



# Review: Assessment of the aquifers in South Sudan with a focus on Lakes State

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## Abstract

The current state of knowledge on groundwater in South Sudan (a data-scarce country) is presented, based on extensive field surveys in Lakes State in the central part of the country, limited published literature, and unpublished consultancy reports. The Basement Complex and the unconsolidated sediments of the Umm Ruwaba Formation are the most extensive geological formations and are the most exploited for groundwater. The water-resource potential properties of the main Umm Ruwaba aquifer (the 'second' aquifer, mostly confined) in Lakes State are generally fair to good, with a shallow piezometric surface (<25 m deep), favourable transmissivity (median 8.4, mean 21.5 m<sup>2</sup>/day), and low salinity and nitrate content. However, some areas have poor groundwater potential due to deep piezometric levels (up to 80 m deep), low transmissivity (mean <5 m<sup>2</sup>/day) and/or brackish salinity. The estimated recharge is modest (1–8 mm/year) due to predominantly confined aquifer conditions. Aquifer recharge mainly occurs along the geological boundary with the Basement Complex and from the Bahr el Jebel River. Published literature shows saline groundwater and a groundwater trough in northeast South Sudan that was interpreted as being related to a buried saline lake. Additional data on groundwater levels indicate that the extent of the trough may be less than originally sketched. In the Basement Complex, the groundwater potential varies over short distances and depends on the thickness and sand content of the weathered top layer and/or the presence of fractures; the transmissivity is generally low (median for Lakes State is 4.2 m<sup>2</sup>/day).

**Keywords** Crystalline rocks · Groundwater development · Recharge · Salinization · South Sudan

## Introduction

Groundwater is an important strategic resource for Sub-Saharan Africa; however, a major challenge to sustainable groundwater resources management and development in Africa is a lack of adequate data and information to guide the planning process (Gaye and Tindimugaya 2019). The Republic of South Sudan (South Sudan), a landlocked country in Central East Africa (Fig. 1), is one of the African countries where the state of knowledge on groundwater is poor.

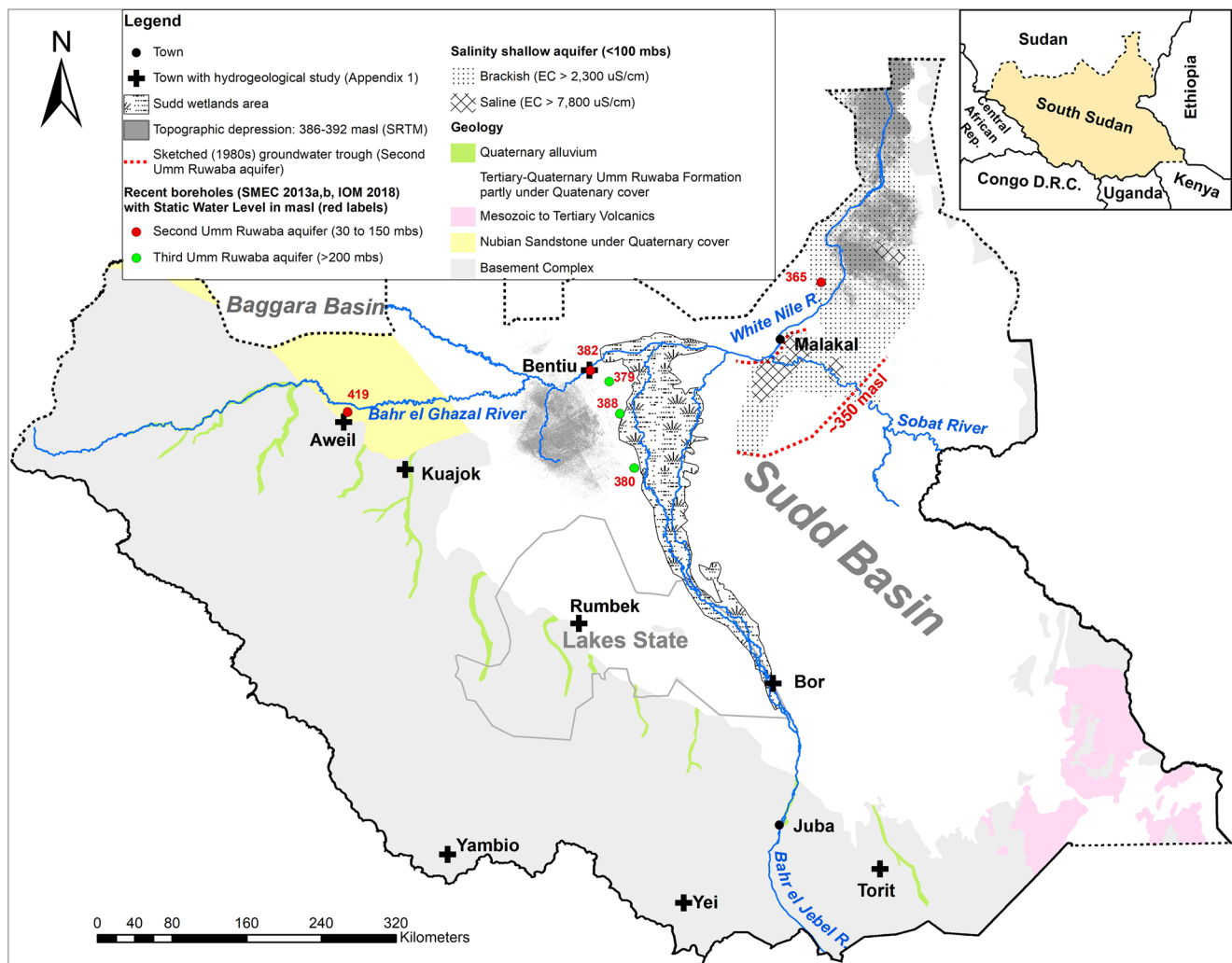
South Sudan (formerly Southern Sudan under the Republic of the Sudan) has a long history of political instability and conflict, including two civil wars, in 1955–1972 and 1983–2005. Violent conflict remains the pattern in most parts of the

country even after it gained independence from the Republic of the Sudan in July 2011 (Kuol 2020). There are also large local communal conflicts, such as those over cattle raiding, that preceded the wars and are likely to succeed it (Krause 2019). In addition to that, the road networks are very poor and are almost entirely unpaved (AfDBG 2013). These challenging conditions at times constrain undertaking field surveys, as experienced, for example, by Lasagna et al. (2020). Public service institutions are weak and lack professionalism (Kuol 2020) and laws on groundwater are nonexistent; however, there is a national Water Policy (GoSS 2007) that provides guiding principles for the development and management of water resources. Nevertheless, detailed regulations to enable implementation of this policy are scanty and when available often have an unclear formal status such as the 'proposed' water quality guidelines developed with assistance from UNICEF (2008).

