Arabian Journal of Geosciences (2022) 15:1319
https://doi.org/10.1007/s12517-022-10552-1

ORIGINAL PAPER

Remote sensing exploration of piezometric depressions in the Taoudeni basin (Mali-Mauritania)

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Received: 3 November 2021 / Accepted: 29 June 2022

Abstract
In the Taoudeni basin, the water table is so deep that the construction and operation of wells and boreholes are exceptionally expensive. For planning water supply programs, it is therefore essential to use reliable piezometric maps to predict the depth and cost of future drilling. To produce such piezometric maps, we tested a method based on the observation of pastoral wells on satellite images. Using high-resolution (< 0.5 m) satellite images from the last 10 years, we were able to identify 1580 pastoral wells. For two-thirds of these wells (1040), the traces left by the animals drawing water are sufficiently clear and precise to measure their length.We have demonstrated that this measurement is a valid proxy for the measurement of water table depth in the wells (mean square error < 5 m). This method is therefore validated for the construction of piezometric maps based on satellite images, in areas where people use livestock to draw water from wells.Thanks to this hitherto unprecedented number of measuring points, we were able to specify the extent, depth, and geometry of the two large aquifer depressions in the border areas of Mali and Mauritania. It is these depressions that constitute the areas where groundwater is most difficult to exploit.

Keywords Remote sensing · Mapping water table · Aquifer depression · Taoudeni basin · Mali-Mauritania

Introduction

Water table depth is one of the main parameters determining the depth and cost of wells (Danert et al. 2010). Therefore, hydrogeologists use piezometric maps to plan and estimate the cost of drilling programs. Such maps are constructed either from water point databases or from in situ groundwater level measurements.

Both types of approaches are difficult to implement in remote areas, as there is too little archived data (Aakash et al. 2021) and in situ measurements are too difficult to complete in these regions prone to insecurity (Fominyen 2020). In such conditions, it would be relevant to use remote sensing methods (Aakash et al. 2021).

To prospect for groundwater resources, satellite images have already been used to map geological formations and fissured zones (Solomon and Duiel 2006), delimit recharge zones (Leblanc et al. 2003), to assess interannual recharge from variations in the gravity field measured by GRACE satellites (Sheffield 2018; Aakash et al. 2021), and even to map the piezometric surface in areas where it is very shallow (Abdel Hady and Karbs 1971; Pan et al. 2008; Bechtold et al. 2018; Burdun et al. 2020). However, to our knowledge, satellite imagery has never been used to map the piezometric surface at great depth.

This is the issue on the borders of Mali and Mauritania, in the Hodh region and Azaouad (Fig. 1), where the water table is so deep that the inhabitants of these regions must harness horses, donkeys, or camels to draw water from wells, some of them deeper than 130 m.

In this environment, the construction and operation of wells and boreholes are exceptionally costly (Danert et al. 2010) and represent a heavy burden for these countries, which are among the poorest in the world (Mali and

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Published online: 22 July 2022

