 10^{-3} m/s) in the alluvial sands are consistent with those found by Descloitres et al. 2013, in the Quaternary deposits of the Komadouga valley, and unconfined aquifer of the Continental Terminal (Boucher et al. 2009a). Estimated transmissivities vary from 2 × 10^{-3} to 3 × 10^{-2} m^2/s (geometric mean: 1.5 × 10^{-2} m^2/s) are similar to that found in the sandy alluvium of Kizamou (1.4 × 10^{-2} m^2/s) by Boucher et al. (2009a). In the sands and sandstones of the Continental Hamadien, the geometric mean K revealed by MRS (5 × 10^{-4} m/s) is very close to that obtained by pumping tests in the aquifers of the Continental Hamadien (6.5 × 10^{-4} m/s) throughout the Dallol Maouri (FAO 1970). K values of around 10^{-5} m/s on the plateau of the Tounouga sector are consistent with those derived by hydrogeological modeling (Guéro 2003).

5.2 Estimation of groundwater flow

Groundwater flow within Quaternary sand formations of the lower valley of the Dallol Maouri is shown schematically in figure 7. Longitudinal variations in the hydraulic head along the paleochannel reveal a change in hydraulic gradient between Bana and Bengou compared to that between Bengou and Tounouga (Fig. 8). Estimated hydraulic gradients, hydraulic conductivities deduced from MRS soundings, cross-sectional areas, and Darcy fluxes are summarized in Table 3.

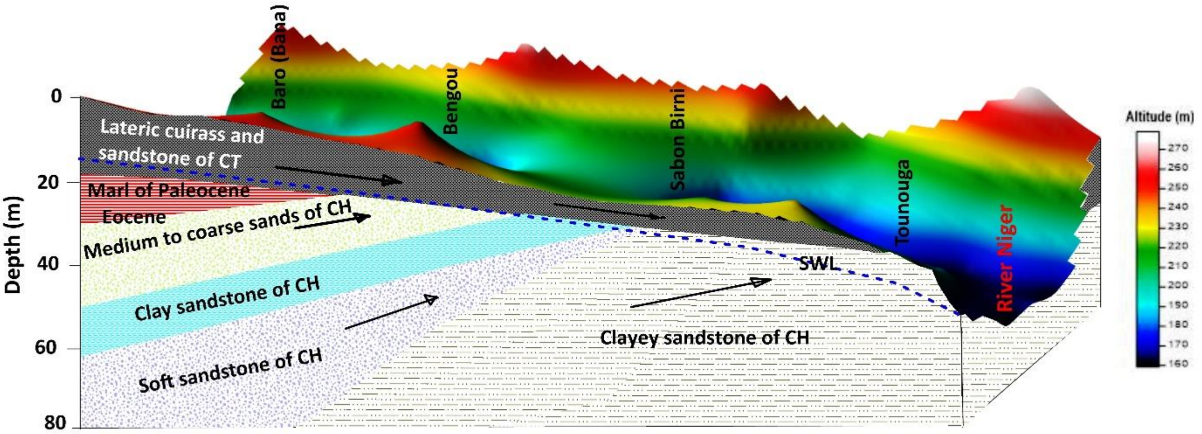


Fig. 7 Conceptual model of groundwater discharge in Quaternary alluvial formations of the lower valley of the Dallol Maouri