Publications on the status of the water resources are scarce, and those presenting continuous river flow series rely on older (up to 1984) records (e.g. Petersen et al. 2008; NBI 2016;

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**Fig. 1** South Sudan hydrogeological map. For information about the northern and southeastern country boundaries, see United Nations (2022). The map is based on sources: GMDR (1981), NCDWRWS-TNO-DGV (1989), Salama (1997), GRAS (2004), SMEC (2013a, b), IOM (2018)

Sutcliffe and Brown 2018). Rainfall-related publications rely mainly on satellite-based products because many stations have either been shut down or have significant gaps in their records (Basheer and Elagib 2019). Knowledge of groundwater is very limited and generally insufficient to support an assessment of sustainable development (WB 2013). Regional overviews of the hydrogeology of South Sudan include Senden (1989) and Omer (2002), while Nile Basin-wide studies include Bonsor et al. (2010), MacAlister et al. (2012), and NBI (2016). The few publications that present analysed field data are Salama (1987, 1997) who used borehole data, and more recently, Engström et al. (2015, 2017), Lasagna et al. (2020) and Kut et al. (2020) who used groundwater quality data.

The objective of this review paper is to assess the current state of knowledge as well as the potential and main information gaps on the aquifers in South Sudan. The assessment consists of two parts of which the first, is a review of the current state of knowledge on the groundwater resources in

the entire country, covering the hydrogeological formations and their aquifer characteristics, groundwater quality, recharge, and water use. The review is based on the dearth of published literature and reports in existence, updated with recent (post-2010) information from unpublished consultancy reports by SMEC (2013a, b, c, d, e, f, g) and Gauff Ingenieure (2018) (summaries given in the Appendix). The second part presents a hydrogeological case study for Lakes State located in the central part of the country (Fig. 1). The case study is based on a field survey of all known boreholes, groundwater head monitoring, drilling reports and geophysical measurements. The data are used to analyse the aquifer characteristics, basic groundwater quality (salinity and nitrate) and head. This is followed by a discussion on groundwater occurrence, recharge, borehole siting, and the groundwater development potential for the surveyed area. In the concluding section, the hydrogeological findings on Lakes State are put into the larger context of South Sudan.

## Water resources in South Sudan

### Rainfall, rivers, and the Sudd wetlands

The annual rainfall in South Sudan generally ranges between 700 millimetres (mm) and 1,300 mm with a mean (1901–2016) of 994 mm (Harris et al. 2020). The rainy season is from mid-April to early November. In the Upper Nile Basin, which includes South Sudan, hot and dry years have become more frequent in recent decades. Under climate change, this trend is likely to continue despite climate model predictions of increasing regional precipitation (Coffel et al. 2019).

Almost the entire country (97.7%, NBI 2016) is located within the White Nile subbasin of the River Nile. Within South Sudan, the White Nile is known as the Bahr el Jebel and its main tributaries are the Bahr el Ghazal and the Sobat rivers (Fig. 1). Upstream, the Bahr el Jebel drains surface water from the East African lakes (Lake Victoria in Uganda, Tanzania, and Kenya is the largest) into South Sudan. Further downstream at Khartoum in Sudan, the White Nile merges with the Blue Nile to form the Nile River which flows to Egypt.

Within South Sudan, the Bahr el Jebel flows through the extensive Sudd wetlands. River flow into the Sudd wetlands increased significantly from the early 1960s, following a rise in water levels in Lake Victoria due to increasing rainfall over the lake (Mohamed and Savenije 2014; Sutcliffe and Brown 2018). As a result, the mean areal extent of the Sudd wetlands, computed using a water balance equation, has been found to have increased by 19,000 km<sup>2</sup> (80%) between 1900 and 2000 (Mohamed and Savenije 2014). The average outflow from the Sudd wetlands is estimated at 41% (Mohamed et al. 2006) to 50% (Sutcliffe and Brown 2018) of the inflow. Some authors argue that the flow reduction is more than can be explained by evaporation, and they speculate that some of the reduced flows may recharge deeper aquifers (Senay et al. 2014; Kebede et al. 2017). However, Shahin (1985) proposes inaccuracies in river flow (e.g. some channels not being measured) as a possible explanation for the estimated flow reduction. Using satellite data and water balance calculations, Mohamed et al. (2006) calculated an average water table over the Sudd wetlands area of approximately 0.1 and 1.0 m below the surface (mbs) for the wet and dry seasons, respectively. At different locations in the Sudd wetlands, approximately 25 km north of Bor (Fig. 1), the soils when dry recharge up to 350 mm of water before the soils fully saturate and become impermeable before allowing wet season flooding to take place (Petersen 2008). Deeper recharge from the soil to the aquifer below was considered negligible because of the presence of an impermeable clay top layer (12–20 m thick at five drilling sites, Petersen and Fohrer 2010).

## Hydrogeology

The geology of the White Nile subbasin is strongly influenced by the Mesozoic Sudanese Rift System, which consists of intracontinental subsidence basins mainly filled with Quaternary and Tertiary unconsolidated fluvial sediments that have accumulated often in the form of fans. The sediments come from the surrounding Precambrian crystalline rocks or, in a few places, Cenozoic-Quaternary volcanics. The part of the Sudanese Rift System that covers the central and north-eastern parts of South Sudan (Fig. 1) is called the Sudd Graben or Sudd Basin (Salama 1997) or South Sudan Rift (Abdalla 2008; Kebede et al. 2017). In Sudan, the Sudd Basin is connected to two other basins, namely Baggara in the northwest and eastern Kordofan in the northeast. The groundwater gradient, and hence the direction of groundwater flow, is from these two connecting basins towards the Sudd Basin (Salama 1976; NCDWRWS-TNO-DGV 1989; Omer 2002). This is despite the fact that in Sudan these two basins, with an average precipitation of less than 400 mm/year, are in a much drier area than is the case with the Sudd Basin in South Sudan. Abdalla (2008) attributes this discrepancy to a sandier soil in Sudan that favours infiltration.

Highly saline groundwater bodies and groundwater troughs have been identified in the rift basins of Sudan and South Sudan. These have been interpreted as being related to sediments from buried saline lakes formed by evaporation coupled with alkaline earth carbonate precipitation, followed by the resolution of salts. The buried saline lakes are at the lowest part of the rift systems and were formed during dry periods (before 12,500 BP) before the White Nile was connected to the main Nile (Salama 1987, 1994, 1997). NCDWRWS-TNO-DGV (1989) and Salama (1997) mapped a saline groundwater body based on salinity measurements from 125 boreholes (depth not given) in the northeastern part of the Sudd Basin (Fig. 1). Recently, saline groundwater (electrical conductivity, EC of 8,220  $\mu\text{S}/\text{cm}$ ) was encountered again within the area in two ~90-m-deep test wells at the former Malakal United Nations compound (JICA 2014). Other recent borehole information indicates that brackish groundwater is also present in the shallow and deeper aquifers in the Bentiu area (SMEC 2013b). The current topographic depressions largely coincide with these brackish areas (Fig. 1), hence, corroborating the thesis on the presence of buried saline lakes at the lowest part of the Sudd Basin. Also, NCDWRWS-TNO-DGV (1989) and Salama (1997) sketched a groundwater trough with a head lower than 350 m above sea level (masl) in the same area (topographic surface of 390–405 masl). These two references, however, do not provide information on which groundwater head measurements of the trough were based. Still another source (IH 1981), confirms a deep water depth of 86 m (about 317 masl) in one 288-m-deep borehole (screen depths are not given) some 85 km south of Malakal.