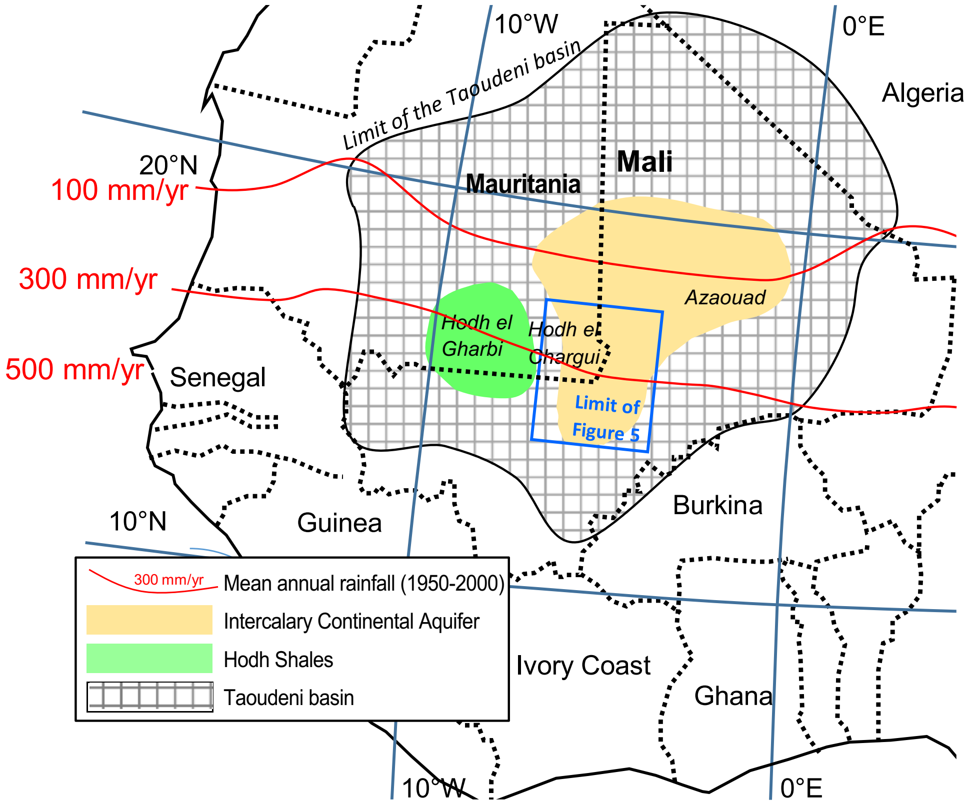

Fig. 1 Location of Taoudeni basin, the main aquifers

Mauritania rank 157 and 184 respectively among the 189 countries ranked according to their HDI by the UNDP (UNDP 2020)).

To plan and finance water supply programs, it is therefore essential to use reliable piezometric maps to predict the depth and the cost of future boreholes. However, establishing such maps involves visiting hundreds of wells and therefore traveling thousands of km of sandy tracks, in areas where access has become particularly dangerous over the last 10 years due to the increase in attacks and kidnappings (Fominyen 2020).

In the absence of direct measurement campaigns, hydrogeologists are restricted to constructing maps from archives listing old boreholes. However, these data are often imprecise (especially the coordinates of the wells) and heterogeneous (the measurements were made in different years and seasons). The piezometric maps that can be deduced from such data are not sufficiently accurate for the engineer's work (Yahya et al. 2001).

To construct a new piezometric map of this region, we decided to test an innovative method, based on the use of high-resolution satellite images (WorldView satellites). Such images cover 90% of the study area.

The use of satellite imagery to infer the depth of the piezometric surface has been tested previously for shallow aquifers (Abdel-Hady and Karbs 1971) and wetlands (Burdun et al. 2020). Soil moisture, which varies with the depth of the water table (0 to 4 feet), is then reflected in variations in soil radiance. Unfortunately, this method is not applicable in the arid Sahel, where the water surface is too deep to influence soil radiance.

We have identified another signature of water table depth in these pastoral regions: the water trails left by the cattle used to draw water from the wells. These traces are clearly visible on very high-resolution satellite images (< 0.5 m). They are a reliable indicator of the depth of the water (Langlais 2017; Collignon 2020).

To establish a detailed piezometric map of the aquifers in the Taoudeni basin, we decided to use this technique on a large scale and test its reliability by comparing the results with water depth measurements made directly in the most recent boreholes (SALSEBIL 2020; SIPPE 2020).

The study area

The Taoudeni basin is a huge sedimentary basin (1.2 million km^2), which extends into the Saharan and Sahelian zones, between Mauritania, Mali, and Algeria (Fig. 1). It is an arid area (50 to 500 mm/year) with a low relief (90% of the basin area is between 150 and 300 m above sea level). The only permanent rivers are the Niger and Senegal rivers, which run along the southern margins of the basin. On the other hand, there are hundreds of small temporary rivers (wadis) that flow for a few days a year and play an important role in the recharge of the aquifers (Osterkamp et al. 1995, Favreau et al. 2002).

Hydrogeological data are very patchy and heterogeneous, due to the difficulties inherent in prospecting in these areas, which are roadless and poorly secured (Fominyen 2020). For this reason, existing piezometric maps are not very accurate and detailed (BURGEAP 2006, ANTEA 2013).

This sedimentary basin contains two extensive aquifers (BURGEAP 1966, 2006): Hodh shales and Intercalary Continental (Fig. 1). In the absence of perennial surface water resources, these aquifers contain the main water resources available to the local populations (including the 840,000 inhabitants of the Hodhs region of Mauritania).

Intercalary Continental aquifer

This study focuses on the Intercalary Continental aquifer, the most extensive and productive in the Taoudeni basin. It is located in eastern Mauritania (Hodh ech Chargui region) and northern Mali (Azaouad region). The aquifer is contained in a 200-m thick sedimentary sequence of continental origin (the so-called Intercalary Continental) that was deposited during the Jurassic and Cretaceous periods (BURGEAP 1966) in the centre of the Taoudeni basin (Fig. 1). It is covered on its southern edge by another sandy-clay series (called "Continental Terminal"), in hydrogeological continuity with the first. Recent dune massifs (Pleistocene and Holocene) partially mask the two previous ones, but their thickness is generally less than 20 m (BURGEAP 1966).

