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Technical note: Biases and uncertainties in estimating water table depths using high-resolution SPOT / Pléiades images of traditional livestock watering practices in the Sahel

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Abstract. Groundwater resources in Africa remain largely understudied despite their crucial role in sustaining socio-economic activities, rural livelihoods and climate resilience. This knowledge gap is mainly due to the scarcity of long-term, reliable and spatially extensive in situ monitoring data. In this work, we assess the reliability of a groundwater survey method based on photo-interpretation of high-resolution satellite imagery (SPOT-6, Pléiades and Pléiades Neo; ≤ 1.5 m in resolution, years 2014 to 2025) to estimate the water table depth (WTD) of thousands of wells exploited through traditional livestock watering practices in the Sahel region. These widespread practices involve drawing groundwater from hand-dug wells using ropes and large leather or rubber buckets pulled at a distance by animals. Repeated animal passages create elongated surface tracks that radiate from the well and may extend over several tens of metres, forming radial patterns visible on high-resolution optical images. Using a long-term, pluri-decadal in situ dataset (2003–2025, AMMA-CATCH observatory), we identified 34 wells in SW Niger used during the dry season for intensive livestock watering, for which WTD in situ measurements were coincident in time and could be compared with high-resolution satellite image tracks length estimates. Dry-season imagery (December–March) coincides with both intensive water abstraction for livestock and a cloud-free troposphere, making this approach all the more suitable for detecting well features and surroundings. Measured water table depths ranged from 15 to 59 m below ground level (dry season), while satellite-derived track lengths systematically overestimated in situ WTD measurements, with a median bias of 6.4 ± 2.0 m (median absolute error). This plurimetric offset was shown to reflect the cumulative contributions of i) geometrical (well's structure and position in the landscape), ii) operational (the way animal herders withdraw groundwater near the well) and iii) hydrogeological (well's productivity and its changes through time) bias terms. With these limitations and biases duly considered, large-scale regional WTD estimates derived from HR images represent a valuable opportunity to map groundwater depth across large parts of the Sahel region (~3 Mkm²), while also updating and densifying water-point

https://doi.org/10.5194/egusphere-2026-4198
Preprint. Discussion started: 6 August 2026

inventories for better planning of water development facilities. This method opens up the possibility of an improved parameterization of large-scale hydrological models with updated and denser datasets at regional, transboundary aquifer scales.

1 Context and concept

Semi-arid regions at a global scale are characterized by strong interannual hydroclimatic variability, making long-term observations essential for understanding, anticipating and modelling changes in water resources under accelerating water use dynamics (Scanlon et al., 2006; Buytaert et al., 2012; Lian et al., 2021). This need is particularly critical in the Sahel region of West Africa, where environmental resources are subject to increasing pressure from enhanced climate variability, demographic growth, land use changes and hence, expanding water demands (Carter and Parker, 2009). At the same time, field-based observations remain sparse, discontinuous and unevenly distributed across space and time, limiting the ability to analyse hydrological processes, detect long-term trends and evaluate coupled land-surface and hydrological models at relevant scales (West et al., 2023). This observational gap is especially important for groundwater, as global water table depth (WTD) maps remain poorly constrained in many tropical and semi-arid regions because of the very low density of in situ observations (Fan et al., 2013; Cuthbert et al., 2019).

The disparity compared to surface water monitoring is particularly revealing. In West Africa, surface water monitoring has benefited from relatively long hydrometric records (Tramblay et al., 2021). By contrast, long-term piezometric records are scarce and often began several decades after the establishment of hydrometric networks, some of Africa's largest rivers having been monitored since the first half of the 20th century (Robins et al., 2006; Mahé et al., 2013). In the Sahel, the limited density of piezometric surveys and the discontinuity of available records still hamper accurate and updated regional mapping of WTD and the monitoring of long-term groundwater level changes. This lack of direct observations also limits the ability to constrain inverse modelling approaches and coupled surface-subsurface models (Boucher et al., 2012; Skaskevych et al., 2020).

Remote sensing has considerably improved the monitoring of continental water resources over recent decades. Recent advances have enabled increasingly detailed observations of surface water bodies, notably through the Surface Water and Ocean Topography (SWOT) mission, which provides high-resolution estimates of water-surface elevation and extent over rivers, lakes, reservoirs and wetlands (Biancamaria et al., 2016; Girard et al., 2025). Gravimetry missions such as GRACE and GRACE–FO have also provided major insights into large-scale changes in terrestrial water storage (Rodell and Famiglietti, 1999; Tapley et al., 2004; Richey et al., 2015; Scanlon et al., 2022; Pfeffer et al., 2023) and have been widely used to infer groundwater storage variations after accounting for other water-storage compartments (Boubé Dobi et al., 2021; Ferreira et al., 2024; Mohasseb et al., 2024). However, these GRACE–derived estimates require complex inversion procedures and assumptions about other storage compartments, including soil moisture, snow and/or surface water (Long et al., 2015; Kolusu et al., 2019). Even after such treatments, estimates in storage changes are available at spatial resolutions much coarser than those of surface water remote sensing products and represent spatially integrated groundwater storage variations rather than

https://doi.org/10.5194/egusphere-2026-4198
Preprint. Discussion started: 6 August 2026

WTD fluctuations. As a result, they cannot directly provide groundwater depth variability information at regional or local scales.

The limited availability of direct groundwater depth observations is also reflected in recent global groundwater datasets and modelling studies (Cao et al., 2026). Although these studies represent important advances for assessing groundwater dynamics and WTD at large scales, West Africa and the Sahel in particular remain poorly constrained because of the scarcity of available observations. Recent global datasets still show strong spatial biases in the distribution of groundwater level time series, with most observations concentrated in North America, Europe, India and Australia (Bäthge et al., 2026). Similarly, recent global assessments of groundwater levels emphasize the central role of in situ monitoring for model parameterization, while large parts of Africa remain underrepresented in observational datasets and model constraints (Reinecke et al., 2024). This persistent data gap highlights the need for complementary approaches capable of increasing groundwater depth information in poorly monitored African drylands.

The Sahel is a broad, ~3M km^2 semi-arid transition zone located between the Sahara Desert to the north and the Sudanian savannas to the south. The wider Sahel region is home to more than 300 million people (UNDP, 2021), with projections suggesting that this population could reach 500 million by 2050 (IFAD, 2026), reflecting high population growth rates across the region (Tomalka et al., 2021). It extends across West, Central and East Africa from the Atlantic coast to the Red Sea, crossing parts of Senegal, Mauritania, Mali, Burkina Faso, Niger, northern Nigeria, northern Cameroon, Chad and Sudan, although its exact limits vary depending on the climatic, ecological, or political criteria used (**Fig. 1a**). The Sahel region is characterized by a strong south-north rainfall gradient and marked seasonal and interannual variability; mean annual rainfall boundaries commonly considered ranges from about 100–200 mm in the north to 700 mm in its southern part. The rainy season is short and concentrated over a few months, while the dry season extends over most of the year (from October–November to May).

This regional setting is central to the concept developed in this study. The Sahel is recognized as one of the most complex and sensitive regions to global change (IPCC: Climate Change, 2022; IPCC: Summary for Policymakers, 2022). Recent studies have also highlighted hydrological regime shifts in Sahelian watersheds, reflecting changes in catchment responses to rainfall variability and land-surface conditions (Le Roux et al., 2025). A better understanding of biophysical processes and aquifer feedbacks across multiple timescales is therefore essential for improving and constraining regional models of the water and energy cycles. However, in this region, the lack of groundwater information is further amplified by logistical and security constraints (OECD, 2012; World Bank and CIWA, 2023), which increasingly limit regular field surveys and the maintenance of long-term monitoring networks. Yet, in this region, groundwater plays a central role in water supply, agriculture, pastoralism, sustaining rural livelihoods and climate resilience across the whole region (Taylor et al., 2013; Nazoumou et al., 2016; MacDonald et al., 2021). Recent studies have also shown some main of the Sahelian vegetation, including an unexpectedly high density of trees and shrubs across the West African Sahara and Sahel and/or regreening trends revealed by high-resolution satellite imagery (Dardel et al., 2014; Brandt et al., 2020). Groundwater depth is a key control on groundwater-

https://doi.org/10.5194/egusphere-2026-4198
Preprint. Discussion started: 6 August 2026

dependent ecosystems, particularly in drylands where access to shallow groundwater can sustain vegetation under water-limited conditions (Rohde et al., 2024). Improving knowledge of groundwater depth and its temporal variability is therefore essential for better characterizing aquifer responses to climate and land use changes, understanding surface water–groundwater interactions and improving the parameterization of regional hydrological and land-surface models (Favreau et al., 2009; Massuel et al., 2011; Goni et al., 2021).

Pastoralism and agro-pastoralism are central components of Sahelian socio-economic systems (Serres et al., 1980; Turner and Hiernaux, 2008; Hiernaux and Assouma, 2020), allowing people to make use of highly variable and seasonally distributed water and feed resources (McGahey et al., 2014; Assouma et al., 2019). Transhumant pastoralism, in particular, represents an important adaptation strategy to scarce and variable natural resources, supporting food production, income and rural livelihoods across the Sahel. However, traditional pastoralism systems are increasingly exposed to combined socio-political and ecological pressures, including climate variability, land use changes, restricted mobility and changing access to land resources (Muhammad et al., 2019). Access to water is therefore a major determinant of livestock mobility, dry season resource use and the spatial organization of pastoral and agricultural activities, which are becoming increasingly sensitive to climate change (McGuirk and Nunn, 2025). In this context, groundwater is often the only reliable water source for pastoral communities in the Sahel, supporting both livestock watering and human needs because of its year-round availability and generally better quality than surface water. Traditional open hand-dug wells, many of which are operated using animal traction, have remained an important means of accessing groundwater in Sahelian pastoral areas (Thébaud et al., 2006), especially because permanent surface water resources are scarce during the dry season (**Fig. 2**) and because of the lack of boreholes dedicated to livestock watering (World Bank and CIWA, 2023).

Hand-dug wells are deeply embedded in local socio-economic systems, as they structure access to grazing areas and livestock mobility (Thébaud and Batterbury, 2001; Thébaud, 2017). During the dry season, groundwater abstraction for livestock watering is still commonly performed using ropes and leather buckets pulled by cattle. This practice creates elongated surface tracks that radiate from the well and may extend over several tens of metres, forming radial patterns visible on high-resolution optical satellite imagery. Because the traction distance required to lift water arithmetically increases with the depth to the water table, track length is a robust indicator of the WTD. To our knowledge, this approach is specifically applicable to Sahelian pastoral systems where groundwater is accessed through several tens of thousands of open hand-dug wells using animal traction and where the resulting surface tracks are preserved and visible on high-resolution optical imagery.

This methodological concept was initially formulated by Langlais et al. (2014); it was then subsequently explored by Langlais (2017), Collignon (2020, 2021, 2024), Collignon et al. (2021) and Collignon and El Moctar Ould Mohamed Vall (2022), based on the visual interpretation of imagery available through the open-access geospatial platform Google Earth Pro. These works highlighted the potential of traditional livestock watering tracks as markers of groundwater depth in pastoral areas. However, the reliability of the resulting estimates was not assessed in detail against independent, synchronous in situ measurements. In addition, using imagery from visualization platforms limits the reproducibility of image selection, preprocessing, spatial

https://doi.org/10.5194/egusphere-2026-4198
Preprint. Discussion started: 6 August 2026

referencing and acquisition metadata. Here, we provide a critical and reproducible evaluation of this approach by confronting image-derived WTD estimates with quality-controlled in situ water level measurements in hand-dug wells used for pastoralism in southwestern Niger, part of the long-term AMMA-CATCH regional observatory database (AMMA-CATCH, 1990; Galle et al., 2018).