The same source presents boreholes in and near Malakal with water levels around 360 masl, and boreholes 50–80 km east of Malakal with water levels between 344 and 363 masl. In the original sketch, the groundwater trough extended to Bentiu, which is not the case currently because the measured head at and south of Bentiu is at least 30 m higher for both the shallow and deep aquifers (SMEC 2013b). Consequentially, based on recent water levels (SMEC 2013b; IOM 2018) and IH (1981), the updated extent of the groundwater trough in the northeastern part of the Sudd Basin (Fig. 1) is less extensive than originally sketched.

### Aquifer characteristics and groundwater quality

An overview of the aquifers with a description and their characteristics is given in Table 1. The upper layers of the Sudd Basin consist principally of Quaternary deposits underlain by the unconsolidated Tertiary to Quaternary Umm Ruwaba Formation. Older more consolidated Cretaceous sediments occur in the deeper parts of the basin (Salama 1997; Abdelsalam 2018). An exception is N–NW South Sudan (near Aweil) where the Quaternary deposits are directly underlain by the Cretaceous Nubian Formation that extends north into the Baggara Basin in Sudan (NCDRWS-TNO-DGV 1989).

The Quaternary deposits that contain small local aquifers are difficult to distinguish in drillings logs from the underlying Umm Ruwaba Formation (Yassin et al. 1984). Where the Umm Ruwaba Formation is thick, three aquifer zones can be

distinguished—namely, the phreatic or first aquifer (0–30 mbs), the largely confined second aquifer, which is the most exploited within this formation (30–150 mbs), and the third aquifer (>150 mbs, Salama 1997, SMEC 2013b). In the transition zone at the borders of the Umm Ruwaba Formation with the Basement Complex where rocks outcrop or where they are suspected to be close to the surface, the saturated thickness of the aquifer is small (Senden 1989). Transition zones with low groundwater potential have been identified in Aweil and Kuajok (Fig. 1) during the small towns' water resources assessments (SMEC 2013a, d). Salinity of groundwater from the second aquifer at Bor is low (mean EC is 366  $\mu\text{S}/\text{cm}$ ), but high levels of nitrate were detected (SMEC 2013c). For Bentiu, at the western edge of the groundwater trough, the first and third aquifers have much higher salinity (700–4,000  $\mu\text{S}/\text{cm}$ ); furthermore, elevated levels for hardness, sulphate and some trace elements have also been measured here (SMEC 2013b). The oil production infrastructure in north and north-east South Sudan can lead to oil spills (Löw et al. 2021), and hence pollute the shallow aquifer; however, there is no accessible information on the scale of the pollution (UNEP 2018). Establishing a causal link between oil infrastructure and polluted groundwater requires comprehensive investigations because there is also mineralised groundwater related to the buried saline lake in the same region. Rueskamp et al. (2014) is, as far as known, the only publication that showed such a link between polluted water in an oil exploration drilling mud pit in the Bentiu region (total polycyclic aromatic

**Table 1** Simplified hydrogeological column for South Sudan (based on: Yassin et al. 1984, NCDRWS-TNO-DGV 1989, Senden 1989, GRAS 1995, Salama 1997, GRAS 2004, SMEC 2013a, b, c, f, g, Gauff Ingenieure 2018 and the Appendix)

Period	Name	Description	Aquifer characteristics
Quaternary	Quaternary deposits	Thin alluvial and swamp sediments formed during annual floods of the rivers, abandoned river channels and ancient sand dunes	Small local aquifers
Tertiary-Quaternary	Umm Ruwaba Formation	Unconsolidated sands, locally gravelly, clayey sands, and clays. Formation thickness ranges from a few metres to over 500 m in the centre of the basin. Where the formation is thick, there are three aquifer zones: phreatic or first aquifer (0–30 mbs), a largely confined second aquifer (30–150 mbs), and a confined third aquifer (>150 mbs)	Second and most exploited aquifer within this formation: transmissivity 25–60 $\text{m}^2/\text{day}$ with a maximum up to 200 $\text{m}^2/\text{day}$ , storage coefficient of $10^{-5}$ to $10^{-3}$
Mesozoic to Tertiary	Volcanics	Volcanic rocks, only in S–SE South Sudan near surface	Groundwater occurs in fractures and faults. Generally considered to have a low groundwater potential
Cretaceous	Nubian Formation	Coarse-grained sandstones, only in N–NW South Sudan near the surface	Transmissivity 100–3,000 $\text{m}^2/\text{day}$
Precambrian	Basement Complex	Mainly schist and gneiss, the rocks are folded, faulted and contain some intrusive bodies. Groundwater occurs in fractured zones and where the weathered top layer is thick and sandy	Local aquifers with variable transmissivities; low (<10 $\text{m}^2/\text{day}$ ) at Yambio and Torit to high (67, 119, and 220 $\text{m}^2/\text{day}$ ) at Yei

Locations of geological formations in Fig. 1



hydrocarbons or TPAH is 0.04 mg/L, lead is 2.15 mg/L, EC is 78,800  $\mu\text{S}/\text{cm}$ ) and nearby shallow groundwater (TPAH is 0.02 mg/L, lead is 0.012 mg/L and EC is 6,800  $\mu\text{S}/\text{cm}$ ). The authors also reported that the ‘wells become less contaminated with increasing distance from potential contamination sources’.

The Nubian Sandstone is the most important aquifer in Sudan (Senden 1989); however, in South Sudan this aquifer is only present in the north–northwest (Fig. 1). The boreholes in the dysfunctional Wak Abil well field located about 10 km north of Aweil are possibly (partly) screened in the Nubian Sandstone Aquifer (see Appendix). The groundwater salinity was low but a high nitrate level was detected (SMEC 2013a).

There are large spans of Precambrian Basement Complex rocks in the west and south of the country (Fig. 1). Local aquifers occur in fractured zones and in areas where the weathered top layer is relatively thick and sandy. They have been classified in the hydrogeological map as having a ‘low potential’; however, no transmissivity values have been mentioned (NCDRWS-TNO-DGV 1989; Senden 1989). Pumping tests from the small towns’ water resource assessments indicate low (two towns) to high (one town) transmissivities (Table 1). Two other assessed towns (Kuajok and Aweil) are partly located on the Basement Complex area (see Appendix); thus, it is hard to state if the transmissivities determined from pumping tests for these two towns can be considered as representative because different geological units occur here.

The groundwater salinity for Yambio and Yei in the Basement Complex area is fresh, and fresh to brackish for Torit (see Appendix), while high manganese was detected in the Basement Complex area at Torit (SMEC 2013f). Chemical analyses of seven groundwater samples for a village bordering Juba showed that concentrations of total chromium in three samples is above the WHO drinking water limit, while the concentration of fluoride in five samples were just below the limit. Both contaminations were attributed to the natural lithological setting, such as the presence of granite or gneiss rocks (Lasagna et al. 2020). The aquifers in the Basement Complex are generally unconfined which makes them extra vulnerable to pollution from the surface. Engström et al. (2015, 2017) detected microbiological contaminants above the health-based recommendations for drinking water in a large proportion (95 out of 147) of the improved groundwater sources in the Basement Complex area at Juba. The outcome of their risk factor analysis suggested that the presence of latrines or damage in the borehole apron was less likely to be contamination mechanisms. The authors attributed the contamination to direct infiltration of contaminated surface water following long-term (5-day and monthly) precipitation prior to the measurements. Microbiological contaminants (coliforms) were also detected in most analysed samples for Yambio, Torit, and Yei (see Appendix).