The Intercalary Continental aquifer is very productive, with 95% of boreholes considered productive (SIPPE database—Système d'inventaire et de programmation des points d'eau). Its transmissivity has been measured during long-term pumping tests and is between 300 and 700 m^3/day (SALSEBIL 2020). The specific flow rates are between 0.7 and 7 m^3/h per meter of drawdown (IGES & CETIS 2020). This aquifer contains freshwater (92% of wells recorded in SIPPE have EC lower than 1 mS/cm). This is quite better than in other sedimentary aquifers in the Sahel, notably in the Lake Chad basin (Collignon 2020). Groundwater chemical facies is calco-carbonic, with very low nitrate content (< 2 ppm), as well as fluor (< 0.5 ppm) and manganese (< 0.05 ppm). 10% of the boreholes contain iron in excess (> 0.5 ppm).

Hodh shales

Further west (in the Hodh el Gharbi) an older sandy-clay sequence is outcropping (Bourguet et al. 2006). Hodh shales are dated as Cambro-Ordovician, and they behave like a fissure aquifer. We have also started a remote sensing study of it, which will be completed later.

Data and methods

Data

The survey is based on satellite images accessible free of charge on Google Earth. More than 90% of all measurements were made with very high-resolution images (< 0.5 m) taken by the WorldView satellites, operated by the Maxar company. Such images were collected on different dates, between 2010 and 2020.

In areas where very high-resolution images are not available, we have completed the mapping using Landsat and SPOT scenes. They have proved very useful in locating pastoral wells. However, it is often not possible to use them to measure the depth of water (Collignon 2021).

In total, we mapped an area of 200,000 km^2, in which 1580 pastoral wells were identified on the satellite images. Of these, 1,040 could be used to measure the water table depth (65% of the wells that were identified), resulting in one measurement point per 200 km^2.

To calibrate the method, we used piezometric data extracted from the national database of wells in Mauritania, which compile measurements made over the last 30 years (SIPPE 2020) as well as additional measurements taken during recent drilling in the Hodh ech Chargui (Iges & Cetis 2020; Salsebil 2020).

Method

To extract piezometric information from satellite images, a method based on the observation of traces left by herds around pastoral wells has been suggested in Niger (Langlais 2017) and developed in Chad (Collignon 2020) and Nigeria (Collignon 2021).

The method principle

Pastoral wells are located on satellite images by the traces left by herds converging to the wells. These traces are generally radial (Fig. 2a), as herds move smoothly on land that is not fenced. For the most famous wells, the length of the traces can reach 5 km and they are marked by clear bands a few tens of meters wide.

In the centre of the radiating traces, a darker area, 40 to 150 m in diameter, can almost always be identified on satellite images (Fig. 2b). This area corresponds to the accumulation of dung from ruminants waiting to drink. The area

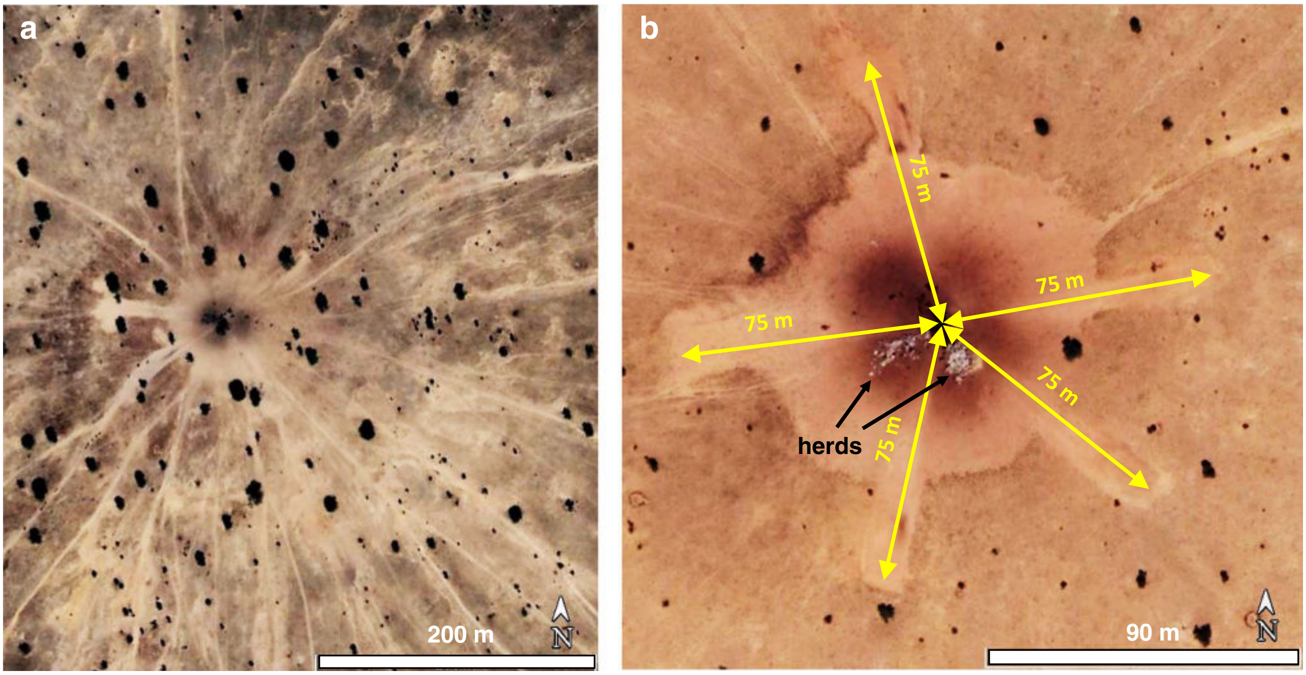

Fig. 2 Satellite image (WorldView) of pastoral water points in the Taoudeni basin. On a large scale, the well can be identified by the radiating traces left by the passage of the herds (**a**). On a small scale, the traces of water extraction can be measured (**b**)