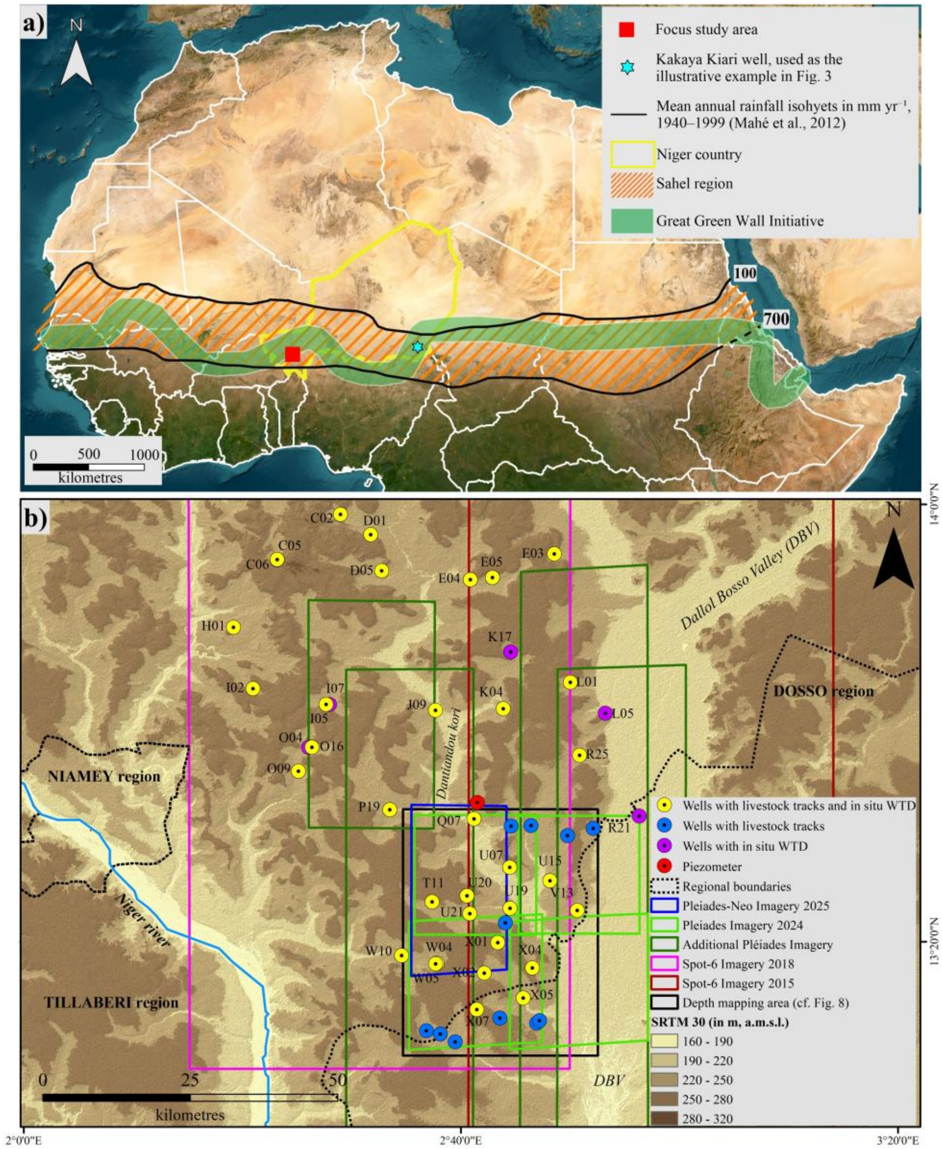


Figure 1. (a) African-scale map showing isohyets from Mahé et al. (2012), with the study area indicated by a red dot within the Sahel region. (b) Detailed view of the study area in SW Niger showing the footprints of the SPOT 6, Pléiades and Pléiades Neo images, together with the locations of the wells used in this study. Only wells with both visible tracks and in situ WTD data are labelled with their code names.

https://doi.org/10.5194/egusphere-2026-4198
Preprint. Discussion started: 6 August 2026

Southwestern Niger provides a suitable, focused study area. It is particularly relevant for assessing groundwater depth estimation from traditional livestock watering tracks because it combines widespread pastoral and agro-pastoral water use, numerous open hand-dug wells and long-term in situ groundwater observations (**Fig. 1b**). The AMMA-CATCH observatory (Niger site) provides a preciously rare opportunity to compare satellite-derived estimates of WTD with field measurements. Such a comparison is necessary because the relationship between track length and WTD may be affected by several sources of uncertainty and biases, including the interpretation of tracks on satellite imagery, well geometry, abstraction practices, well productivity, soil surface conditions, long-term groundwater level changes and the possible mixing of wells tapping different aquifers. As a result, reliable WTD estimates derived from satellite imagery should first be evaluated against in situ observations before the method can be applied more broadly for groundwater mapping.

This technical note therefore aims to: (i) estimate uncertainties related to the visual interpretation of traction-related tracks on high-resolution satellite imagery; (ii) assess the agreement between image-derived and in situ WTD; and (iii) identify the main sources of biases affecting groundwater depth estimates derived from traditional livestock watering tracks radiating from wells in the Sahel.

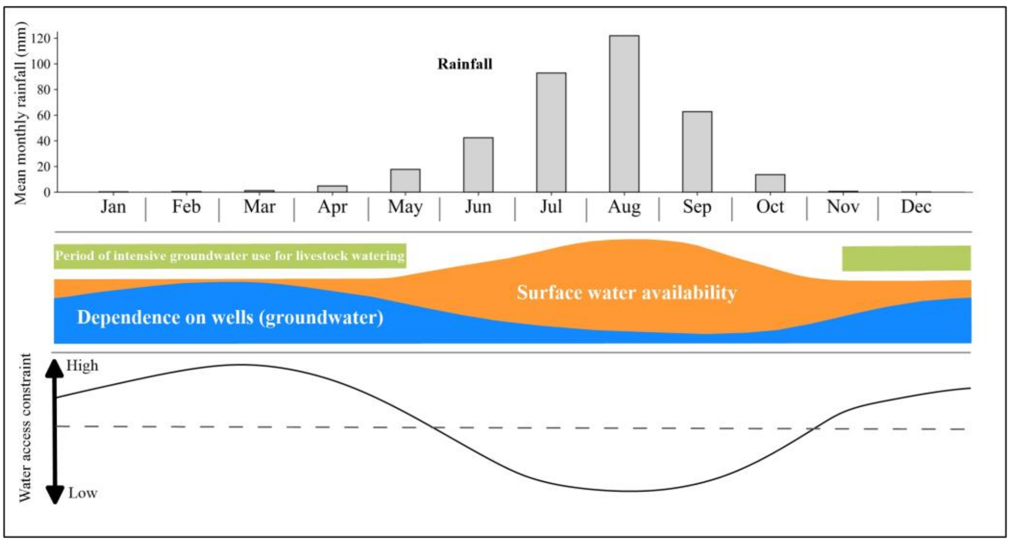


Figure 2. Conceptual representation of the seasonal dynamics of rainfall over the Sahel, based on the Global Precipitation Climatology Centre (GPCC) data compiled for the period 1981–2020 (Schneider et al., 2022), together with the associated seasonal dynamics of access to surface water and groundwater and indicative constraints on water availability in Sahelian pastoral systems.

2 Data and methods

2.1 Water table depth surveys

In situ WTD measurements were obtained from the AMMA-CATCH long-term critical zone observatory in West Africa database. AMMA-CATCH documents the eco-hydrological functioning of the West African critical zone along a strong

https://doi.org/10.5194/egusphere-2026-4198
Preprint. Discussion started: 6 August 2026

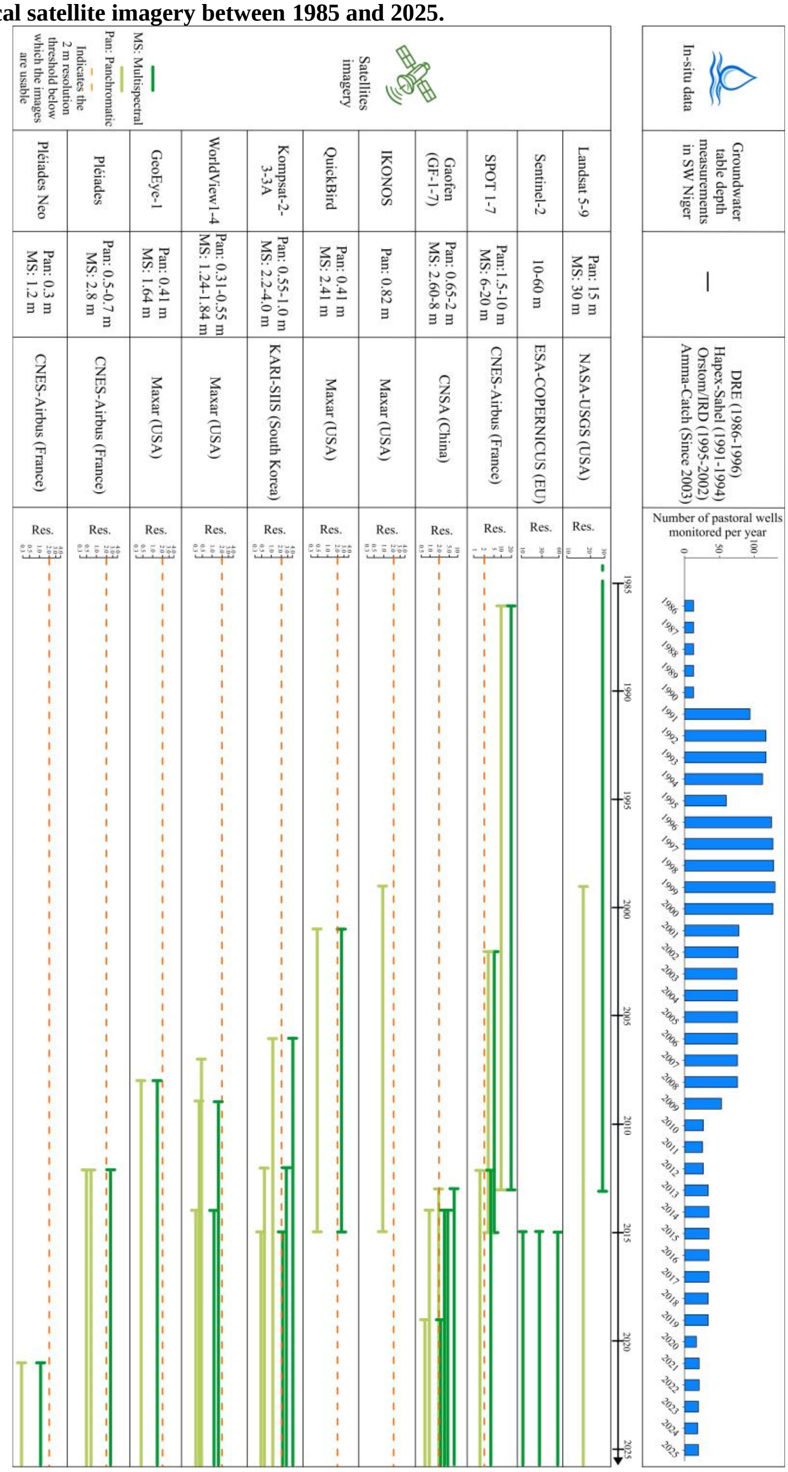
climatic gradient, through four densely instrumented sites located in Benin, Niger, Mali (measurements stopped in 2018) and Senegal (Lebel et al., 2009; Galle et al., 2018). Since 1990, the observatory has collected long-term data of meteorology, surface water, groundwater, soil moisture, surface fluxes, vegetation dynamics and water quality. The Niger site, located in Southwestern Niger (**Fig. 1**), provides long-term observations of hydrological, vegetation and land-surface processes (Cappelaere et al., 2009). The first field observations in this area date back to 1988, with the SEBEX (Sahelian Energy Balance Experiment) and EPSAT (Estimation of Precipitation by Satellite) experiments, followed by the HAPEX-Sahel experiment in 1992 (Goutorbe et al., 1997).