A recent groundwater quality assessment of 176 samples from Eastern Equatoria State (around Torit) showed that a large proportion of the samples exceeded the WHO drinking water limits (Kut et al. 2019)—for example, fluoride (9% of samples in the dry season and 0% in the wet season), cadmium (96 and 92%) and lead (100 and 92%). The cadmium dry season concentrations varied from 0.003 (WHO drinking water limit) to 0.009 mg/L (mean 0.005 mg/L). The mean salinity was between 914 and 1,015  $\mu\text{S}/\text{cm}$  for the dry and wet seasons, respectively. The study attributed the elevated concentrations to ‘rock–water interaction’ and did not distinguish the results according to geological formations.

## Aquifer recharge

Based on a numerical simulation, Abdalla (2008) postulates that a natural water balance equilibrium has been reached for the Sudd groundwater trough in the Umm Ruwaba (not directly stated which) aquifer. In the simulation, evapotranspirative discharge by dense vegetation of phreatophytes around the Sudd groundwater trough is roughly in balance with that of an average river leakage (2.76 mm/year) and that of a combined constant head and direct infiltration recharge (4.04 mm/year). The author evaluated data from more than 500 boreholes covering both Sudan and South Sudan. The author states that direct infiltration is unlikely in South Sudan “where the impermeable continuous clay layer is very extensive and covers the entire south”. Earlier, Senden (1989) and Omer (2002) estimated a slightly lower groundwater recharge for the ‘confined or semiconfined’ (probably second) Umm Ruwaba aquifer of the Sudd Basin of approximately 1 mm/year ( $340\text{--}341 \times 10^6 \text{ m}^3$  over an area of 365,268  $\text{km}^2$ ). The authors did not explain how they arrived at the estimate. Field evidence from large tritium concentrations (229–278 TU) measured in samples taken from three boreholes in the Malakal area indicates that present-day recharge from rain and/or surface streams does exist (IH 1981).

Based on remotely sensed seasonal gravity variations, Bonsor et al. (2010) calculated a mean (2003–2005) groundwater recharge of 30–100 mm/year for eastern South Sudan to 100–300 mm/year for western South Sudan (including Lakes State). This high recharge value was aggregated over all aquifers and hence also includes the phreatic aquifer. The authors state that by far most of the recharge is used by direct evapotranspiration from shallow groundwater because they assume neither a large net annual gain or loss, groundwater abstraction is limited, and the annual discharge of the Nile Delta is less than 2% of the annual rainfall input to the Nile basin.

## Water use

South Sudan had a population of just over 11 million in 2019 (WB 2021) with less than 20% of the population living in

urban areas (WB 2013). It is estimated that 40% of the population has access to safe water (UNICEF 2020). Groundwater is the principal source of drinking water but very little work has been undertaken to determine the distribution and abstraction levels of this resource (AfDB 2013). Where groundwater utilization data exist, there are discrepancies and conflicting sources of information (MacAlister et al. 2012). Since its independence in 2011, many new water supply boreholes have been drilled, often with donor-supported funding. Most groundwater abstractions are small-scale through hand-pump-equipped boreholes. The reported mean (data from 2009 and 2012) functionality of 4,951 surveyed handpumps in five of the ten states in South Sudan (not including Lakes State) is 80% (Foster et al. 2020). The Ministry of Water Resources and Irrigation (RSS-MWRI 2011a) estimated, based on 'limited data' from 2009, a much lower functionality between 50 and 70%.

In some locations especially in (semi) urban areas, groundwater is abstracted through diesel or solar-powered pumps that are often connected to a small overhead tank (usual volume 5–20 m<sup>3</sup> but occasionally up to 100 m<sup>3</sup>). These are locally called 'water yards'. A few towns along the Nile River and some tributaries also have a small river-water abstraction system combined with a small water treatment plant meant for public water supply (e.g. Juba, Torit, Bor).

Irrigated farming in South Sudan is small-scale (NBI 2016), relying on simple water-lifting techniques from rivers and/or pumped groundwater. Apart from small isolated private irrigation schemes, a few public pilot schemes were constructed in the 1970s, but they have never been fully operational and are largely neglected (WB 2013). Currently, there is one functioning scheme, the Aweil (Fig. 1) scheme, that is using water from the Lol River (Bahr el Ghazal subbasin) with an area equipped for irrigation of 500 ha and an estimated cropping intensity of 30% of the area (NBI 2016).

There are an estimated 12 million cattle in South Sudan (AfDB 2013) that mostly use surface water from streams and ponds. All communities generally practice movement of livestock in search of pastures and water during the dry season (SNV 2010).