around the wells is thus a place where organic matter is concentrated (Diawara et al. 2014).

The light bands separating the dark areas correspond to the tracks of the animals that move back and forth around the well to draw water. The animals used for water extraction follow a very regular path in the shape of an elongated drop of water (Fig. 3). They start by moving away from the well in a straight line until the water bag reaches the surface. The shepherd then unties the rope, and the animal makes a semicircle of a few meters' radius, before returning to the well in a straight line. The length of this trace (L) is equal to the depth of the piezometric level (P).

To determine the depth of the water table, it is then sufficient to measure the length of the track on the satellite image. By multiplying the measurements for different tracks or different satellite images, the accuracy of the result can be further improved (Fig. 4).

Results

Mapping of pastoral wells

For this research, we used image mosaics that are freely available on the Google Earth platform. Medium-resolution images (Landsat—30 m) can sometimes be used to identify pastoral wells, thanks to the halo of dark organic matter surrounding the wells, but it is difficult to differentiate them from other dark objects (lakes, buildings, etc.). In contrast, using high resolution (SPOT type—2 m) and very high resolution (WorldView type—0.5 m) imagery, we could clearly identify pastoral wells and the tracks left by livestock converging on the pits (Collignon 2020, 2021). In this way, we have identified 1580 pastoral wells in the Taoudeni basin.

Water depth measurement

For two-thirds of these wells (1040, out of a total of 1580), we were able to measure with a better than 3 m accuracy the length of the trace left on the ground by the animals used to draw water from the well (horses, donkeys, or camels). This trace is a proxy of the depth of the water table (see the "Discussion" section).

Mapping the water table

Based on the measurements of 1,040 wells, a new piezometric map of the Intercalary Continental aquifer was established (Fig. 5a).

This map highlights two piezometric depressions, 30 and 50 m deep (the depth of the depression is the difference in altitude between the bottom of the depression and the highest closed piezometric contour line), and several piezometric domes (Fig. 5a). The depression to the north-east of Bassikonou had already been identified from a