This study focuses on the left bank area of the Niger River within the AMMA-CATCH Niger site. The area belongs to the large Iullemmeden sedimentary basin and is mostly characterized by endorheic hydrology, with small catchments draining towards depressions or temporary ponds along ancient river beds (Descroix et al., 2009). The upper sedimentary formation mainly corresponds to the Continental Terminal (CT) aquifer, locally covered by alluvial deposits (Favreau et al., 2012; Chardon et al., 2016). WTD is spatially highly variable, ranging from more than 75 m below ground level beneath the plateaus to less than 10 m or locally outcropping groundwaters (Favreau, 2000; Nazoumou et al., 2016). Groundwater monitoring within the site relies on piezometers and large (~1 to ~2 m in diameter) hand-dug wells used for domestic, pastoral, or mixed purposes (AMMA-CATCH, 2003). Over the 2003–2025 period, the AMMA-CATCH southwestern Niger groundwater database includes 192 traditional wells, for which a total of ~16 000 WTD measurements were available, with a median of 80 measurements per well over the whole period. The monitored structures are named according to the numbering system described by Leduc and Lenoir (1995), which combines the village name with an alphabetical and numerical code (VillageName_code). In this study, we selected wells with pastoral or mixed uses, provided that animal traction was used for water abstraction. The number of monitored pastoral wells available in the database varied strongly over time. It was limited to 13 wells between 1986 and 1990, increased during the early 1990s and reached its maximum between 1996 and 2000, with 125 to 130 monitored wells per year. The network then progressively decreased, from 78 wells in 2001 to 17–21 wells between 2020 and 2025 (**Tab. 1**). This decrease first reflects a rationalization of the monitoring network, following improved understanding of the main hydrological processes and groundwater dynamics and was later (> year 2020) restricted by increasing insecurity affecting administrative authorizations delivered for field surveys in the area.

A preliminary screening of the monitored wells was conducted using the Google Earth Pro platform to identify pastoral and/or mixed-use wells with visible animal-traction tracks on satellite imagery. This screening resulted in the selection of 34 wells that had both in situ WTD measurements between 2003 and 2025 and visible surface tracks associated with livestock watering practices (**Fig. 1b**). The main characteristics of the selected wells, including location and data availability timeline, are provided in **Supplementary Material 1**.

https://doi.org/10.5194/egusphere-2026-4198
Preprint. Discussion started: 6 August 2026

Table 1. Change through time of available in situ water table measurements in southwestern Niger, reported as the number of monitored wells that were shown to be used for pastoralism and seasonal livestock watering, together with the availability and spatial resolution changes of optical satellite imagery between 1985 and 2025.



https://doi.org/10.5194/egusphere-2026-4198
Preprint. Discussion started: 6 August 2026

2.2 high-resolution satellite imagery

Optical satellite imagery was used for identifying pastoral wells and interpreting traction tracks. In practice, traction-related tracks were only clearly discernible on images with a spatial resolution of 1.5 m or finer (Collignon, 2022), which therefore defined the minimum resolution considered in this study. The main image dataset included SPOT-6, Pléiades and Pléiades Neo scenes, with spatial resolutions of 1.5 m, 0.7 m and 0.3 m, respectively (**Tab. 1**). Image search and acquisition were conducted through the DINAMIS Data Terra platform, which was used to identify scenes matching the study area, the well locations and the relevant dry season acquisition period.

For each scene, the main metadata considered were sensor type, acquisition date, spatial resolution and spatial coverage. SPOT-6 imagery was accessed on 28 July 2025 and consisted of two scenes acquired on 30 January 2015 and 26 January 2018 and covered all 34 wells (**Fig. 1b**). Thirteen wells were located in the overlap area between the two scenes and could therefore be observed at both dates. Pléiades imagery was accessed through the Pléiades World Heritage tool on 13 March 2026 and consisted of four scenes: two acquired on 25 January 2024 and two on 20 February 2024. As no notable surface evolution is observed between late January and late February, these scenes were treated as representing a single observation period and covered a total of 15 wells. Pléiades Neo imagery, acquired on 17 February 2025, was provided by the DINAMIS Data Terra platform on 20 March 2026 and covered 7 wells. Overall, the combination of these three sensors provided a multi-resolution basis for track interpretation. For wells located both in the overlap area of the two SPOT-6 scenes and within the Pléiades and Pléiades Neo coverage (**Fig. 1b**), the dataset also enabled a temporal analysis of track-derived WTD estimates.

Additional Pléiades images acquired on different dates were also used for complementary purposes. They provide punctual image-derived estimates for selected WTD time series shown in **Fig. 7**. The footprints of the complementary images used are shown in **Fig. 1b**.

On high-resolution optical images, pastoral wells were identified using a combination of visual features. These include the central well structure, a surrounding area often marked by darker organic-rich material related to repeated livestock presence and one or several elongated traction-related tracks radiating from the well. Some wells are located close to settlements or villages, whereas others are isolated in seasonally cultivated or herbaceous pastoral areas. **Fig. 3a** illustrates the main elements searched for during satellite image interpretation. Track visibility was strongly controlled by acquisition date. Tracks were generally visible during the dry season, from November to May, with the highest confidence in track identification from late December to late March (**Fig. 3b**).

2.3 Methods

2.3.1 Photo-interpretation and aggregation of traction tracks

Visible linear tracks around wells were independently digitized by four observers for SPOT-6 and Pléiades images and by five observers for Pléiades Neo images (see author's contributions), due to the smaller number of wells covered by this sensor. This multi-observer interpretation was designed to quantify the uncertainty associated with visual image interpretation.

https://doi.org/10.5194/egusphere-2026-4198
Preprint. Discussion started: 6 August 2026

Digitization was performed in QGIS version 3.44.7 (Dawson et al., 2026) using the three main image datasets described in **Sect. 2.2**. For each visible traction-related track, each observer independently positioned the centre of the well and the end of the track according to their own interpretation of the imagery (**Supplementary material 2**). The digitized line therefore represented the estimated horizontal traction-path length from the well centre to the end of the visible surface track. This approach ensured that interpretation uncertainty included both the identification of the tracks themselves and the exact positioning of their geometry. It also allowed differences among observers to be quantified before any aggregation step.

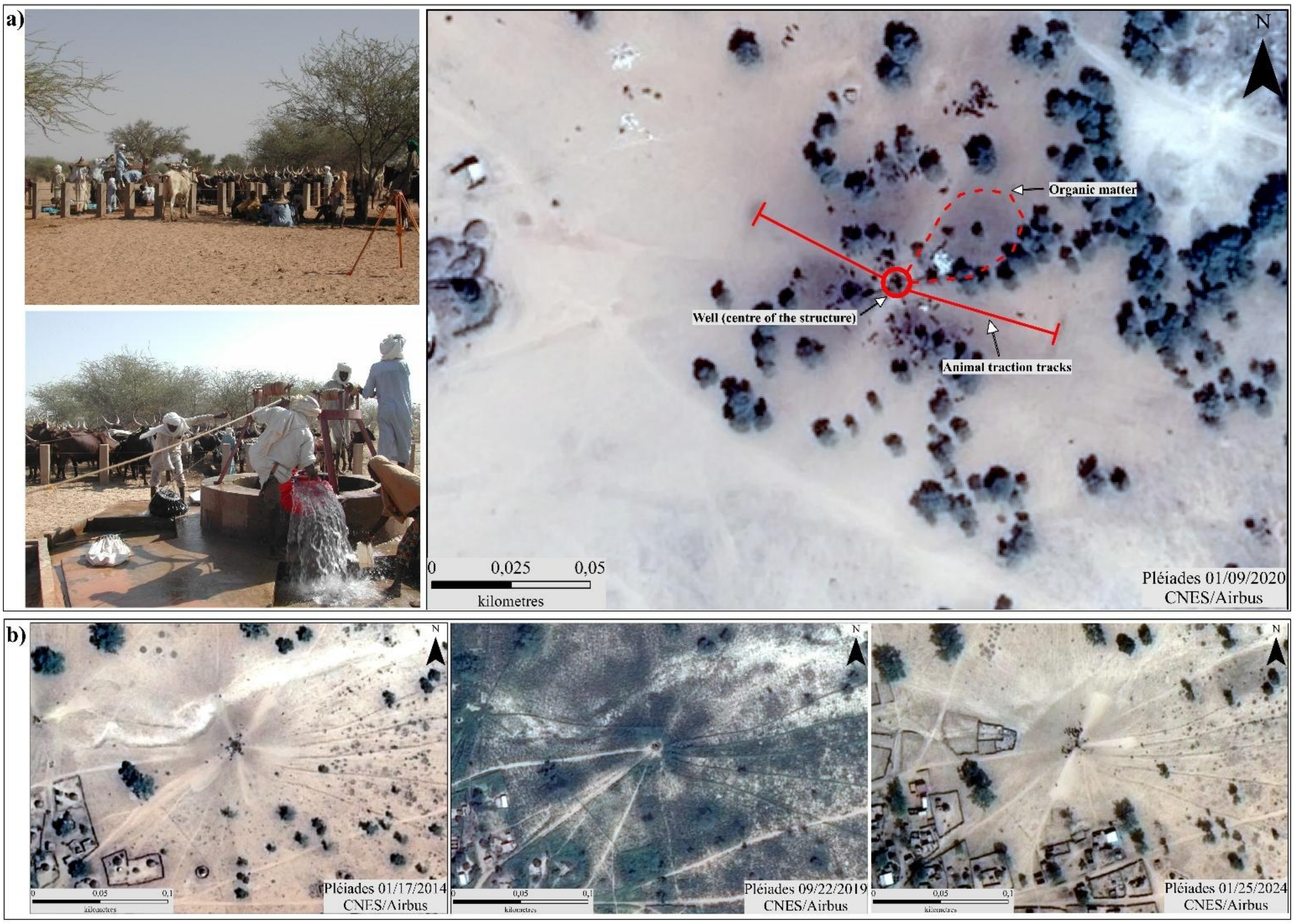


Figure 3. (a) Ground photograph of the Kakaya Kyari well, Diffa Region, southeastern Niger (blue star in Fig. 1b; 13.375997° N, 12.466981° E; © IRD – F. Delclaux, 29 November 2003), alongside a high-resolution satellite image of the same well showing the well structure and associated surface tracks. (b) Multi-temporal views of the Boktili_X02 well, illustrating the potential for temporal monitoring and showing that the well structure is not visible during the rainy season (see bottom central image acquired on 22 September 2019). For Pléiades images, Copyright CNES, Date: 11 May 2026. "Distribution Airbus DS DINAMIS".

A Python script was used to format the digitized tracks, harmonize label names, associate each observer-labelled track with the nearest well and optionally reorder track points or update well positions based on the digitized tracks (**Supplementary**

material 3). For each line, track orientation and track length were computed. This yielded an initial interpretation database containing, for each observer, well, image date and sensor, the number of identified tracks and their associated geometric characteristics (**Supplementary material 2**).