## Groundwater in Lakes State

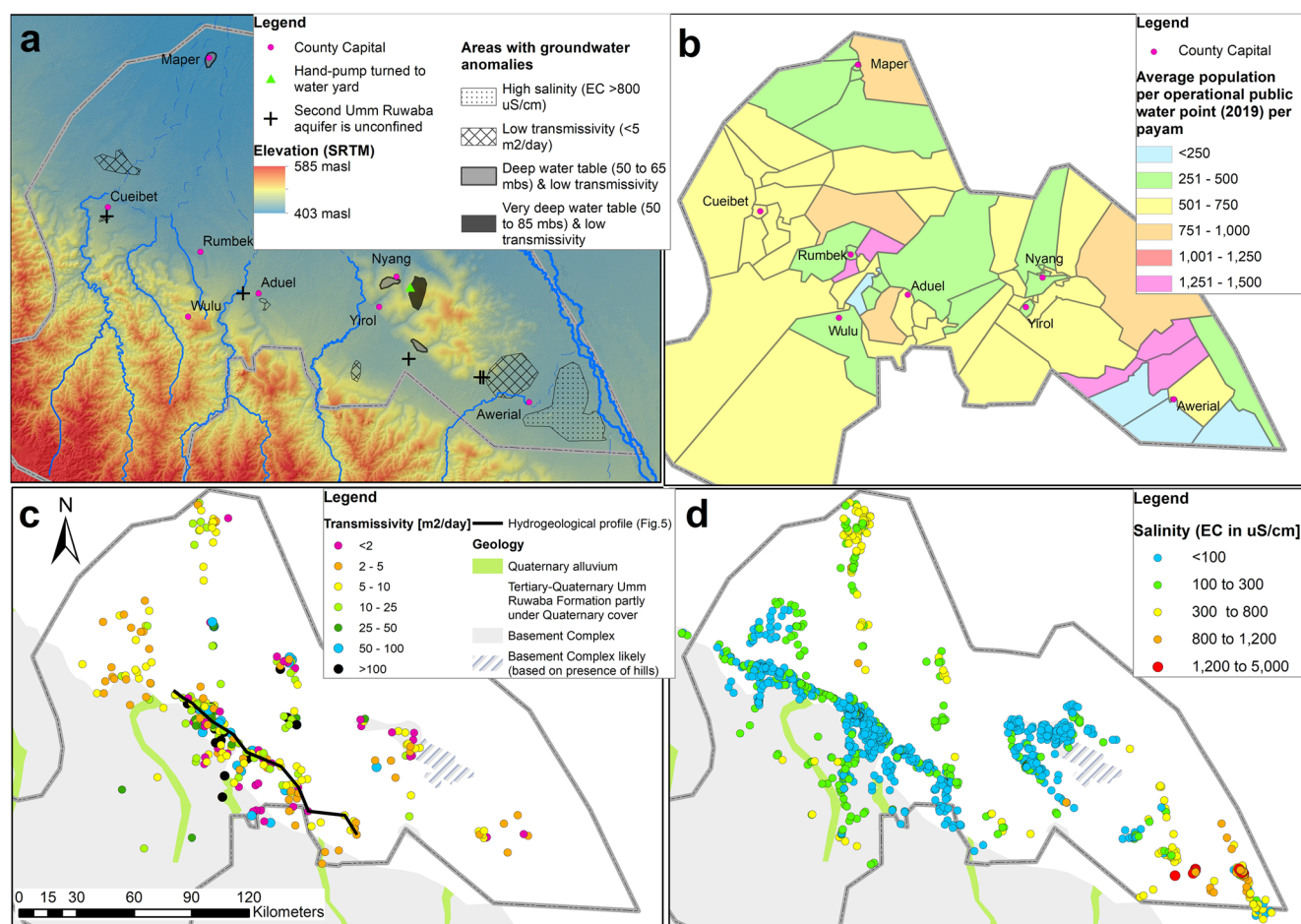
### Introduction: Lakes State

Lakes State is in Central South Sudan (Fig. 1) and covers an area of 43,500 km<sup>2</sup> with hills in the south and west (600–440 masl) and a flat floodplain terrain in the north and east (440–400 masl, Fig. 2a). In 2019, Lakes State had an estimated population of 881,000 people, an estimate that is based on the 2008 census (SSCCSE 2009) increased with a mean growth rate of 26.6% for the population of South Sudan

between 2008 to 2019 (WB 2021). Administratively, Lakes State is subdivided into eight counties with each county further divided into 5–9 *payams*, a *payam* is a lower local administrative unit. *Payams* are important for the planning of new public boreholes because they are the smallest administrative units with population data. Since there was no *payam* map for Lakes State, one was newly developed (Fig. 2b and Fig. S1 of the electronic supplementary material, [ESM](#)) using the location of the surveyed boreholes (discussed in the following) and their recorded *payam* name. Occasionally a *payam* spreads over two unconnected geographical areas because communities may have relocated, mostly due to insecurity; but they and also local Government officials kept on using the name of their *payam* of origin. So in some cases, *payam* boundaries are quite fluid.

The land cover mainly consists of shrubs (38.5% of the area), trees (35.5%), herbaceous vegetation (20.9%), and agricultural land (4.2%; FAO 2011). There are several seasonal (late May to mid-November) rivers that drain into floodplains, wetlands, and lakes on the west bank of the Bahr el Jebel River (Fig. 2a). The mean (2000–2019) satellite-based rainfall estimate (based on data from USGS FEWSNET 2020) is 1,153 mm/year, with over 85% of the rain falling during the wet season (April–October). The year 2020 was an extremely wet year with a satellite-based rainfall estimate of 1,905 mm. For Rumbek town, the mean (2000–2019) current satellite-based rainfall estimate of 1,157 mm/year is approximately 10% higher than the mean historically (1907–1937) measured rainfall of 1,041 mm/year (Hurst and Black 1943), which is in line with the climate change projections of increasing regional precipitation (Coffel et al. 2019). An analysis of Landsat Imagery (EMM 2019) showed that 22% of Lakes State was flooded during the wet season of 2014, which was the year with the third highest satellite-based rainfall estimate in two decades (2000–2020). Many roads are regularly impassable for cars from the second half of the wet season until the beginning of the dry season (June to early January). At times, there are security related incidents (such as cattle raiding and revenging, and banditry) on some road sections; thus, undertaking field surveys can be challenging.

The geology (Figs. 2c,d and 3) consists of Basement Complex (35% of the area) and the Umm Ruwaba Formation, which is locally covered by Quaternary sediments (65%). On the original (hydro) geological maps (GMRD 1981; NCDWRWS-TNO-DGV 1989; GRAS 2004), the outcrop of the Basement Complex north of Yirol was mapped to only include a part of the hills that are visible on the elevation map (Fig. 2a). It is however likely that such resistant rocks are representative of the entire area where these hills are present; hence, the geological boundary on the maps has been updated accordingly.



**Fig. 2** Features for Lakes State (location in Fig. 1): **a** Elevation and zones with groundwater anomalies, **b** Sketch map of payams (payam names are shown on Fig. S1 of the [ESM](#)) with average population per functional public groundwater point in 2019, per payam. **c** Transmissivity of the second Umm Ruwaba and Basement Complex aquifers from single-

well pumping and recovery tests. **d** Groundwater salinity (electrical conductivity, EC) of the second Umm Ruwaba and Basement Complex aquifers. The geological boundaries are based on sources: GMDR (1981), NCDRWRS-TNO-DGV (1989), GRAS (2004)