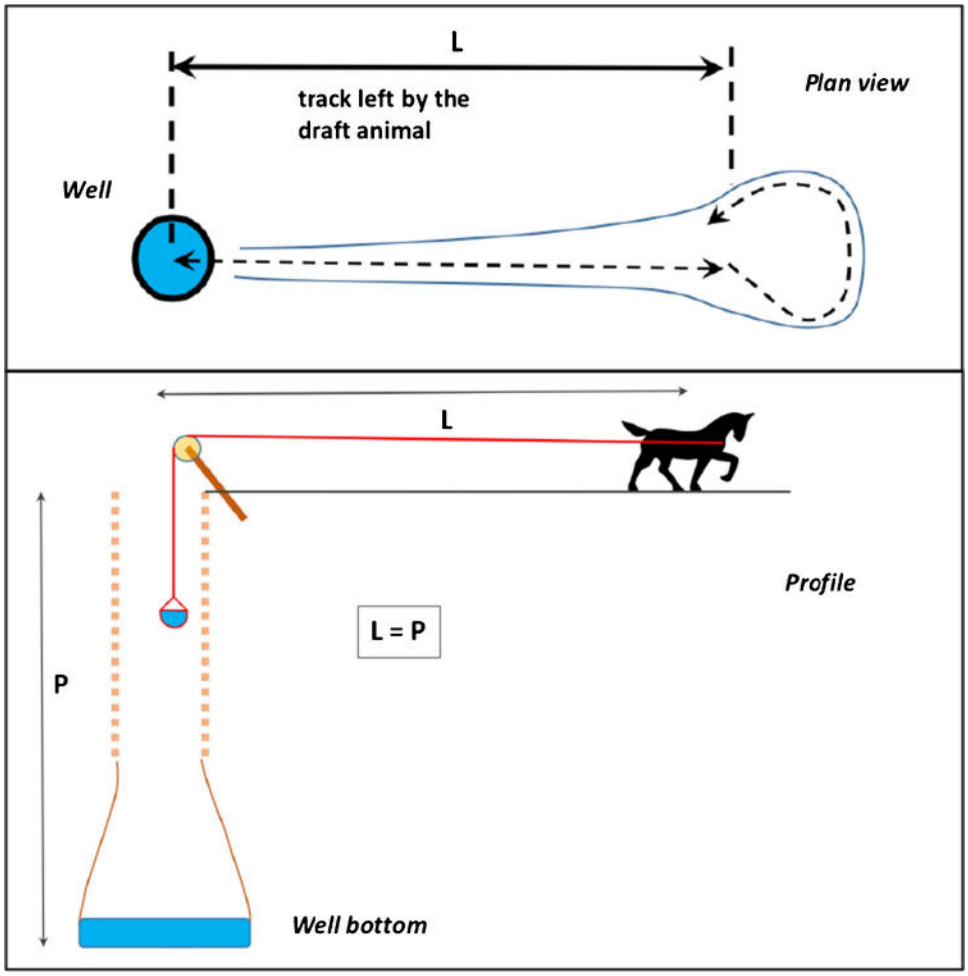

Fig. 3 Principle of the remote sensing piezometry method

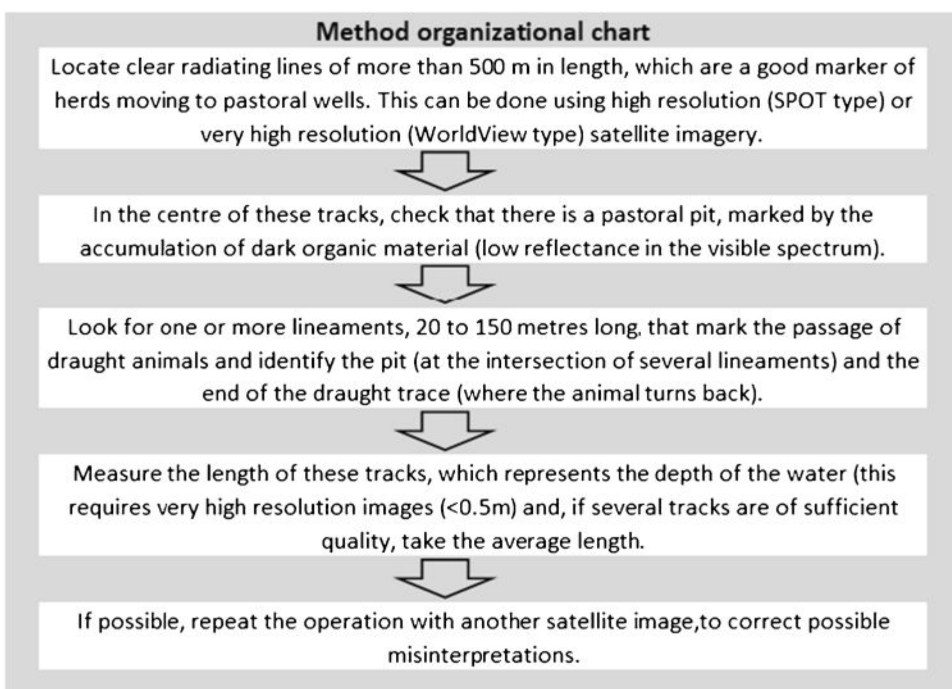

Fig. 4 Organisational chart of the remote sensing piezometry method for pastoral wells