A set of filtering criteria was then applied to harmonize track identification across observers using a Python script (**Supplementary material 4**). Two tracks were considered to represent the same feature when their orientations differed by no more than ±20° between observers. In addition, a track was retained only if it had been identified by at least two observers, regardless of the total number of observers available for a given image dataset. These criteria were introduced to reduce the influence of isolated or ambiguous interpretations while preserving features showing a minimum level of inter-observer agreement. The filtered database (**Supplementary material 2**) formed the basis for all subsequent uncertainty analyses and comparisons with in situ measurements.

Several aggregation steps were applied to derive representative values from the observer-based track dataset. The procedure followed a hierarchical structure from individual observer measurements to track-scale estimates and then to well-scale estimates for each image date and sensor. In the whole study, the median was preferred to the mean because it is less sensitive to outliers and isolated interpretation differences. First, inter-observer statistics were calculated for each retained track, including the variability in track length estimates among observers. For each track, the median length across observers was therefore computed to derive a single representative track length. Second, for wells where more than one traction-related track was observed, the median length across retained tracks was calculated to obtain a single representative image-derived traction-path length for each well and each image date or sensor (**Supplementary material 2**).

2.3.2 Uncertainty and bias assessment

For each retained track, the standard deviation between the lengths measured by the different observers was calculated. The median of these track-specific standard deviations was then used as an indicator of inter-observer uncertainty to quantify the sensitivity of track measurement to visual interpretation.

The aggregated track lengths measured from satellite imagery were compared with near-synchronous in situ WTD measurements to assess the empirical relationship between the two quantities (length, in metres). For each satellite image date, the closest (in time) available in situ WTD measurement was selected for each well. When several field measurements were available during the same dry season period, the measurement closest in time to the satellite acquisition date was retained. For wells observed on several image dates or by several sensors, comparisons were performed separately for each track length estimate and its corresponding in situ measurement. Agreement between estimated and measured WTD was assessed using several complementary performance metrics: median bias, median absolute error, root mean square error (RMSE), coefficient of determination (R^2) and Pearson's correlation coefficient (r).

The potential sources of biases between track length and in situ WTD were then evaluated using a conceptual representation of the water withdrawal system. This representation was based on the official Niger administration well cross-section

https://doi.org/10.5194/egusphere-2026-4198
Preprint. Discussion started: 6 August 2026

(OFEDES or *Office des Eaux et du Sous-Sol*; cf. NISSHO IWAI, 1998; Thébaud et al., 2006) complemented by the technical characteristics of these wells described by Burgeap (1980), field knowledge of pastoral water-abstraction practices and the known functioning of groundwater systems through pumping tests in hand-dug wells in the study area (Favreau et al., 2000; Boucher et al., 2009). This conceptual framework was used to identify and discuss the main geometrical, hydrological and operational factors that may explain observed differences between satellite-derived track lengths and measured water table depths.

WTD time series were plotted for a subset of selected wells over the 2003–2025 period. These wells were chosen to cover the spatial variability of the study area, a range of groundwater depths and different numbers of visible traction tracks. For each selected well, image-derived track length estimates from the different satellite datasets were compared to the corresponding WTD time series. Additional estimates derived from the Google Earth Pro platform imagery for the years 2010 and 2011 (dry season, months 01 and 03) were also included to extend the temporal range of comparisons.

2.3.3 Groundwater depth mapping

Groundwater depth maps were produced over ~1300 km² area (**Fig. 1b**), corresponding to the recent 2024 Pléiades image coverage, where both livestock tracks and in situ water-table depth measurements were sufficiently dense. This area also includes wells for which field-levelled elevations were available. The SRTM30 DEM (NASA JPL, 2013) at 30 m resolution was corrected using nine field elevation selected points (differential GPS levelling from 1992 through 1998 of the rim of the wells, estimated accuracy 0.1 m, IGNN Niger; data reported in Favreau, 2000) ; twelve well datasets were used to interpolate the piezometric head surface. Three interpolation methods were tested: inverse distance weighting (IDW), ordinary kriging (OK) and radial basis functions (RBF). IDW was retained for the final maps because it produced the most spatially coherent piezometric altitude map (**Supplementary material 5**), when compared with previous, larger-scale piezometric mapping (Massuel et al., 2011; Boucher et al., 2012; Bosch and Heckmann, 2019). Groundwater depth was then calculated as the difference between the in situ ground levelling surveys - corrected SRTM30 elevation and the interpolated piezometric surface. A median filter was applied to reduce residual raster noise. Window sizes of 3, 5, 7, 9, and 11 pixels were tested, and the 3-pixel window provided the best result, reducing the mean error between field-measured and SRTM30-derived elevations from 1.95 to 1.65 m. Eleven additional wells with visible livestock tracks, but not included in the initial database, were used as independent validation wells for water table depth mapping.

3 Results

3.1 Year-to-year variability in traction tracks

The temporal consistency of traction tracks was examined for wells observed on several image dates. The number of visible tracks can be interpreted as a qualitative indicator of well-use intensity. For the 13 wells in common to SPOT-6 and Pléiades

https://doi.org/10.5194/egusphere-2026-4198
Preprint. Discussion started: 6 August 2026

images, the number of visible traction tracks varied from 1 to 5 per well in 2015, from 1 to 3 in 2018 and from 1 to 4 in 2024, with median values ranging from 1 to 2 tracks. For the five wells common to SPOT-6, Pléiades and Pléiades Neo, the number of visible tracks ranged from 1 to 3 in 2015 and 2018, from 1 to 4 in 2024 and 2025, with median values also ranging from 1 to 2 tracks. These results indicate that the number of visible tracks was moderately variable through time, suggesting that livestock watering practices around a given well were partly persistent but could also be reorganized between image acquisitions. The orientation of traction tracks showed clearer temporal persistence. Using an orientation consistency threshold of ±20°, 66% of the tracks observed on the 13 SPOT-6/Pléiades common wells were matched between successive image dates. For the smaller subset of five wells common to SPOT-6, Pléiades and Pléiades Neo, the proportion of persistent tracks reached 83% between successive dates, although this result should be interpreted cautiously because of the limited number of wells observed on all sensors.

These findings indicate that the main directions of animal traction paths were often maintained over several years (**Fig. 4a**), probably because they are controlled by stable local constraints such as well structure, access routes, vegetation patches, or topography. For wells located near settlements, track configurations may also evolve in response to changes such as the expansion of houses, paths, or other built-up features. However, the appearance and disappearance of some tracks also suggest changes in well-use intensity, seasonal preservation of surface marks, livestock circulation patterns, or local surface disturbances. Overall, this comparison shows that traction tracks are not purely transient features. Their number and orientation can persist over several years for the same well, supporting the use of multi-temporal satellite images to identify and measure them.

3.2 Inter-observer uncertainty in track length visualization

Track length interpretation was assessed by comparing measurements obtained independently by several observers on the same satellite images. After applying the criteria described in **Sect. 2.3.1**, 375 measurements corresponding to 112 tracks were retained for the inter-observer comparison, representing 71% of the initially digitized tracks. The comparison included 28 wells observed on SPOT-6 images, 13 wells observed on Pléiades images and 6 wells observed on the Pléiades Neo image.

Overall, the visual interpretation of traction-related tracks was relatively consistent among observers. Across all images, the median inter-observer standard deviation in track length was 1.7 m, with values ranging from 0.1 to 15.7 m (extreme values are discussed below in **Sect. 3.3**) depending on image date and sensor. Inter-observer variability differed slightly between sensors and image dates. For the SPOT-6 images, the median standard deviation was 1.6 m in 2015 and 2.0 m in 2018. Although both SPOT-6 images had the same spatial resolution, the 2018 image was often visually blurred, which made the end of some traction tracks more difficult to delineate. For the Pléiades images acquired in 2024, the median standard deviation was 1.3 m, while for the Pléiades Neo image acquired in 2025, it was 1.9 m.

A direct comparison based on common wells was then conducted to reduce the effect of differences in well samples between sensors. For the 13 wells common to SPOT-6 and Pléiades, corresponding to 48 tracks in total, 25 tracks were retained for

https://doi.org/10.5194/egusphere-2026-4198
Preprint. Discussion started: 6 August 2026

SPOT-6 and 23 for Pléiades. For this subset, the median standard deviation was 1.5 m for SPOT-6 and 1.3 m for Pléiades. For the five wells common to SPOT-6, Pléiades and Pléiades Neo, corresponding to 29 tracks in total, 10 tracks were retained for SPOT-6, 10 for Pléiades and 9 for Pléiades Neo. For this smaller subset, the median standard deviations were 3.1 m, 2.6 m and 1.2 m, respectively (**Fig. 4b**). These results suggest that the improvement in spatial resolution from SPOT-6 to Pléiades and Pléiades Neo tended to reduce uncertainty in track length interpretation when the comparison was restricted to common wells. However, this trend was not fully systematic across the complete dataset and the Pléiades Neo results should be interpreted cautiously because they are based on a smaller number of common wells. Overall, interpretation uncertainty was not controlled by image resolution alone, but also by image sharpness, track visibility, surface contrast, local disturbances and the difficulty of identifying the exact end of the traction path.