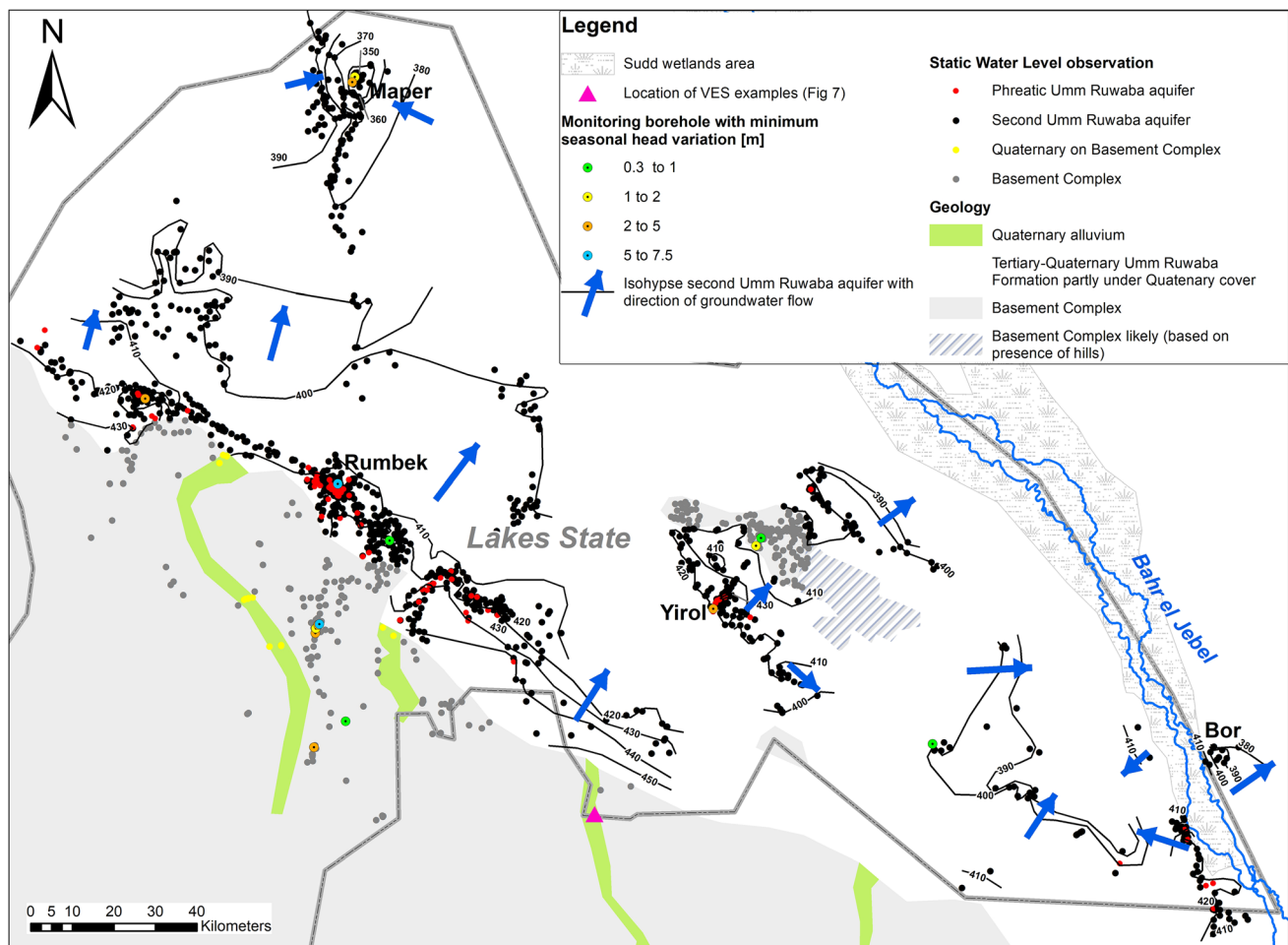
## Methodology

Hydrogeological data were collected between 2014 and 2019 during the implementation of the Water for Lakes State Project (W4L, see the Acknowledgements for further information). The database is presented in EMM (2019) and includes: (1) a survey of existing groundwater points, (2) groundwater head monitoring, (3) reports on newly drilled boreholes, and (4) geophysical measurements. The data collection and analyses techniques are discussed in the following list.

1. All known (2,159) public and (293) private water points were surveyed during the dry seasons (2014–2019). The public water points cover 2,029 boreholes (mostly hand-pump equipped), and 130 hand-dug wells (76% equipped with a hand-pump). Ninety-five public boreholes and hand-dug wells were turned into water yards. The water points survey included, amongst others, the following

classifications: location (GPS coordinates, names of village and payam), accessibility (public or private), functionality, basic water quality parameters including salinity (EC using Omega CDH222 meter), nitrate and nitrite (using eSha Aqua-Quick-Test), depth, and the groundwater level. The field water quality parameter (EC), which shows distinct regional variations, has been presented on a map (Fig. 2d). At 316 locations in the second Umm Ruwaba and Basement Complex aquifers, water levels were measured directly either in the field and/or taken from drilling reports. It was not possible to measure water levels at other sites, due to pump installations that prevented access for the well dipper. For these sites (1,201), the payam pump mechanic was asked if he knew the water depth from the time the borehole was drilled or from maintenance works. The depths provided by the mechanic, as far as they conformed to nearby or regional measurements, plus the measurements, were used to develop a groundwater head map (Fig. 3). Groundwater





**Fig. 3** Lakes State (location on Fig. 1) with boreholes and dry season (2016–2018) groundwater head for the second Umm Ruwaba aquifer. The geological boundaries are based on sources: GMDR (1981), NCDWRWS-TNO-DGV (1989), GRAS (2004)

head observations for Bor (SMEC 2013b) have been added to the survey data because these boreholes border Lakes State on the other (eastern) bank of the Bahr el Jebel River (Fig. 1). An ASTER digital elevation model (DEM) was used to recalculate the head from mbs into masl. The mapped isolines were then taken as representative for an average recent dry season (2014–2019) but with a fairly large uncertainty margin of  $\pm 4$  m. This is because the water depths used are from different dry seasons and the need to account for uncertainty margins in the depths reported by the pump mechanics and the ASTER values. The isolines have been used to map zones with a deep piezometric surface and the direction of groundwater flow.

2. The groundwater head of an abandoned borehole in Rumbek with its screen in the second Umm Ruwaba aquifer was monitored weekly over a period of 4 years (2015–2019). For others (14 abandoned boreholes spread over Lakes State, Fig. 3), the groundwater head had been monitored only a few times per year. It was not always

possible to measure the groundwater level as originally intended at least once in the late wet season (September–October) and once in the late dry season (March–April) due to security issues and/or poor road conditions. Hence, the observed seasonal variation for the sites with low-frequency monitoring has been considered as an indicative ‘minimal’ variation. The monitoring data have been used to establish seasonal head variations in relation to rainfall.

3. A total of 326 new boreholes were made by drilling contractors overseen in the field by trained governmental supervisors. After a data quality check and a verification of the GPS coordinates, the following usable information was taken from a few older and recent drilling reports (2015–2018):

- *328 single-well constant-rate pumping (mostly 6 h) and recovery tests.* The tests have been interpreted for aquifer transmissivity using the average of the Jacob’s and the Theis recovery methods as described in MacDonald et al. (2005).



- *238 lithological borehole descriptions.* The lithological logs were used to determine the dominant sediment in the first 10 m and to draw regional hydrogeological profiles using specialist software (Golden Software 2016).

The depth of the boreholes ranges between 52 and 117 m (average 85 m). The boreholes have 9- to 15-m-long screens generally within the bottom 30 m; thus, depending on the geology at the borehole location, the screens are either within the second Umm Ruwaba aquifer or the weathered and/or fractured Basement Complex aquifer.

4. In total, 375 geophysical measurements, or vertical electrical soundings (VES), have been undertaken with a Terrameter SAS 1000, mostly prior to drilling the new boreholes. The VES data were interpreted into hydrogeological layers with a computer program (Hemker and Post 2011). The interpreted VES have been used for siting the new boreholes.

Most recent boreholes also have chemical and microbiological water quality test reports from local laboratories. However, it is difficult to vouch for accuracies of the test reports—for example, some results are handwritten and difficult to read, some results have suspected misplacement of decimal points, some parameters are only detected by one of the laboratories and never by the other. These reports have therefore not been used.

## Results

### Public groundwater points

The average number of people per functional public groundwater point has been calculated per payam based on their population (discussed in the preceding) and the borehole survey (Fig. 2b). Currently (2019), 33 out of the 54 payams, on average, still do not comply with the minimum water supply standard for South Sudan of 500 people or less per functional public water point (RSS-MWRI 2011b). People fetching water for domestic use from rivers and local ponds were commonly observed during the survey, especially in the wet season. During the dry season, some of these people temporarily migrate to villages that have boreholes. The functionality of the surveyed public water points was 71%, while the functionality of the private water points was much higher at 86% (EMM 2019).