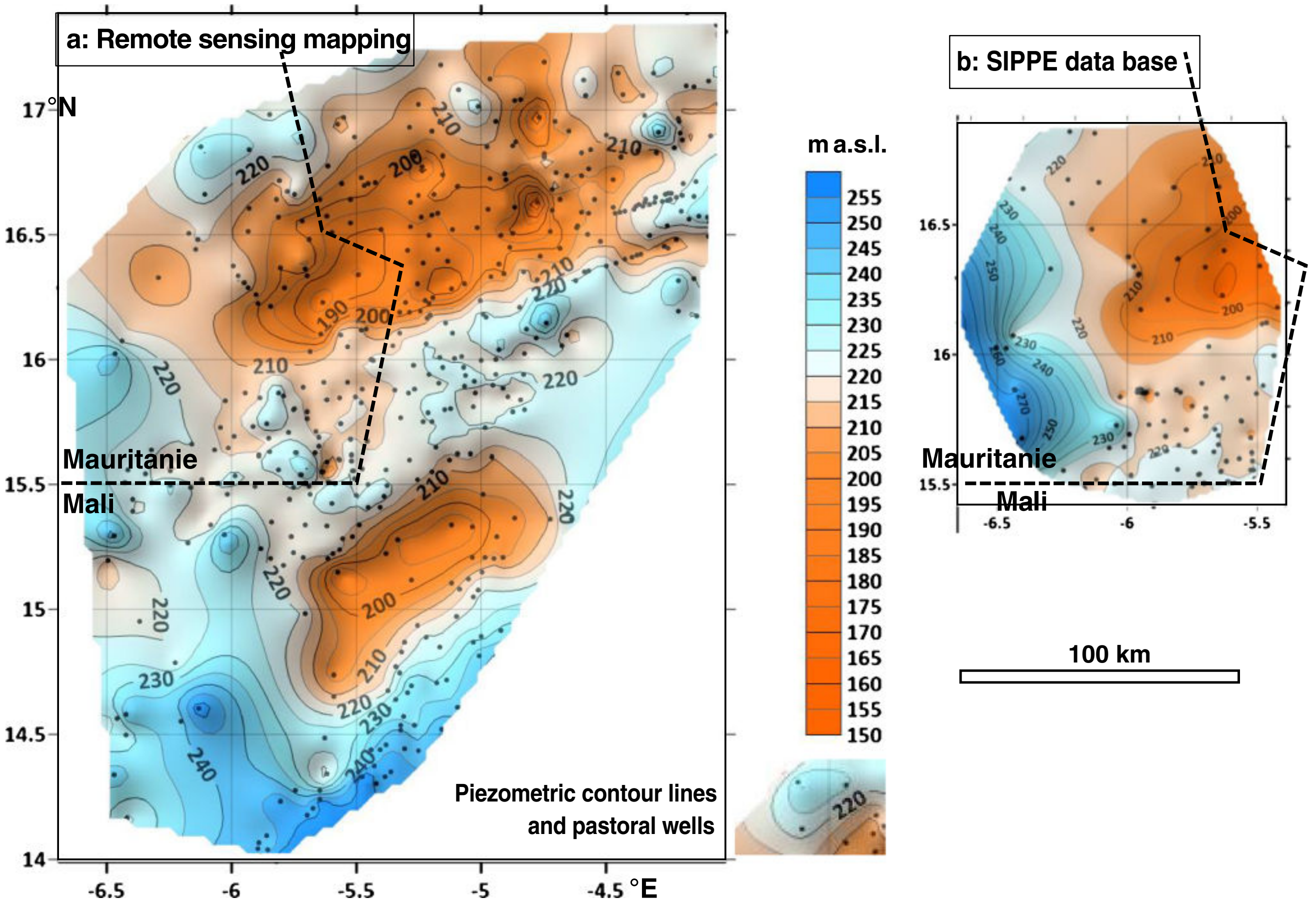

Fig. 5 Piezometric map of Intercalary Continental aquifer build with **a** remote sensing of pastoral wells and **b** direct measurement recorded in SIPPE database and recent boreholes

limited number of borehole measurements (BURGEAP 1963). This depression is also clearly visible on the piezometric map build with the SIPPE database (Fig. 5b). The map that has just been drawn up by remote sensing is more detailed as it is based on more measuring points. This structure extends far to the east, beyond the border with Mali.

The remote sensing map shows the existence of another, smaller depression, in Mali, south of Lere and Nampala, that had never been mapped so far. There is no hydrogeological connexion between these two depressions.

Similar aquifer depressions have been described in other Sahelian areas (Favreau, 2002). The extent and depth of these depressions have very important consequences for rural populations: the static level is very deep, which leads to high costs for building and operating wells and boreholes. Half of the pastoral wells in the study area are over 60 m deep and some are over 130 m (Fig. 6).

Discussion

Calibration of the remote sensing measurement

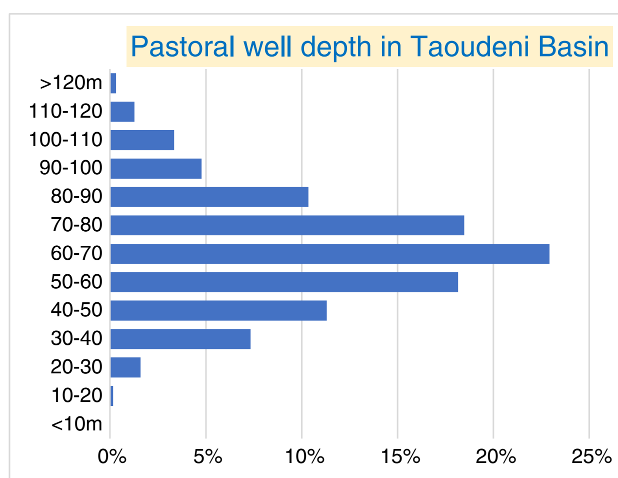

Fig. 6 Depth of the water table for Intercalary Continental aquifer

method

To verify that the water level estimated with remote sensing is a reliable proxy of the water table depth, it was compared with direct measurements from wells and boreholes in the same area extracted from three databases (SIPPE 2020; Iges & Cetis 2020; Salsebil 2020).

The correlation between the two types of measurements is excellent and validates this use of satellite imagery to draw up piezometric maps in the Sahel (Fig. 7).