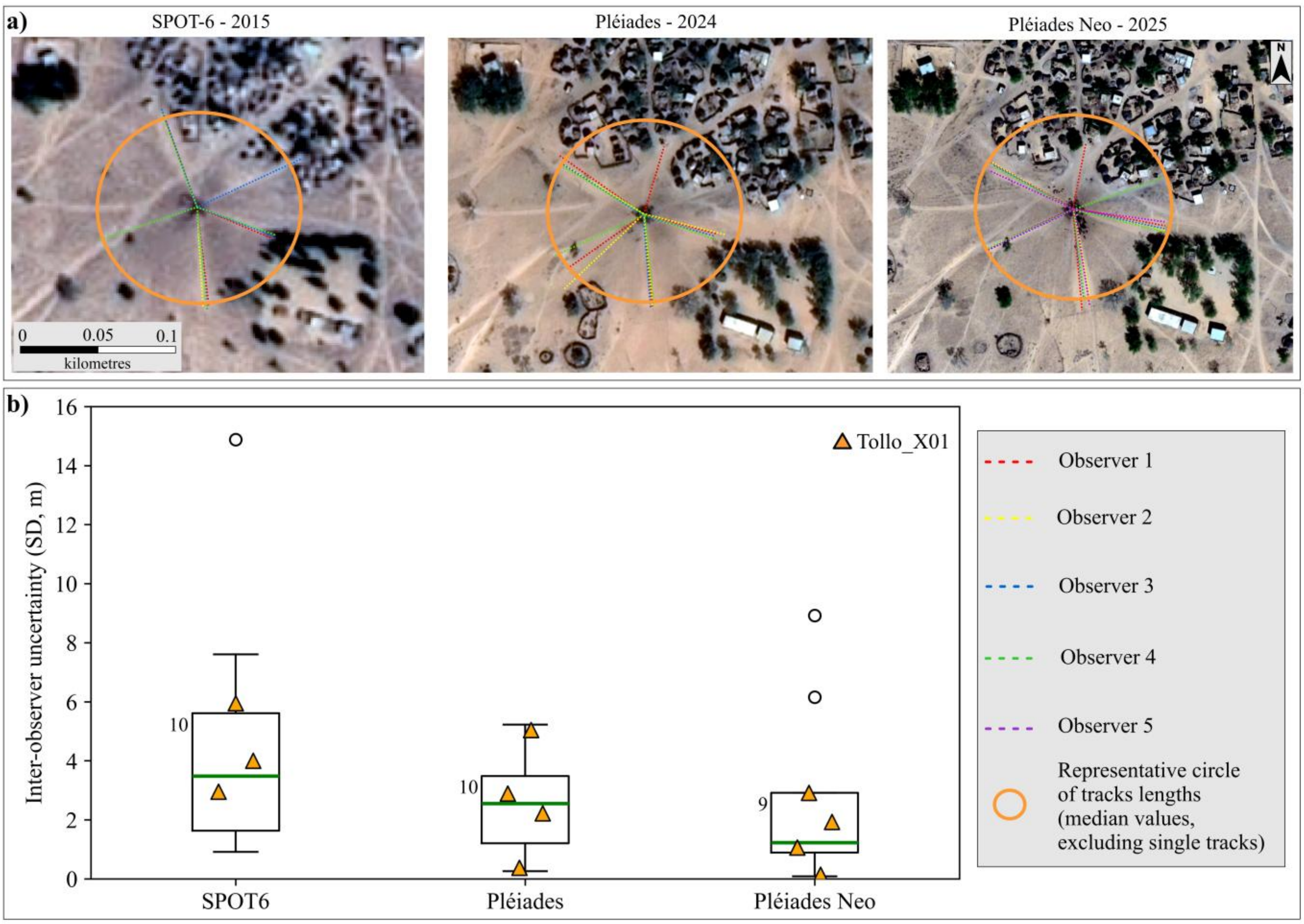


Figure 4. a) Views of the Tollo_X01 well from the different satellite images, showing the surface tracks independently delineated by the different observers. b) Boxplots summarizing the inter-observer standard deviation of track length for the wells common to the three sensors. The green horizontal line indicates the median standard deviation. The orange triangles show the standard deviation values associated with each track identified for the Tollo_X01 well. The number next to each boxplot indicates the total number of tracks retained after filtering for the common wells. SPOT 6-7: “Copyright ADS, " Date: 28 July 2025. “Distribution Airbus DS DINAMIS”. Pleiades: “Copyright CNES, " Date: 13 March 2026. “Distribution Airbus DS DINAMIS”. Pleiades NEO: “Copyright ADS, " Date: 20 March 2026. “Distribution Airbus DS DINAMIS”.

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Preprint. Discussion started: 6 August 2026

3.3 Relationship between track length and in situ water table depth

Satellite-derived track lengths were compared with in situ WTD measurements for 57 paired image-well observations, corresponding to 28 wells. These included 17 wells observed on the SPOT-6 2015 image, 22 on the SPOT-6 2018 image, 13 on the Pléiades 2024 images and 6 on the Pléiades Neo 2025 image. Measured water table depths ranged from 15.2 to 58.9 m below ground level, while satellite-derived track lengths ranged from 17.8 to 63.9 m. The comparison showed a strong positive relationship between track length and measured WTD, with an overall correlation coefficient of 0.9 and a coefficient of determination of 0.8. This confirms that animal traction track length contains information on groundwater depth and can be used as a proxy for spatial variations in WTD.

However, the estimates also showed non-negligible deviations from the 1:1 line. The median absolute error (median of the absolute differences between image-derived track length and measured WTD) was 6.4 m and the root mean square error was 7.9 m. The overall median difference between image-derived track length and measured WTD was 6.1 m, with an interquartile range of the bias is 4.1–8.5 m. The median absolute deviation around this median bias, defined as the median absolute distance of individual bias values from the median bias, was 2.4 m. 91% of the estimates showed a positive bias, indicating that satellite-derived track lengths usually overestimated measured WTD.

A few notable exceptions can be noticed in the relationships depending on years and wells (**Fig. 5**, labelled data). For instance, well X07 appears as a strong underestimation in the 2024 Pléiades plot, with a much larger uncertainty. For this well, the area surrounding the well has been progressively encroached upon by nearby houses, making the end of the traction tracks less clear and increasingly ambiguous in track delineation. This ambiguity is also reflected in the large inter-observer uncertainty on the SPOT-6 2015 image, where the well was also visible (**Fig. 5**). In 2024, this uncertainty translated into a strong discrepancy between the image-derived estimate and the in situ measurement. This example confirms that even high-resolution imagery does not necessarily reduce interpretation uncertainty when the local surface context around the well is disturbed or when traction tracks are partly obscured by surrounding land-use features. This local evolution is illustrated in **Supplementary Material 6**, which shows the track estimates made by different observers on the 2015 SPOT-6 and 2024 Pléiades images of the X07 well. Wells W04 and E04 also showed lower track lengths than measured WTD (**Fig. 5**). For W04, this discrepancy is likely related to difficult interpretation conditions associated with nearby roads and urban land use, which affected the visibility and delineation of the track end. For E04, the underestimation likely reflects partial erasure of the track following the abandonment of the well for pastoral use, as shown in **Supplementary Material 6**. Another slight underestimation was observed for well X01 in 2018. In this case, the difference was-0.4 m and was probably related to the lower sharpness of the 2018 SPOT-6 image. Because X01 was observed on all the other images in the dataset without showing systematic underestimation, this value was retained in the dataset. By contrast, the four other underestimated values were excluded from the calculation of the representative median bias because they were associated with identifiable local interpretation or well-use issues rather than with the general relationship between track length and WTD.

https://doi.org/10.5194/egusphere-2026-4198
Preprint. Discussion started: 6 August 2026

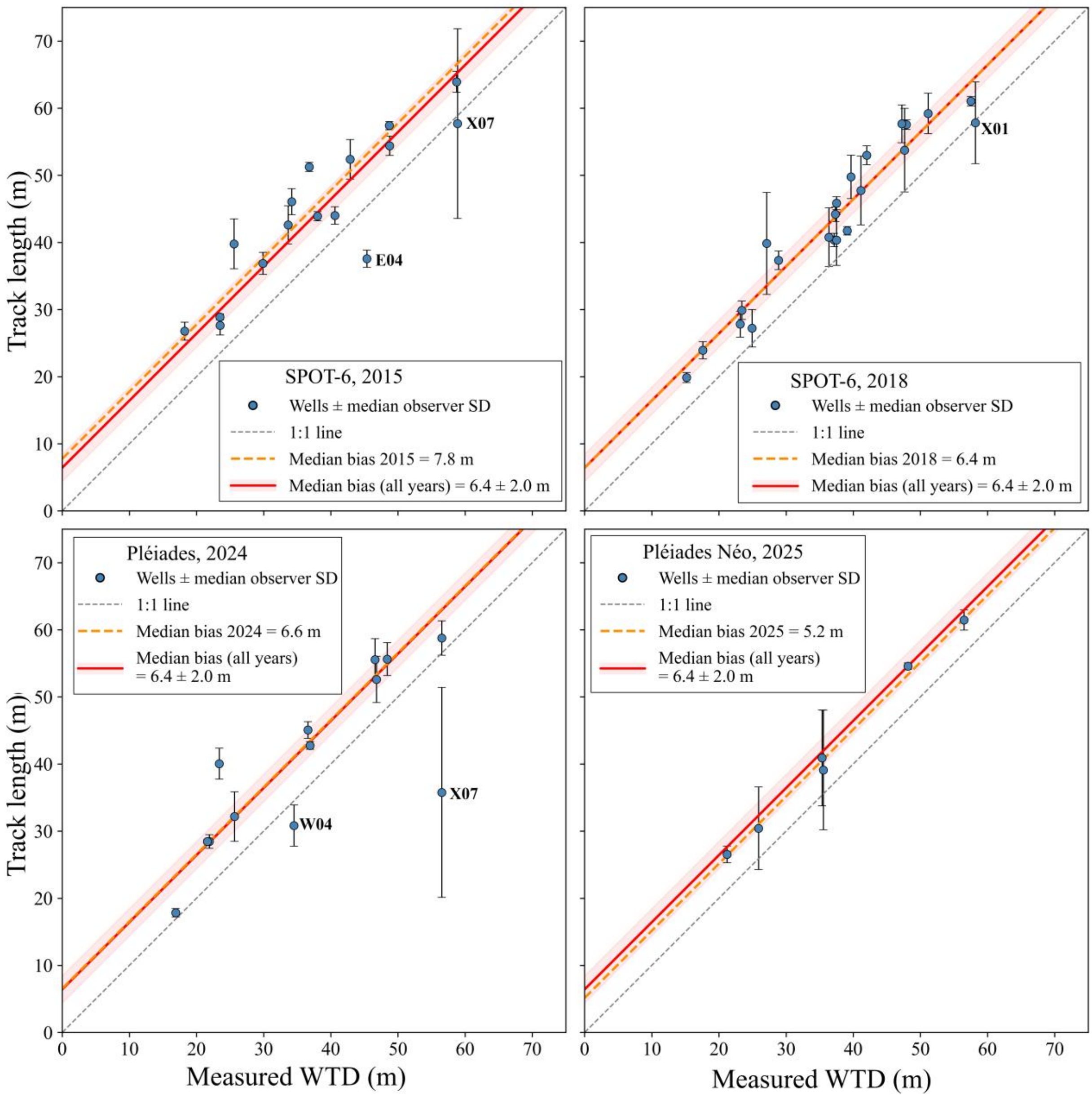

Figure 5. Scatter plots of measured track length versus measured WTD for different years and sensors (SPOT6-2015, SPOT6-2018, Pléiades-2024 and Pléiades Neo-2025).

After this filtering, the representative median bias was 6.4 m, with an interquartile range of 4.7–8.6 m and a median absolute deviation of 2.0 m. When analysed by satellite and image year after filtering, the median bias was 7.8 m for SPOT-6 2015 and 6.4 m for SPOT-6 2018 (**Fig. 5**), despite differences in image sharpness and track visibility in 2018. The Pléiades estimates showed a comparable median bias of 6.6 m in 2024 (**Fig. 5**), indicating that the higher spatial resolution did not remove the systematic offset between track length and measured WTD. For Pléiades Neo in 2025, the median bias was slightly lower, at 5.2 m (**Fig. 5**), although this result is based on a smaller number of wells and should therefore be interpreted cautiously. These results indicate that the overestimation is not primarily sensor-specific, but rather reflects a systematic offset between the measured track length and the actual depth to water. This offset likely results from site-specific geometrical, operational and hydrogeological factors. These factors are examined further in the following section on bias analysis.

3.4 Conceptual analysis of bias sources

The systematic overestimation of measured WTD by satellite-derived track length can be interpreted using the conceptual representation of the water withdrawal process shown in **Fig. 6**. In this system, the visible traction track measured on satellite imagery corresponds to the horizontal displacement of the animal during water abstraction. This distance does not strictly correspond to the vertical depth to the measured static or dynamic water level in the well. Several geometrical, operational and hydrogeological components can therefore contribute to the difference between measured track length and measured WTD. A first group of bias terms is related to the well structure and surface layout. The traction track is generally measured from the well centre visible on the image, whereas the effective rope path starts from the pulley system, which may be laterally offset from the centre of the well. The well rim, represented by (*a*), may add 0.1 to 1.0 m, depending on whether the well has a raised rim or not. However, in this study, this term does not contribute to the estimated bias because in situ WTD measurements were taken from the well rim. It was therefore not included in the range of extreme bias values considered here. The pulley height, represented by (*b*), may range from 0 to 1 m, depending on whether the pulley is installed close to ground level or elevated on an artisanal wooden structure or a more modern metal frame. The well radius, represented by (*c*), may range from approximately 0.5 to 1.5 m, depending on whether the well is privately funded (irregular values) or cemented according to state rules (usually 1.1 or 1.3 m in radius in SW Niger).
A second group of bias terms is related to traction practice. Animals do not start pulling directly from the well's edge. A safety distance, represented by (*d*), is generally maintained between the animals and the well to prevent them from falling into the opening and to help in managing watering by the cattle herder. For cemented wells, this distance may also be imposed by the presence of a cemented protective platform around the well. It may also vary with the number of animals involved in traction or gathered around the watering point, as larger livestock groups may require more space for movement and handling. This component may range from approximately 1 to 7 m, depending on well layout, herd size and local handling practices. The effective traction length also includes part of the animal's body length and the harness system. In Sahelian pastoral areas, animal traction may be performed mostly using cattle, camels, or donkeys depending on local practices and agro-pastoral contexts. In the study area, water abstraction is mainly carried out using camels and donkeys. The additional distance, represented by (*e*), may therefore range from approximately 0.6 to 1.2 m and is included in the track length measured from satellite imagery. The actual distance walked by the animals during water abstraction, represented by **D** (**Fig.6**), may also be slightly longer than its horizontal projection measured on satellite imagery because of the inclination of the traction path,

https://doi.org/10.5194/egusphere-2026-4198
Preprint. Discussion started: 6 August 2026

represented by the angle (α). In the study area, this slope is generally very low, with maximum values of about 5 %. For a 100 m traction distance, such a slope would make the horizontal length measured on satellite imagery only about 0.1 m shorter than the actual distance walked by the animals. This effect therefore acts in the opposite direction to the main positive bias terms, but its magnitude is very small and can be considered negligible.