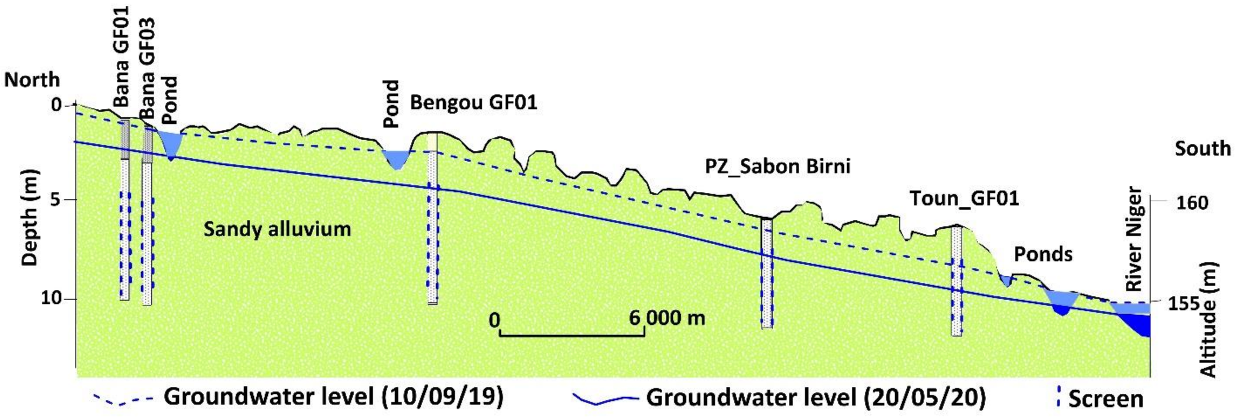
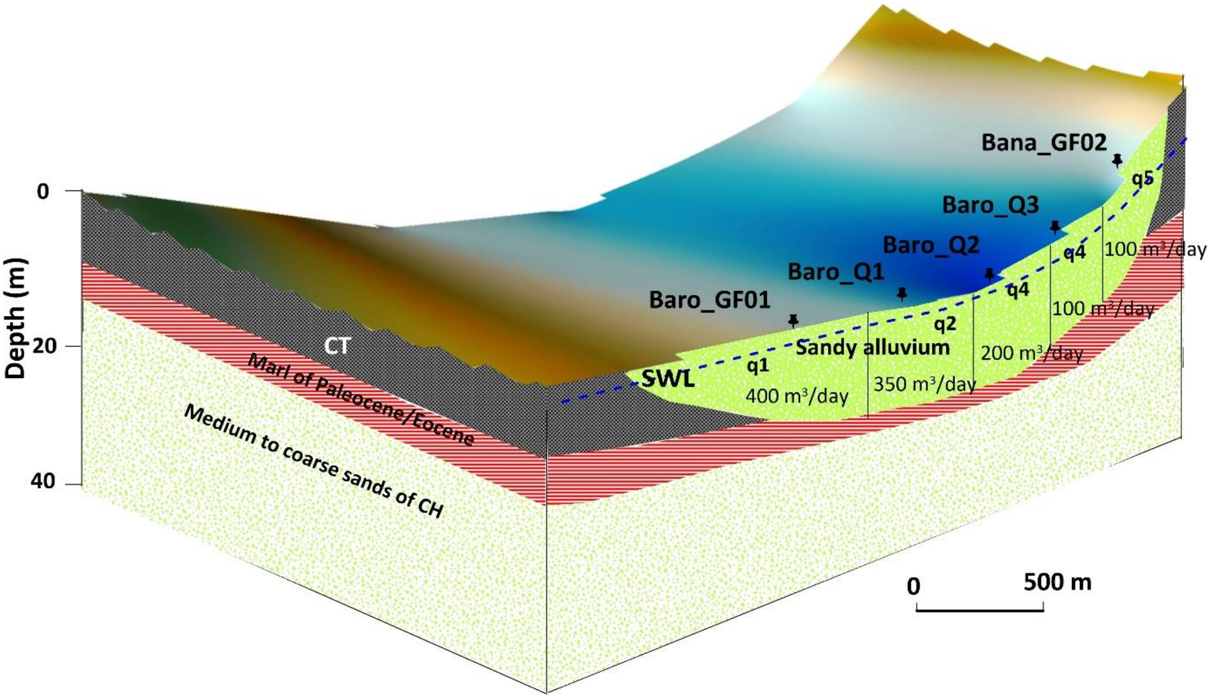


Fig. 8 Longitudinal variations in hydraulic head of the unconfined aquifer of Quaternary alluvium along the paleo-drainage channel of the Dallol Maouri.