Accuracy of the water table depth measurements

The accuracy of these measurements is constrained by three main sources of uncertainty, in decreasing order of importance: (1) the accuracy of ground elevations derived from STRM 30: the difference between the model and conventionally measured elevations is less than 5.6 m for 90% of points in Africa (Farr et al. 2007); (2) daily and seasonal water level variations: the seasonal variation of the piezometric surface is < 2 m (ANTEA and JMB 2013); (3) the accuracy of the measurement of the trace's length is < 2 m when using very high-resolution satellite images such as WorldView (Collignon 2021).

The cumulation of these three sources of uncertainty results in total uncertainty of 5 to 10 m in the absolute altitude of the piezometric surface. It should be noted that direct field piezometric measurements in wells and boreholes are also affected by the first two sources of uncertainty (ground elevation and water table seasonal and daily variations) and that their accuracy is therefore of the same order of magnitude.

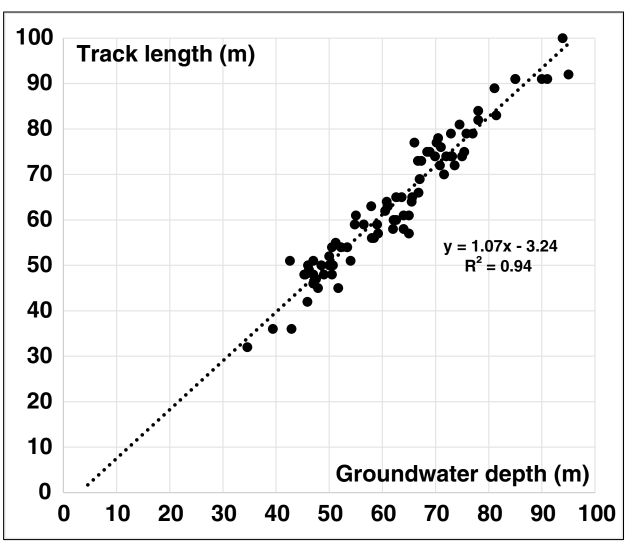

Fig. 7 Calibration of the remote sensing method

This accuracy is sufficient to draw up regional piezometric maps (at a scale of between 1/200,000 and 1/2,000,000). On the other hand, to construct detailed piezometric maps (on a scale larger than 1:200,000), it is recommended to achieve an accuracy of < 2 m for relative altitudes, which requires a direct topographic survey of the wells and measuring groundwater depth in a short time during the dry season (as to observe an "instantaneous" situation of the piezometric surface).

Accuracy of the mapping

To check the accuracy of the method, another map (Fig. 5b), based on direct piezometric level measurements, was made for recent wells and boreholes (SALSEBIL 2020; IGES & CETIS 2020) and for those listed in the national database (SIPPE 2020).

The comparison of the two maps shows that the remote sensing method is reliable and even allows a higher level of detail to be achieved, as many pastoral wells are not recorded in the national database.

Field of application

The remote sensing piezometry method is applicable in Sahel pastoral regions, where shepherds use livestock to draw water from wells. The method assumes the existence of wells that are sufficiently productive to feed a herd and it is, therefore, better suited to sandy aquifers than to fractured basement aquifers where wells are too unproductive to cover the water needs of a herd (Collignon 2021).

It should also be noted that the method is not applicable where the piezometric surface is less than 15 m deep, as shepherds then draw water directly by hand, without harnessing draught animals.

Conclusions

The remote sensing method we have developed has been successfully used to establish an accurate piezometric map of the Intercalary Continental aquifer in the Taoudeni basin.

This map is fully consistent with those established from direct measurements in wells and boreholes, which validates the principle of using cattle tracks to determine the depth of the water table.

This method is efficient: in less than 2 months, we were able to survey a thousand measurement points over an area of 200,000 km^2. Thanks to this hitherto unprecedented level of detail, we were able to specify the extent, depth, and geometry of two vast piezometric depressions in the border areas of Mali and Mauritania.

This is a very interesting result, as knowledge of these depressions allows for better planning of rural water supply programs.

Author contribution Bernard Collignon developed the remote sensing method and applied it to satellite images in the Taoudeni basin. Mohamed Moctar supervised the exploration of boreholes, elaborated reference aquifer maps, and collected the pre-existing data for this study.

Data availability The original datasets have been included as an additional supporting file.

Declarations

Competing interests The authors declare no competing interests.