### Aquifer characteristics

The majority of the 2,400 surveyed groundwater points (81.4%) are within the area covered by the Umm Ruwaba Formation (Fig. 3). They are distributed over the phreatic

aquifer (6.8%) and the second aquifer (93.2%), while the remainder (18.6%) are within the Basement Complex area. As the Umm Ruwaba Formation thickens towards the centre of the Sudd Basin, it is likely that the third Umm Ruwaba aquifer is present in the northeastern part of Lakes State, similar to what was observed south of Bentiu (Fig. 1; SMEC 2013b). Nonetheless, as far as known, none of the surveyed boreholes are deep enough ( $\leq 140$  mbs) to reach the third aquifer. The second Umm Ruwaba aquifer, and the weathered and/or fractured Basement Complex aquifer are thus the most exploited groundwater resources in Lakes State.

In about half the drilling reports of boreholes in both the Umm Ruwaba Formation and the Basement Complex areas, the top layer (0–10 m) is dominated by clay (Table 2). While 8% (in Basement Complex area) to 10% (in Umm Ruwaba area) of the drillings have a sandy and/or gravelly top layer, which is more favourable for recharging the phreatic aquifer. These drillings with permeable top layers are not limited to particular geographical areas when plotted on a map (not presented here). For the remainder of the drillings, the top layer consists of mixed sediments. The second Umm Ruwaba aquifer can be considered as predominantly confined because only 3.1% (6 out of 196) of the drillings in the Umm Ruwaba area lack significant clay ( $< 2$  m when aggregated) above the second aquifer (Fig. 2a).

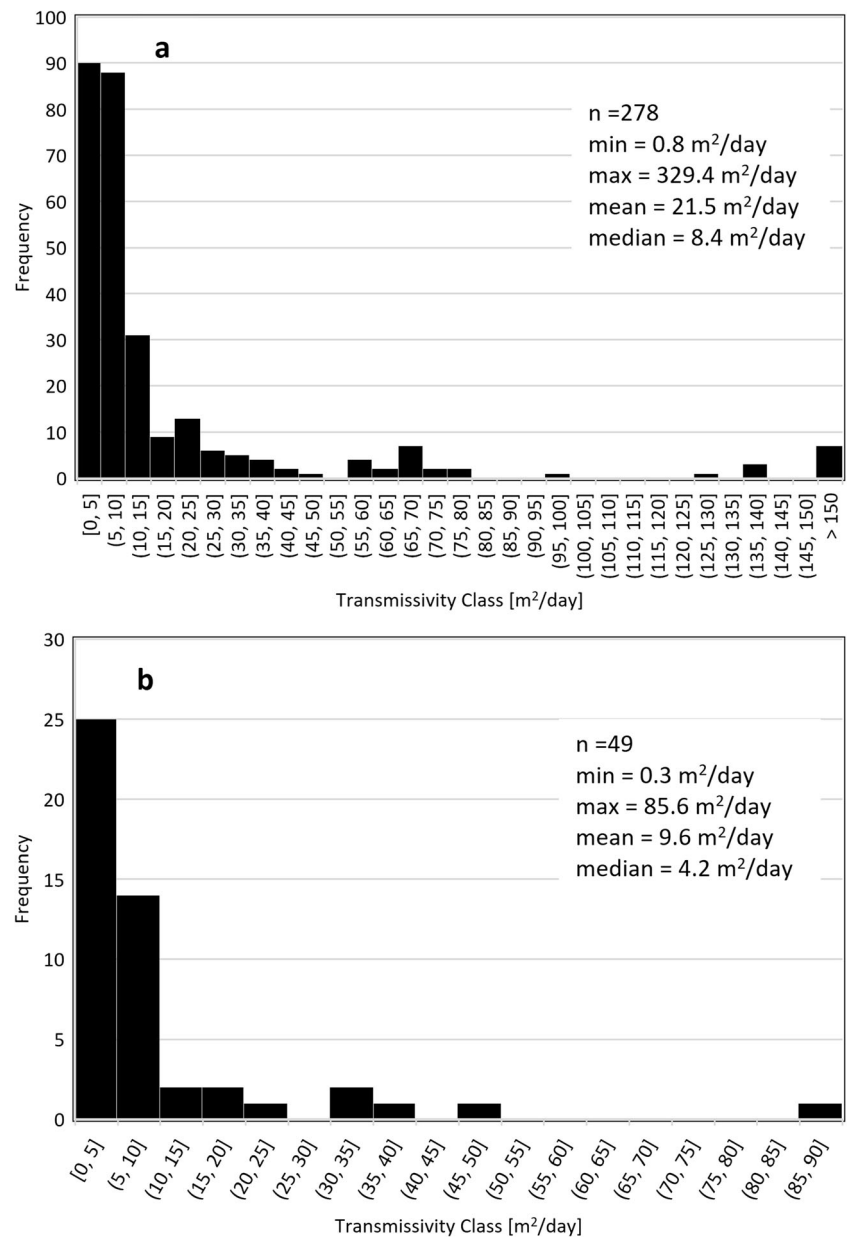
The histograms with the aquifer transmissivities for the second Umm Ruwaba and the Basement Complex aquifers are right-skewed (Fig. 4). For the second Umm Ruwaba aquifer the mean ( $21.5 \text{ m}^2/\text{day}$ ) is slightly and the median ( $8.4 \text{ m}^2/\text{day}$ ) is well below the literature values for South Sudan ( $25\text{--}60 \text{ m}^2/\text{day}$ , Table 1). For the Basement Complex, the mean ( $9.6 \text{ m}^2/\text{day}$ ) and median ( $4.2 \text{ m}^2/\text{day}$ ) in Lakes State are similar as encountered at Yambio and Torit but below Yei (see Appendix). There are zones where all the measured aquifer transmissivities are less than  $5 \text{ m}^2/\text{day}$  (Fig. 2a,c). There are no known pumping tests for the phreatic Umm Ruwaba aquifer—for example, see Fig. 5, where the regional (130 km long) hydrogeological profile over the Umm Ruwaba Formation is shown). Not all available drilling descriptions are shown on the profile because the lithology and the related aquifer transmissivity (Fig. 2c) can vary significantly between closely spaced (several 100 m) boreholes due to the large lateral heterogeneity. The profile includes one of the six previously discussed drillings (numbers 16–29) where the second aquifer is unconfined.