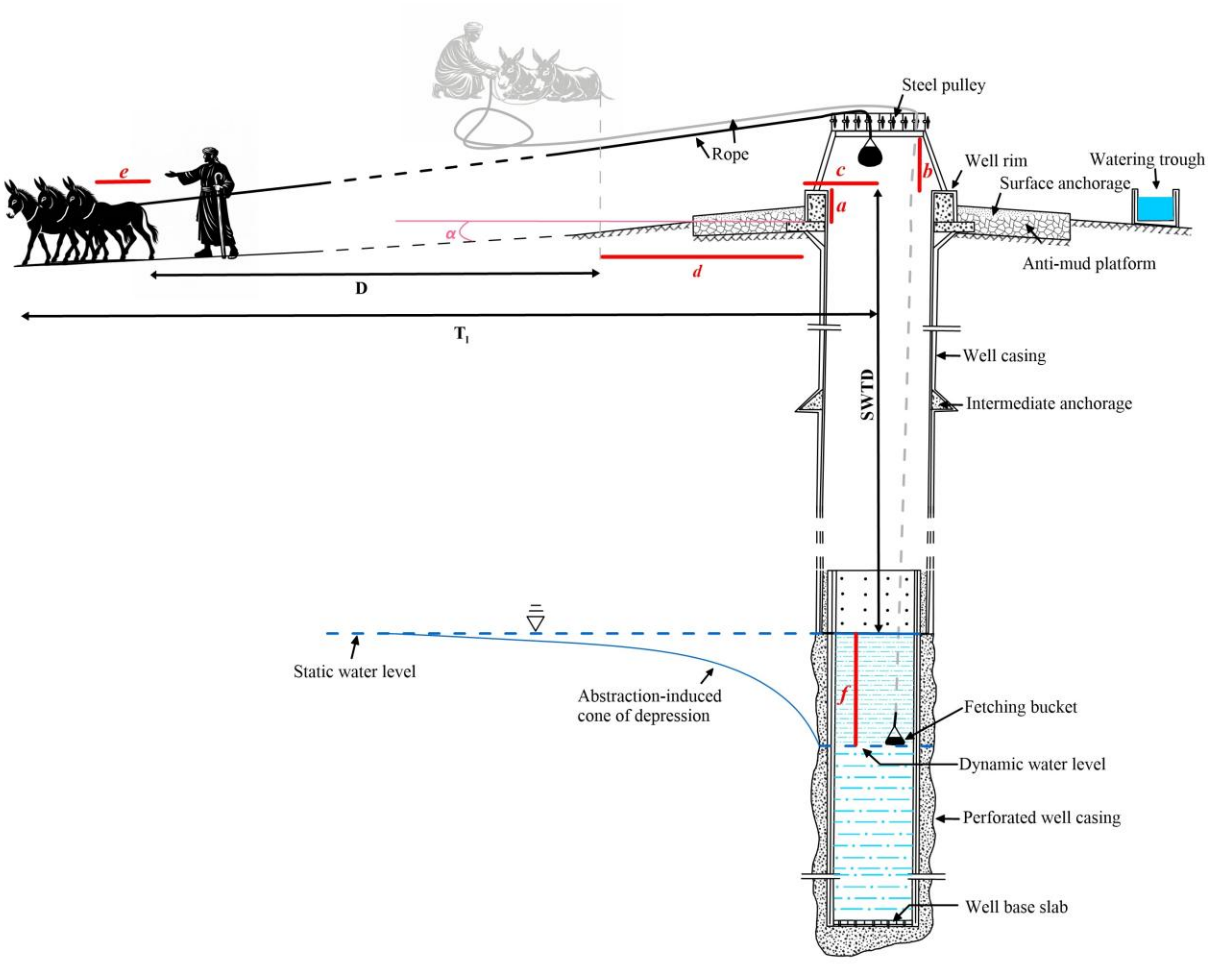

Figure 6. Conceptual representation of water withdrawal processes and the associated sources of bias. *a* represents the well rim, *b* the pulley height, *c* the well radius, *d* the safety distance from the well edge before the animals start pulling, *e* the length of the animal(s) pulling and *f* the variation between the static and dynamic water level.

A third component is hydrogeological, aquifer-related. In situ measurements in these wells generally refer to near-static WTD, whereas traction tracks may reflect water abstraction under dynamic conditions. During intensive use, the bucket is lowered to a dynamic water level that can be deeper than the static water table because of drawdown in the well. The difference between static and dynamic water levels, represented by (*f*), may therefore contribute approximately 0.5 to 2.5 m to the observed offset (Favreau et al., 2000), depending on abstraction intensity, well yield and the timing of the field measurement relative to water withdrawal.

https://doi.org/10.5194/egusphere-2026-4198
Preprint. Discussion started: 6 August 2026

Together, these components explain why satellite-derived track lengths are longer than measured water table depths. In the study area, excluding the well rim term (*a*), because in situ WTD measurements can only be taken from the well rim, and excluding the drawdown term (*f*), which is included in the DWTD, the cumulative contribution of these bias terms can therefore be approximated to range between the extremes of 2.1 and 10.7 m. The relationship between track length and water table depth can be expressed conceptually as **Eq. (1)**:

$$T_l = \sum_b^e Bias \; + \; (SWTD + f),$$

where T_l is the track length measured on HR satellite images, SWTD is the static water table depth measured in situ from the well rim a $(SWTD + f = DWTD)$ with DWTD, the dynamic water table depth.

4 Discussion

4.1 Seasonal and abstraction-resulting water level fluctuations

Water table depth time series from pastoral and mixed-use wells distributed across the study area are presented in **Fig. 7** for the period 2003–2026. The in situ records provide the main hydrological reference for interpreting the satellite-derived estimates. Still, they also highlight the difficulty of defining a strictly static water level in wells that are regularly used for water abstraction. In these time series, WTD values expressed in metres below ground level are measured from the well rim, which is considered here as a practical proxy for ground level. This convention ensures consistency among field measurements, despite frequent local changes in the ground surface around wells due to sand accumulation and/or erosion, which are common in southwestern Niger and in similar Sahelian environments. The time series derived from pastoral and mixed-use wells show interannual variations that may, at first sight, appear as seasonal groundwater fluctuations. However, part of this variability is likely related to abstraction effects. Field measurements in these wells therefore probably represent a mixture of near-static water levels and dynamic water levels influenced by recent or ongoing water withdrawal. This distinction is important because the satellite-derived estimates are also based on surface tracks that appear during water abstraction and are therefore dependent on well-use conditions.

The Tondi_Kiboro_Q07 well, located approximately 400 m from the Dantiandou kori (**Fig. 1b**), shows apparent seasonal fluctuations that may reflect both recharge processes and a weaker abstraction effect. Since 2009, only one traction track has generally been visible around this well, suggesting relatively limited abstraction intensity. Marked recharge periods are visible on the time series in 2008, 2012, 2013 and 2014, complementing the years of strong recharge previously identified by Favreau et al. (2009) and showing the influence of the kori. However, the long-term record from the Tondi Kiboro piezometer, which monitors the same aquifer and is located approximately 3 km from the well, shows that seasonal fluctuations are not perceptible in the static piezometric record, probably because the piezometer is located farther from the kori axis. This comparison suggests that part of the variability observed in the well record is related to local abstraction conditions and proximity to focused recharge zones, rather than to aquifer-scale seasonal water table fluctuations alone.

https://doi.org/10.5194/egusphere-2026-4198
Preprint. Discussion started: 6 August 2026

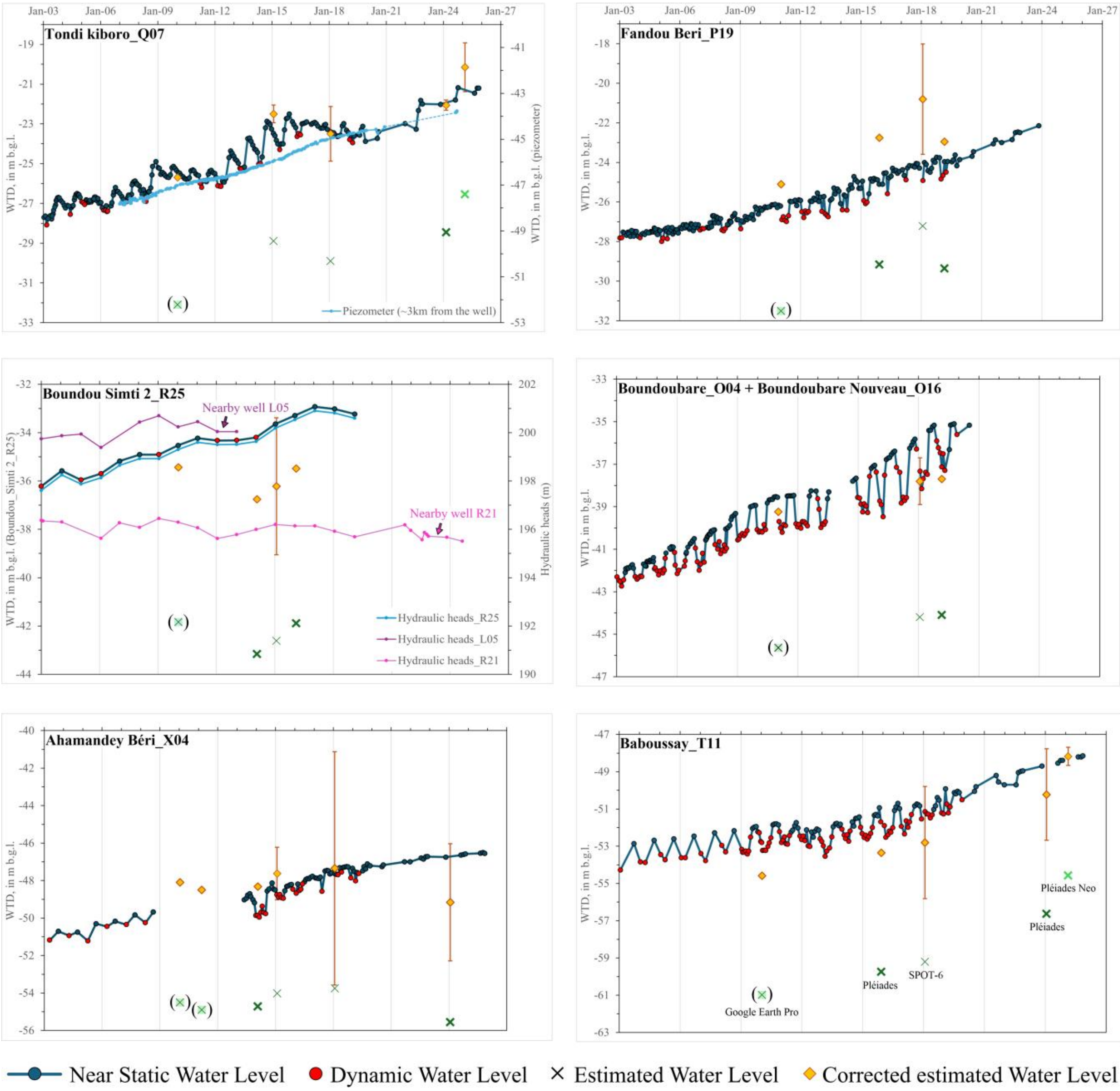

Figure 7. Water table depth time series for six wells in the study area, whose locations are shown in Fig. 1b, with WTD estimates derived from the different satellite images shown on each record. The "Dynamic water level" points correspond to measurements collected between mid-November and mid-May, a period of intensive well use for livestock watering. These points are associated with deeper water table depths than the seasonal mean and are therefore interpreted as reflecting abstraction-related variations from background conditions. Corrected estimated water levels correspond to satellite-derived estimates corrected using the overall median bias. Uncertainty bars on these corrected estimates correspond to the median inter-observer standard deviation calculated for the tracks interpreted at the corresponding well and image year. Estimates derived from Google Earth Pro (GEP) are shown in parentheses to indicate that they did not follow the same level of analytical and interpretative control, as the GEP image-processing workflow could not be fully traced or verified in this study. The image source of each estimate is indicated in the bottom-right panel.