References

Aakash A, Knight R, Sarfaraz A, Pauloo R, Melton F (2021) Assessing the utility of remote sensing data to accurately estimate changes in groundwater storage. Sci Total Environ 807(Pt 1):150635. https://doi.org/10.1016/j.scitotenv.2021.150635

Abdel-Hady M, Karbs HH (1971) Depth to ground-water table by remote sensing. J Irrig Drain Eng 97(1):355–367

ANTEA, JMB (2013) Gestion intégrée et concertée des ressources en eau des systèmes d'Iullemeden, de Taoudeni/Tanezrouft et du fleuve Niger. Rapp. OSS-GICRESAIT n°19

Bechtold M, Schlaffer S, Tiemeyer B, De Lannoy G (2018) Inferring water table depth dynamics from ENVISAT-ASAR over a range of Peatlands from deeply drained to natural conditions. Remote Sens 10(4):536. https://doi.org/10.3390/rs10040536

Bourguet L, Moctar M, Morel JC, Ould Mohamedou Y, Ould Bouniomine EH, Rey S (2006) Carte hydrogéologique préliminaire de la Mauritanie – feuille Nema. Projet PRISM II. Ed. Min. Mines & Industrie (Nouakchott)

Burdun I et al (2020) Satellite determination of peatland water table temporal dynamics by localizing representative pixels of a SWIR-based moisture index. Remote Sens 12(18):2936. https://doi.org/10.3390/rs12182936

BURGEAP (1963) Etude hydrogéologique du Sud-Est du Hodh oriental. Bureau de recherche géologique appliquée. Bureau de recherche géologique appliquée. Rapport du service Hydraulique, Mauritanie, 37 p. + annexes

BURGEAP (1966) Etude hydrogéologique du Sud-Est mauritanien. Carte hydrogéologique au 1 000 000

BURGEAP (2006) Notice de la carte hydrogéologique au 500 000. Projet PRISM II. Ed. Min. Mines & Industrie (Nouakchott)

Collignon B (2020) A new tool for the remote sensing of groundwater table: satellite images of pastoral wells. Open Geospatial Data, Software and Standards, vol 5. Springer, p 4. https://doi.org/10.1186/s40965-020-00077-3

Collignon B (2021) Apport de la télédétection des puits pastoraux à la cartographie des eaux souterraines du Sahel. Rev Fr Photogrammétrie et Télédétection N 223:189–199. https://doi.org/10.52638/rfpt.2021.602

Danert K, Luutu A, Carter R, Olschewski A (2010) Costing and pricing – a guide for water drilling enterprises. Rural Water Supply Network, Field Note 2010–6. https://doi.org/10.13140/2.1.4552.8328

Diawara M, Gagneron F, Hiernaux P (2014) Quelle accessibilité aux ressources pastorales du Sahel. Afrique Contemporaine n 249:21–35. https://doi.org/10.3917/afco.249.0021

Farr TG et al (2007) The shuttle radar topography mission. Rev Geophys 45:2. https://doi.org/10.1029/2005RG000183

Favreau G, Leduc C, Marlin C, Guero A (2002) Une dépression piézométrique naturelle en hausse au Sahel. C.R Geosci 334:395–401

Fominyen G (2020) Five things to know about spiralling insecurity in the Sahel. WFP - . https://www.wfp.org/stories/five-things-know-about-spiralling-insecurity-sahel. Accessed 24 Jan 2020

IGES, CETIS (2020) Compte rendu des travaux de forage dans la wilaya du Hodh Ech Chergui. Intermountain GeoEnvironmental Services and Cabinet d'études, d'ingénierie et de suivi. Rapport d'exécution pour l'UNICEF

Langlais S (2017) L'eau au Sahel : Expériences au Niger, en pays Touareg. Association Masnat. Ed.du Fournel

Leblanc M, Leduc C, Razack M, Memoalle J, Dagorne D, Mofor L (2003) Applications of remote sensing and GIS for groundwater modelling of large semiarid areas. Hydrology of the Mediterranean and Semiarid Regions. IAHS Publ. N° 278

Osterkamp WR, Lane LJ, Menges CM (1995) Techniques for groundwater recharge estimates in arid/semi-arid areas. J Arid Environ 31:349–369

Pan SB, Wang ZJ, Su QX, Sun T, Zhang Y (2008) Groundwater level monitoring using multi-temporal images in arid region of Northwest China. The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences. Vol. XXXVII. Part B8. Beijing 2008

SALSEBIL (2020) Travaux de pompages d'essai dans le département de Bassikonou. Rapport d'exécution pour le CICR (Comité International de la Croix Rouge).

SIPPE (2020) Extraction de la base de données des points d'eau de Mauritanie. Système d'Inventaire et de Programmation des Points d'Eau

UNDP (2020) Human Development Report 2020

Sheffield J (2018) Satellite remote sensing for water resources management: potential for supporting sustainable development in data-poor regions. Water Resour Res. https://doi.org/10.1029/2017WR022437

Solomon S, Duiel F (2006) Groundwater study using remote sensing and GIS in the central highlands of Erotrea. Hydrogeol J pp 729–741. https://doi.org/10.1007/s10040-005-0477-y

Yahya MLO, El Joud MYO, Gonzalez S, Campredon R (2001) Les ressources en eau du Dhar de Néma – Recherche de nouvelles ressources en eau à l'aide d'images satellite. Les Amis De La Mauritanie 19:10–18