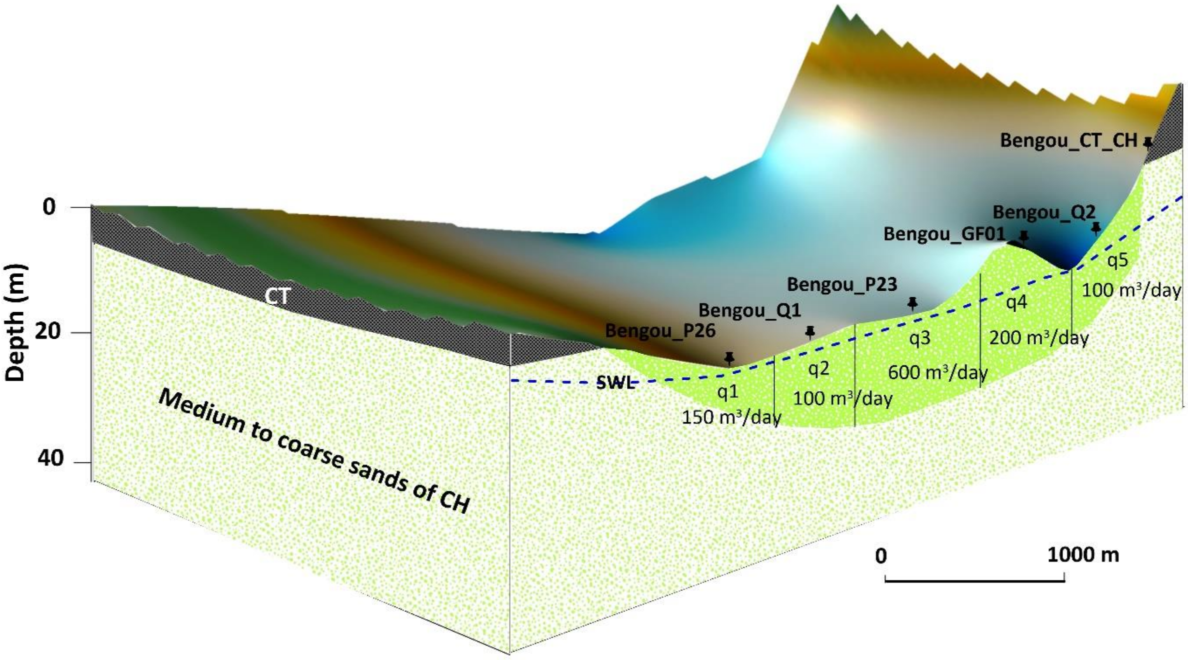
Table 3 Groundwater discharge and its velocity in the Quaternary alluvium evaluated at the three (3) cross sections investigated

Section	**Sub-section**	***i***	**Distance/River (km)**	***K*** **(10^{-3} m/s)**	***A*** **(m^2)**	***Q*** **(m^3/day)**	***v*** **(cm/day)**
Bana	1	0.0002	40	2	10 000	400	50
	2			2	9 000	350	
	3			1.5	6 000	200	
	4			0.9	5 000	100	
	5			1	5 000	100	
Total					**35 000**	**1 200**	
Bengou	1	0.0002	30	1,5	5 600	150	75
	2			0.7	6 400	100	
	3			2	14 000	500	
	4			0.8	15 000	200	
	5			0.7	10 200	100	
Total					**45 000**	**1 000**	
Tounouga	1	0.0003	10	0.3	3 000	100	80
	2			2	6 000	400	
	3			0.6	4 000	100	
	4			2	8 000	450	
	5			2	14 000	700	
Total					**40 000**	**2 000**	