https://doi.org/10.5194/egusphere-2026-4198
Preprint. Discussion started: 6 August 2026

A similar interpretation can be proposed for Baboussay_T11 and Boundoubare (O04 + nouveau_O16). These wells are located far from major local recharge points such as ponds or koris (**Fig. 1b**) and therefore far from the main infiltration zones. They correspond to wells that are mainly used during the dry season and are only weakly used, or even abandoned, during the rainy season (Favreau et al., 2000). Their time series do not show clear seasonal fluctuations, but rather reflect the combined influence of abstraction and the integrated long-term groundwater trend described in the region by Favreau (2000). The use of these wells may also have evolved towards more frequent use during the rainy season under increasing water demand, especially for Baboussay_T11, which is located close to a village.

In recent years, the time series has generally shown fewer short-term fluctuations. This may partly result from the lower frequency of field measurements, which reduces the ability to observe rapid variations. It may also reflect a decrease in pastoral water abstraction, mainly related to increasing insecurity in the region and the resulting reduction in livestock mobility and well use, consistent with reported effects of insecurity on pastoral systems in the Sahel (Ayantunde et al., 2025). This observation reinforces the interpretation that most of the fluctuations observed in the well records are linked to abstraction dynamics rather than to seasonal aquifer-scale groundwater fluctuations alone. However, the magnitude of these fluctuations also depends on the aquifer and well hydrodynamic properties.

The impact of pastoral abstraction dynamics can be illustrated from simple order-of-magnitude estimates based on well-specific discharge and water lifting practices. Specific discharge estimates for wells in the study area range from 0.1 to 15.4 $m^3\ h^{-1}\ m^{-1}$, with a median value of 3.0 $m^3\ h^{-1}\ m^{-1}$ (Favreau et al., 2000). Among the wells considered in the present study, specific discharge data were available for eight wells, with values ranging from 0.8 to 4.8 $m^3\ h^{-1}\ m^{-1}$. In pastoral Sahelian areas, animal traction water lifting commonly uses buckets of about 40 L (Serre, 1980). However, in our study area, located near the southern margin of the pastoral zone and characterized by agro-pastoral practices, smaller buckets of approximately 12–15 L are generally used. Water abstraction typically starts between 06:00 and 07:00 and may continue until around 20:00, corresponding to approximately 14 h of daily well use. For the Fandou_Béri_P19 well (**Fig. 7**), the initial total depth of the well was approximately 49 m, with screened intervals located between 29 and 31 m (Favreau et al., 2000). In 2015, three traction tracks were visible around the well (**Supplementary material 7**) and the measured water depth was 25.1 m. Assuming bucket volumes of 12–15 L and 10 lifting cycles per hour, the abstraction rate can be estimated at approximately 0.4–0.5 $m^3\ h^{-1}$. Given the reported specific capacity of 4.3 $m^3\ h^{-1}\ m^{-1}$, the expected drawdown would be only about 0.10 m. However, the observed maximum drawdown reached approximately 1.2 m, implying an effective specific capacity of about 0.3–0.4 $m^3\ h^{-1}\ m^{-1}$. In 2019, four traction tracks were visible (**Supplementary material 7**), while the measured water depth was 23.9 m. The estimated abstraction rate would increase slightly to about 0.5–0.6 $m^3\ h^{-1}$, corresponding to an expected drawdown of about 0.1 m using the reported specific capacity. The observed maximum drawdown was nevertheless about 0.6 m, implying an effective specific capacity of about 0.8–1.0 $m^3\ h^{-1}\ m^{-1}$. Although this value remains lower than the reported initial specific capacity, it is higher than the value inferred for 2015, suggesting improved hydraulic efficiency. This example shows that short-term fluctuations observed in well records may reflect not only abstraction intensity, as inferred from the number of active traction tracks, but also changes in well hydraulic efficiency. In addition, the number of visible tracks does not necessarily scale linearly with pumping intensity, as water abstraction may also vary with herd size, watering duration and the number of animals using the well at a given time.

These observations indicate that high-resolution satellite estimates are influenced by water abstraction practices and aquifer's hydraulic properties. However, this influence is also what makes the track length approach physically relevant in pastoral wells. Since the short-term fluctuations observed in well records are largely controlled by abstraction dynamics, the surface tracks generated during water withdrawal provide an integrated signal of the effective depth reached during well use. The method is therefore appropriate for estimating groundwater depth in the context of pastoral water abstraction, while long-term piezometric records remain necessary to distinguish local well-use effects from broader aquifer-scale seasonal groundwater variations.

4.2 Long-term rise in the water table

The time series presented in **Fig. 7** indicate a long-term rise in groundwater levels across the study area. This trend is consistent with previous studies that documented a regional increase in the water table in Southwestern Niger (Leduc et al., 2001; Favreau et al., 2002, 2009, 2012; Abdou Mahaman et al., 2023), with a mean rise on the order of 0.2 m yr^{-1} (Favreau, 2000). This long-term behaviour is particularly visible in the in situ records, which provide the temporal depth needed to distinguish persistent piezometric trends from short-term fluctuations related to abstraction or recharge.

Satellite-derived estimates also suggest an upward trend for some wells, particularly Baboussay_T11, Boundou_Simti 2_R25 and Boundoubare (O04 + nouveau_O16). For these wells, the multi-date image estimates are consistent with the long-term rise observed in the field records. However, the trend is less clearly represented for other wells, such as Ahamandey_Beri_X04 and Fandou_Beri_P09. This difference may be explained by the limited temporal depth of the satellite archive used in this study and by the uncertainty associated with track length visualization.

Indeed, with SPOT-6 and Pléiades imagery, the high-resolution satellite record only covers approximately the last decade. Assuming a regional rise of about 0.2 m yr^{-1}, the expected increase over 10–13 years would be approximately 2–3 m. Such an amplitude is comparable to the uncertainty associated with track interpretation and is inferior to the systematic bias between measured track length and static WTD. As a result, the long-term rise cannot always be clearly distinguished from the uncertainty envelope of the satellite-derived estimates over this relatively short period.

This does not invalidate the track length approach, but it limits its ability to quantify subtle decadal piezometric trends. A larger-amplitude groundwater level change, or a longer and denser time series of comparable high-resolution images, would be more easily detectable. At this stage, satellite-derived track lengths can therefore support the identification of broad long-term tendencies, but cannot replace long-term piezometric monitoring for quantifying gradual water table rise of only a few metres.

https://doi.org/10.5194/egusphere-2026-4198
Preprint. Discussion started: 6 August 2026

4.3 Hydraulic gradients and groundwater fluxes

Beyond the estimation of WTD at individual wells, satellite-derived track lengths may also provide useful information for interpreting hydraulic gradients and groundwater flow directions, provided that the systematic bias identified in this study is taken into account. This point is illustrated by the wells Kola_Bossey_R21, Boundou_Simti_R25 and Kogori_Tondi_Kiré_L05, which are located along a south-north transect across the Dallol Bosso valley area (**Fig. 1b**). Kola_Bossey_R21 is located in the southern part and taps the alluvial aquifer, Boundou_Simti_R25 taps the unconfined Continental Terminal (CT) aquifer and Kogori_Tondi_Kiré_L05 is located at the boundary between the alluvial aquifer and the CT.

The hydraulic heads represented for these three wells in **Fig. 7** indicate a north-south hydraulic gradient, from the CT towards the alluvial aquifer, consistent with previous hydrogeological interpretations of the area (Boucher et al., 2012; Abdou Mahaman et al., 2023). Kola_Bossey_R21 and Kogori_Tondi_Kiré_L05 are not pastoral wells and therefore cannot be directly assessed using the traction-track method. In contrast, Boundou_Simti_R25 is a pastoral well for which satellite-derived track length estimates can complement field measurements. This provides an opportunity to densify the available piezometric information and to better evaluate hydraulic relationships between aquifers.

However, this interpretation is strongly dependent on the correction of the systematic bias between track length and static WTD. If the bias is not accounted for, the satellite-derived estimate at Boundou_Simti_R25 would imply a lower hydraulic head than those observed at Kola_Bossey_R21 and Kogori_Tondi_Kiré_L05. Such an interpretation would lead to an erroneous groundwater flow direction and would not be representative of the actual hydraulic configuration. In this context, assuming a direct equality between track length and WTD, as in the simplified relationship (T_{el} = SWTD) proposed in some previous studies (e.g., Collignon et al., 2020, 2024), may result in misleading piezometric maps and incorrect interpretations of groundwater flow directions.

These results show that the proposed approach is sufficiently sensitive to contribute to the interpretation of hydraulic gradients and groundwater fluxes, but only when the conceptual and systematic bias is explicitly considered. Corrected satellite-derived estimates can therefore help densify sparse in situ monitoring networks. They may also support the identification of groundwater flow directions and potential surface water–groundwater interactions, particularly in sedimentary aquifer systems where pastoral wells provide access to otherwise poorly monitored areas.

4.4 Applicability and limitations of the method through time and space

The applicability of the track length approach relies on a specific temporal coincidence between long-standing pastoral water-lifting practices and the recent availability of high-resolution satellite imagery. Animal traction has been used for decades and in some areas for centuries to abstract groundwater from deep pastoral wells in the Sahel. However, the possibility of observing the resulting surface tracks from space only emerged with the development of metric to sub-metric optical satellite imagery.

https://doi.org/10.5194/egusphere-2026-4198
Preprint. Discussion started: 6 August 2026

This coincidence creates a unique opportunity to extract hydrogeological information from traditional water use practices over large and poorly monitored areas.