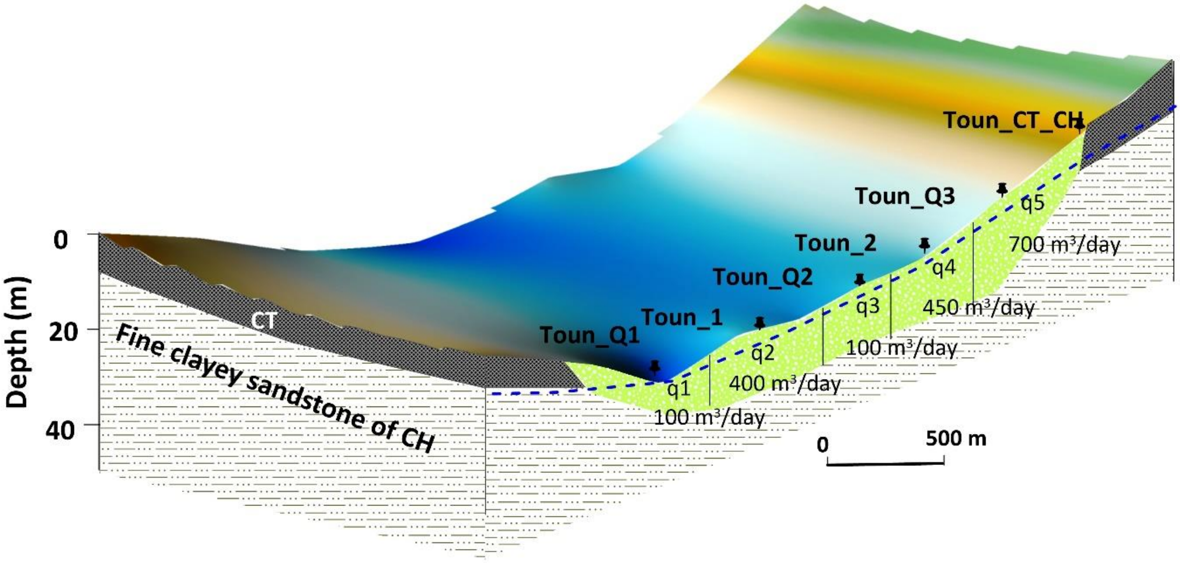
Groundwater flow calculated by Darcy's Law for the cross-section at Bana (Fig. 9a), located 40 km from the River Niger with an hydraulic gradient of 0.2‰, is estimated to 1200 m^3/day or $\sim 4.5 \times 10^5$ m^3/year. The value calculated for the Bengou cross-section (Fig. 9b) is 1000 m^3/day, or $\sim 4 \times 10^5$ m^3/year whereas that calculated for the cross-section at Tounouga, which is located 10 km from the River with an hydraulic gradient of 0.3 ‰ (Fig. 9c), is 2000 m^3/day or $\sim 7 \times 10^5$ m^3/year. The average linear velocity of groundwater is 50 cm/day at the Bana section, 75 cm/day at the Bengou section, and 80 cm/day at Tounouga. Upstream, groundwater discharge at Bana (1200 ± 60 m^3/day) exceeds that computed mid-stream at Bengou (1000 ± 90 m^3/day). The difference observed between these two discharges may derive from uncertainty in parameters (K, i, cross-sectional area) that inform these calculations. Downstream discharge at Tounouga records a greater flow (2000 ± 250 m^3/day), due to the change in the hydraulic gradient and especially to the contribution of the regional aquifer (converging flow) to the valley for the Tounouga section. The groundwater discharge computed at the Dallol Maouri paleochannel is equivalent to a basin-wide specific discharge of much less 1 mm/year and comparable to the groundwater discharges quantified at the Gillingarra paleochannel and at Heihe River in the drylands of Australia and China respectively (Speed and Killen 2020 ; Yao et al. 2017).