The method is particularly relevant for large sedimentary aquifer systems of the Sahel, where groundwater is commonly accessed through deep pastoral wells and where conventional piezometric monitoring remains sparse. These systems correspond mainly to transboundary aquifers, which represent approximately 42 % of the continental area of Africa and are crucial for regional water security (Altchenko et al., 2013). Such hydrogeological settings extend over 1 to 2 million km² across the Sahel region, offering a large potential domain of application. In addition, several tens of thousands of pastoral-use wells likely support livestock watering and pastoral mobility across the Sahel, although their spatial distribution, functional status, and depth remain poorly documented at the regional scale. In these contexts, the contrast between the limited number of conventional piezometric monitoring points, on the order of a few hundred across large Sahelian aquifer systems (Favreau et al., 2012; Bosch and Heckmann, 2019), and the presence of several tens of thousands of pastoral use wells is a key strength of the approach. The density of these wells provides a much larger number of potential observation points, allowing satellite-derived track lengths to complement existing piezometric networks, identify broad spatial variations in groundwater depth, and support the interpretation of piezometric gradients where field measurements are limited or difficult to obtain.

Beyond groundwater depth mapping, the method may also support the planning and rehabilitation of hydraulic infrastructures in pastoral areas. Active traction tracks indicate that a well is effectively used by pastoral communities, suggesting that groundwater is accessible, of acceptable quality for livestock watering and sufficiently renewable under current local practices. By identifying both the approximate depth of the exploited water table and the functional use of wells, the approach can help prioritize water-point investments in data-scarce dryland regions, where poorly constrained infrastructures may be vulnerable to failure or drying (Jasechko and Perrone, 2021). The method may also provide an indirect way to map zones of active pastoral water use, as visible traction tracks identify wells currently integrated into livestock watering routes. This could complement existing approaches based on herders' accounts across agropastoral landscapes (Turner and Hiernaux, 2002).

The groundwater depth maps produced over the 2024 Pléiades coverage area further illustrate this potential by showing how track-based estimates can be converted into spatially continuous information (**Fig. 8**). The comparison between the map derived from near-static measured WTD, the raw estimated WTD map and the corrected estimated WTD maps highlights the importance of accounting for systematic bias. The raw estimated WTD map preserves the main spatial structure but tends to overestimate groundwater depth (**Fig. 8b**). In contrast, the corrected estimated WTD maps (**Fig. 8c** and **8d**) are nearly identical to the map based on in situ (**Fig. 8a**). The similarity between the maps corrected using the specific bias and the median bias indicates that there is no major difference between these two correction approaches at the mapping scale. The map based on corrected estimated WTD using the median bias is particularly relevant because it relies on a single correction value that can be applied when detailed site-specific information on well geometry and water-lifting conditions is unavailable. The eleven independent validation wells, which were not included in the initial database but showed visible livestock tracks on the 2024 Pléiades images, provide an additional check. Once corrected using the median bias, their estimated depths fall within the

https://doi.org/10.5194/egusphere-2026-4198
Preprint. Discussion started: 6 August 2026

expected depth ranges shown on the corresponding groundwater depth map (**Fig. 8d**). This supports the use of the median bias as a transferable first-order correction within the mapped area, at least under similar environmental and pastoral-water-use conditions.

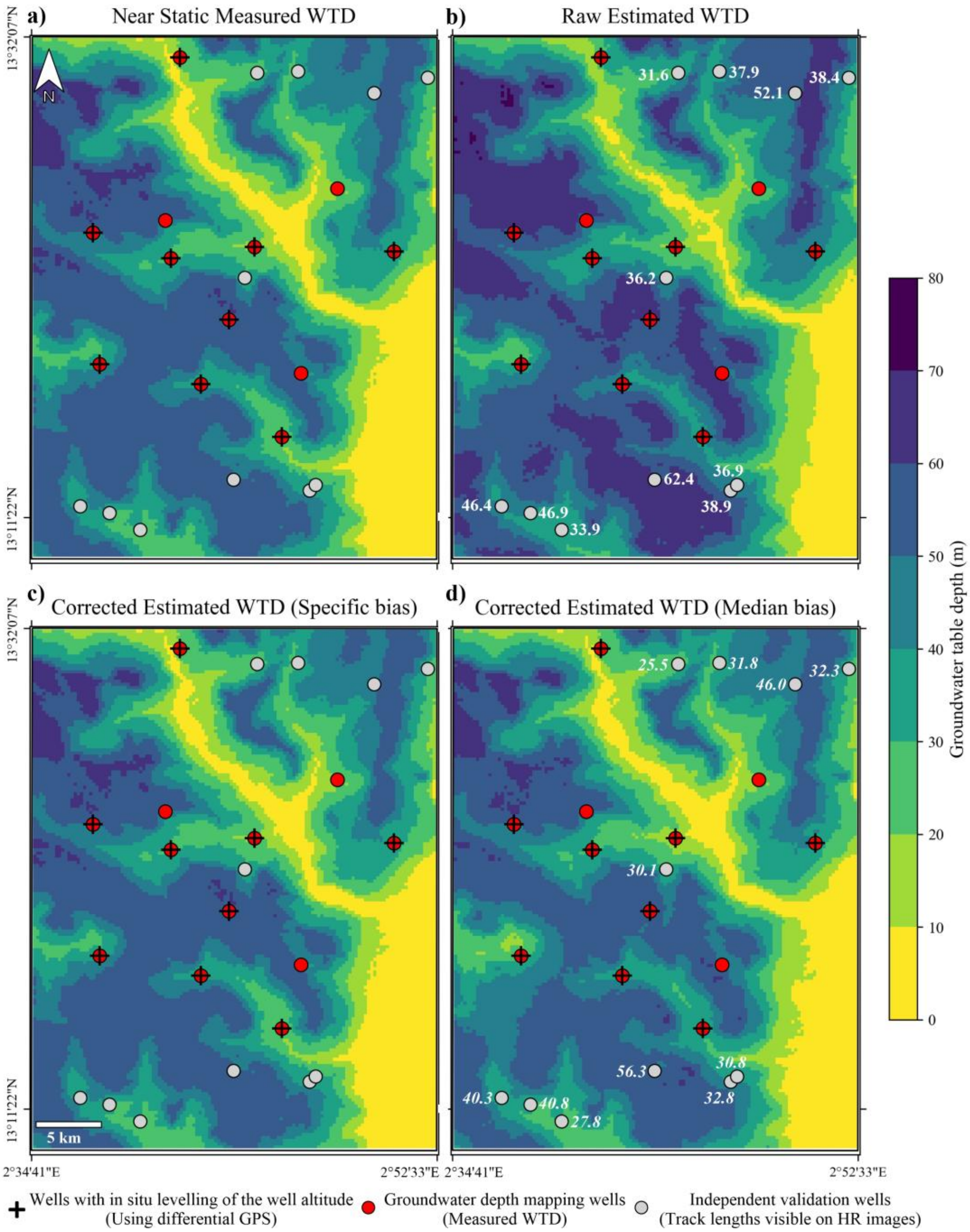

Figure 8. Groundwater depth maps derived from a) in situ measured WTD, b) raw estimates of the WTD using HR images and c) and d) bias-corrected estimates of the WTD using HR images.

https://doi.org/10.5194/egusphere-2026-4198
Preprint. Discussion started: 6 August 2026

However, the method is constrained by both water use practices and image seasonality. It can only be applied where animal traction is still active and where traction paths are sufficiently visible on optical images. It is therefore less suitable in areas where motor pumps have replaced animal traction, where wells are abandoned, or where surface tracks are rapidly erased by vegetation growth, land use practices, urban expansion, or wind and runoff processes. The method also depends on the availability of cloud-free high-resolution images during the dry season, when water abstraction is most intense and traction tracks are most likely to be visible. This dry-season dependence also limits the temporal interpretation of the estimates. Even if high-resolution images were available at a much higher frequency, the method would mainly provide information during the dry season, when traction tracks are preserved and visible. During the rainy season, pastoral wells are generally less used because alternative water and feed resources become available. In addition, surface tracks are often erased or obscured by rainfall, vegetation growth, runoff, or changes in surface conditions. As a result, the method is not suitable for monitoring seasonal groundwater fluctuations throughout the year. It provides a dry-season estimate of WTD influenced by abstraction conditions, rather than a continuous seasonal record of static groundwater levels.

5 Conclusion and perspectives

This technical note assessed the potential and limitations of using high-resolution optical satellite imagery to estimate groundwater depth from animal traction tracks around traditional pastoral wells in the Sahel region. The approach is based on the physical relationship between the length of the traction path produced during water abstraction and the depth from which water is lifted. By combining in situ water level measurements, multi-date satellite images and inter-observer interpretation, this study provides a first quantitative assessment of the uncertainties and biases associated with this method.

The results show that traction tracks are identifiable on metric to sub-metric satellite imagery and that their length is generally consistent with the expected range of groundwater depths measured in situ. Inter-observer comparison indicates that track length interpretation is relatively robust, with a median standard deviation of 1.7 m. The temporal comparison also shows that the orientation and number of traction tracks can persist over several years, although they may vary with well-use intensity, surface conditions and changes in local practices.

Satellite-derived track lengths systematically overestimate measured groundwater level, with a median bias of 6.4 ± 2.0 m (median absolute error). This bias is not primarily sensor-specific, as it is observed for SPOT-6, Pléiades and Pléiades Neo images. It reflects the fact that the visible traction length includes several geometrical, operational and hydrogeological components that are not part of the vertical groundwater depth. These include well radius, pulley height, safety distance, animal and harness length and the difference between static and dynamic water levels during abstraction. In the study area, the cumulative contribution of these bias terms is estimated to range between the extremes of 2.1 and 10.7 m.

The comparison with long-term in situ records shows that the method should not be interpreted as a direct measurement of static seasonal groundwater variability. Field measurements in pastoral and mixed-use wells are influenced by abstraction and satellite-derived estimates are necessarily linked to the water-lifting process that produces the surface tracks. This limitation

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Preprint. Discussion started: 6 August 2026

also explains why subtle seasonal fluctuations or gradual decadal water level rises of only a few metres are difficult to detect from the current high-resolution satellite archive. Long-term piezometric monitoring remains essential for distinguishing local well-use effects from aquifer-scale dynamics.

Despite these limitations, the method provides valuable spatial information in regions where conventional groundwater monitoring is sparse. When the systematic bias is explicitly considered, satellite-derived track lengths can help densify existing piezometric observations, support the interpretation of hydraulic gradients and contribute to the identification of groundwater flow directions and surface water–groundwater interactions. The approach is particularly relevant for large sedimentary aquifer systems of the Sahel, where open wells, animal traction and visible dry season surface tracks coexist over extensive areas.

Overall, this study shows that traditional pastoral water-lifting practices, when observed through high-resolution satellite imagery, can provide a useful proxy for groundwater depth in data-scarce environments. The method is intended to complement field measurements or piezometric monitoring by extending groundwater information over large and difficult-to-access areas. Future work should focus on expanding field calibration across different hydrogeological settings to support large-scale groundwater mapping in the Sahel region.

Data availability: In situ groundwater level measurements are available from the AMMA-CATCH database at http://bd.amma-catch.org/ (https://doi.org/10.17178/AMMA-CATCH.CL.GwatWell_N). High-resolution satellite imagery is available from the DINAMIS Data Terra catalogue (https://catalogue-dinamis.data-terra.org/), subject to the access conditions defined in the DINAMIS data access charter.

Supplementary material: The supplement related to this article includes Supplementary Materials S1 to S7.

Author contributions: FBD, GF and YN conceived and designed the study. FBD, GF, AZ, TC and MB independently interpreted the satellite imagery and digitized the traction-related tracks. FBD, GF and AZ compiled the database, processed the observer outputs and carried out the statistical analyses. FBD and GF prepared the figures. YM, TP, MSAB, MB, BIO and YN contributed to the interpretation of the results and to the discussion of the hydrogeological and field context. FBD and GF wrote the first draft of the manuscript. All authors reviewed, edited and approved the final manuscript.

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