(a)



(b)



(c)

Fig. 9 Groundwater discharge quantified at **(a)** Bana section, **(b)** Bengou section, **(c)** Tounouga; q1, q2, q3, q4 and q5 denote groundwater fluxes through sub-sections delimited from geophysical investigations.

5.3 Paleochannel discharge in the Niger Basin

Groundwater discharge of 2000 m^3/day (0.02 m^3/s) quantified during the dry season at the most downstream station of the lower valley of the Dallol Maouri, constitutes an environmental flow (baseflow) contributing to the flow of the River Niger during low-flow periods. The average flow of the River Niger during the period of low flow in May (1971-2019) at the gauging station in Niamey is 22 m^3/s though exceptional low flows have occurred during the Sahelian drought including no flow conditions recorded from 16 to 22 June 1986. Although groundwater discharges in paleochannels are rarely quantified, the maintenance of environmental flows (i.e. baseflow) to the River Niger is governed by Annex 1 of the Niger Basin Water Charter relating to environmental protection in its "Article 95". The latter stipulates that: "The States Parties undertake, within the framework of the qualitative and quantitative protection of water resources, to preserve an environmental flow in the rivers of the basin to ensure the life of the aquatic ecosystems and to maintain the services and goods they provide to populations" (ABN 2011). Preservation of this environmental flow is stipulated and defined in Article 6 of Annex 2 of the Niger Basin Water Charter (ABN 2019). Article 4 of the Water Code of Niger Republic also enshrines the right of everyone to have water corresponding to the satisfaction of their personal and domestic needs. But these assets are subject to certain provisions underlined by article 47 of this code, which stipulates that all activities likely to reduce water resources or to substantially modify the level, the flow mode or the regime of water, damaging the biodiversity of aquatic ecosystems, are subject to a declaration.

Given the limited contribution of the estimated groundwater discharge from the Dallol Maouri paleochannel (i.e. 0.1% of the mean low flow of the River Niger), its potential use for drinking water, livestock watering and supplementary irrigation is not expected to impact substantially the flow regime of the River Niger. Communities in the lower valley of the Dallol Maouri are moving towards the use of groundwater for irrigation to amplify the productivity of rainfed agriculture. Indeed, the study area is considered to have significant potential for irrigable land (Guéro 2003; Cochand 2007; CEIPI 2011). Despite this significant land potential for irrigation, only a few individual plots currently exist within the valley. Under the Government of Niger's new "3N" initiative emphasizing the use of groundwater for irrigation, the Dallol Maouri may provide modest opportunities for supplementary irrigation of rain-fed agriculture.

6 Conclusion

Surface geophysical investigations applying TDEM (Time Domain ElectroMagnetic) and (Magnetic Resonance Soundings) have assessed lithlogical variations in the lower valley of the Dallol Maouri of southern Niger and estimated groundwater flow within the paleochannel, which discharges to the River Niger. The thickness of Quaternary alluvial sediments in the valley vary between 10 to 20 m. Further, MRS (Magnetic Resonance Sounding) reveals substantial groundwater storage in the Quaternary alluvium with effective porosities ranging from 20 to 38% and hydraulic conductivities ranging from 9×10^{-4} to 1.4×10^{-3} m/s. Groundwater flow estimated from Darcy's Law in the Dallol Maouri paleochannel increases downstream from 4.5×10^{5} and 4×10^{5} m^3/year at Bana and Bengou cross-sections, respectively, to 7×10^{5} m^3/year at the cross-section of Tounouga, close to its terminus at the River Niger. Groundwater discharge draining the lower valley of Dallol Maouri contributes to the baseflow of the River Niger but this estimated contribution is small (~0.1% of dry-season flow). . Groundwater flowing within the paleochannel and through fine to coarse sands of the Continental Hamadien may, however, serve locally to increase access to drinking water, livestock watering, and smallholder supplementary irrigation augmenting rain-fed food production.

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Declarations

Conflict of interest All authors certify that, they have no confict of interest.

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