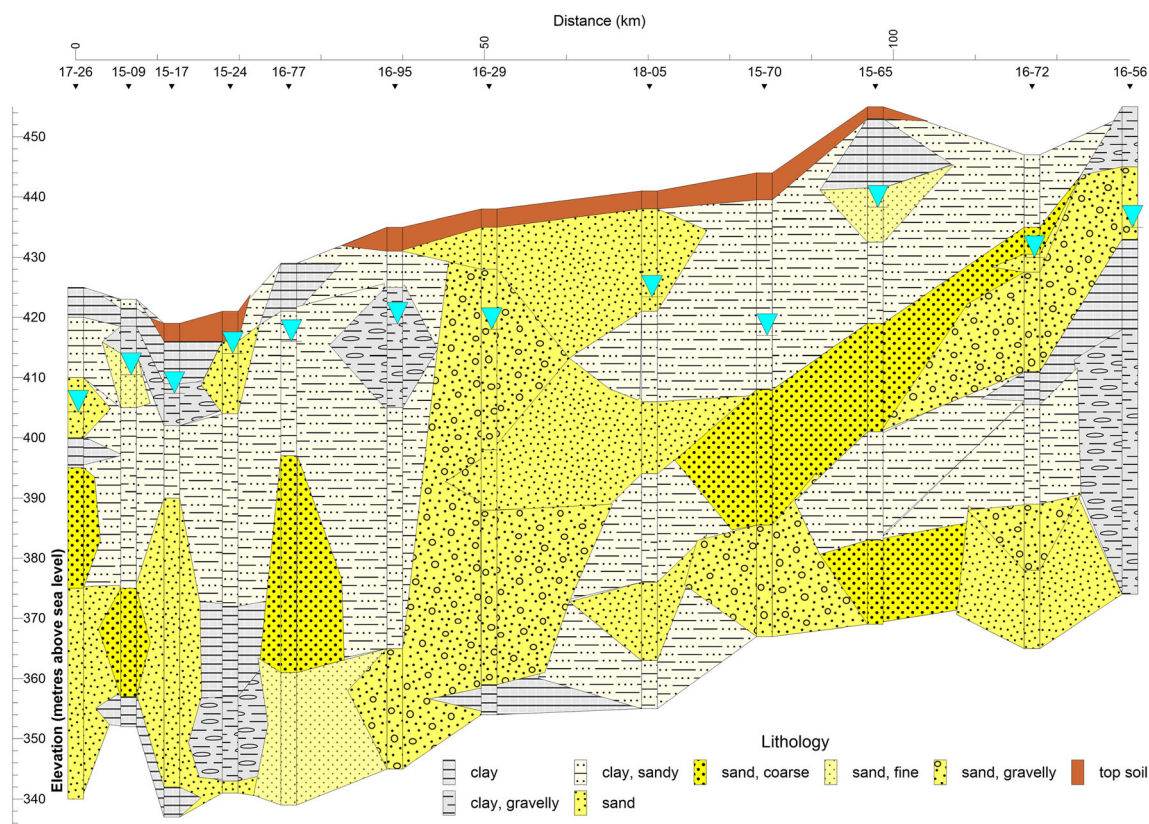
### Groundwater quality

Of the approximately 1,400 groundwater points that were field-tested for water quality (EMM 2019), most (95.5%) had a low nitrate content (0–3 mg/L). A few sites (2.1%) showed a slightly elevated content of 3–10 mg/L and 10–50 mg/L (2.0%). One hand-dug well (in the phreatic Umm

**Table 2** Sediment in borelogs for the first 10 m for the main geological areas in Lakes State

Recharge potential	Dominant sediment in first 10 m	Umm Ruwaba area		Basement Complex area	
		No.	% of total	No.	% of total
Low	≥8 m clay	72	36.7%	14	35.9%
	5–8 m clay, <1 m sand/gravel, remainder sandy/gravelly clay	23	11.7%	4	10.3%
Moderate	Dominated by sandy/gravelly clay	81	41.3%	18	46.2%
High	5–8 m sand/gravel, <1 m clay, remainder sandy/gravelly clay	5	2.6%	0	0.0%
	≥ 8 m sand/gravel	15	7.7%	3	7.7%
Total		196	–	39	–

**Fig. 4** Histograms showing data from single-well pumping and recovery tests: transmissivities for the **a** second Umm Ruwaba aquifer and **b** Basement Complex aquifer, in Lakes State



**Fig. 5** Lakes State hydrogeological profile: NW–SE with locations of drillings (prepared with Strater, profile line shown on Fig. 2c)

Ruwaba aquifer) and four boreholes (all in the second Umm Ruwaba aquifer) had nitrate contents of 50 mg/L or higher (WHO drinking water limit). These have been attributed to local surface pollution (e.g. from cow dung) leaching into the aquifer. The nitrite content was also generally low with 99.1% of the tests showing less than 0.5 mg/L.

The salinity (EC) of the water in the second Umm Ruwaba and Basement Complex aquifers (Fig. 2d) is generally very low (<100  $\mu\text{S}/\text{cm}$ , 60.4% of the tested water points) or low (100–300  $\mu\text{S}/\text{cm}$ , 25.7%). At greater distance from the Basement Complex boundary areas, the salinity in the second Umm Ruwaba aquifer is slightly higher, between 300–800  $\mu\text{S}/\text{cm}$  (9.7%). Few (3.5%) water points had a slightly elevated EC of 800–1,200  $\mu\text{S}/\text{cm}$ , while 0.6% of the water points were brackish with an EC above 1,200  $\mu\text{S}/\text{cm}$  up to a maximum of 4,670  $\mu\text{S}/\text{cm}$ . The brackish groundwater was found in the second Umm Ruwaba aquifer in the S–SE corner under the western floodplains of the Bahr el Jebel River (Fig. 2a,d).

### Groundwater level

The mean dry season depth to groundwater level in the Umm Ruwaba Formation ranges from 11.3 mbs (phreatic aquifer, based on data from 66 locations) to 20.8 mbs (second aquifer, 892 locations). In the Basement Complex, the mean depth to the piezometric surface varies from 16.3 mbs in the southwest

(170 locations) and 39.1 mbs near Yirol (138 locations). Four areas within the second Umm Ruwaba and Basement Complex aquifers have very deep groundwater levels (>50 mbs; Fig. 2a).

Isolines for the absolute groundwater head of the second Umm Ruwaba aquifer (in masl) have been drawn in Fig. 3 based on the previously discussed water point survey. There are no contour lines for the Basement Complex because it consists of local aquifers with an uncertain interconnectivity. The groundwater head generally slopes, and hence, flows from the southwest to the northeast away from the geological boundary with the Basement Complex towards the Bahr el Jebel River. The gradient is steepest near the Basement boundary (0.001–0.0015) and becomes less steep in the northwest (0.00005). By substituting the gradient and the mean transmissivity (21.5  $\text{m}^2/\text{day}$ , Fig. 4) into the Darcy equation, the lateral groundwater flow within the second aquifer is estimated to be between 12,000 (near Basement) and 400 (northwest)  $\text{m}^3/\text{year}$  per kilometer of the aquifer width. In some areas, the head does not follow the regional trend (discussed in the following).

In the 14 abandoned boreholes that were occasionally monitored, minimum seasonal head variations ranged from less than 1 to 7.5 m (Fig. 3). For the borehole in the second Umm Ruwaba aquifer that was monitored weekly, the seasonal head difference was between 3.14 m (2019) and 7.35 m (2016) with an average (2016–2019) of 5.13 m. Figure 6 shows that there is a clear link between rainfall and

groundwater recharge; the head is at its deepest at the start of the wet season (April/May) and rises during most of the wet season, with a peak during the second half of the wet season (between mid-August and mid-October). Since the aquifer is largely confined, there is only a weak relation between the height of the peaks and the cumulative annual rainfall around the borehole (circle with 14 km radius) prior to the peaks. During the 2016 to 2018 dry seasons, there was a consistent water level decline of 0.023 m/day, which is attributed to groundwater abstraction from the over 340 boreholes in Rumbek Town payam (approximately 1 per 0.14 km<sup>2</sup>) and regional groundwater flow towards the northeast.

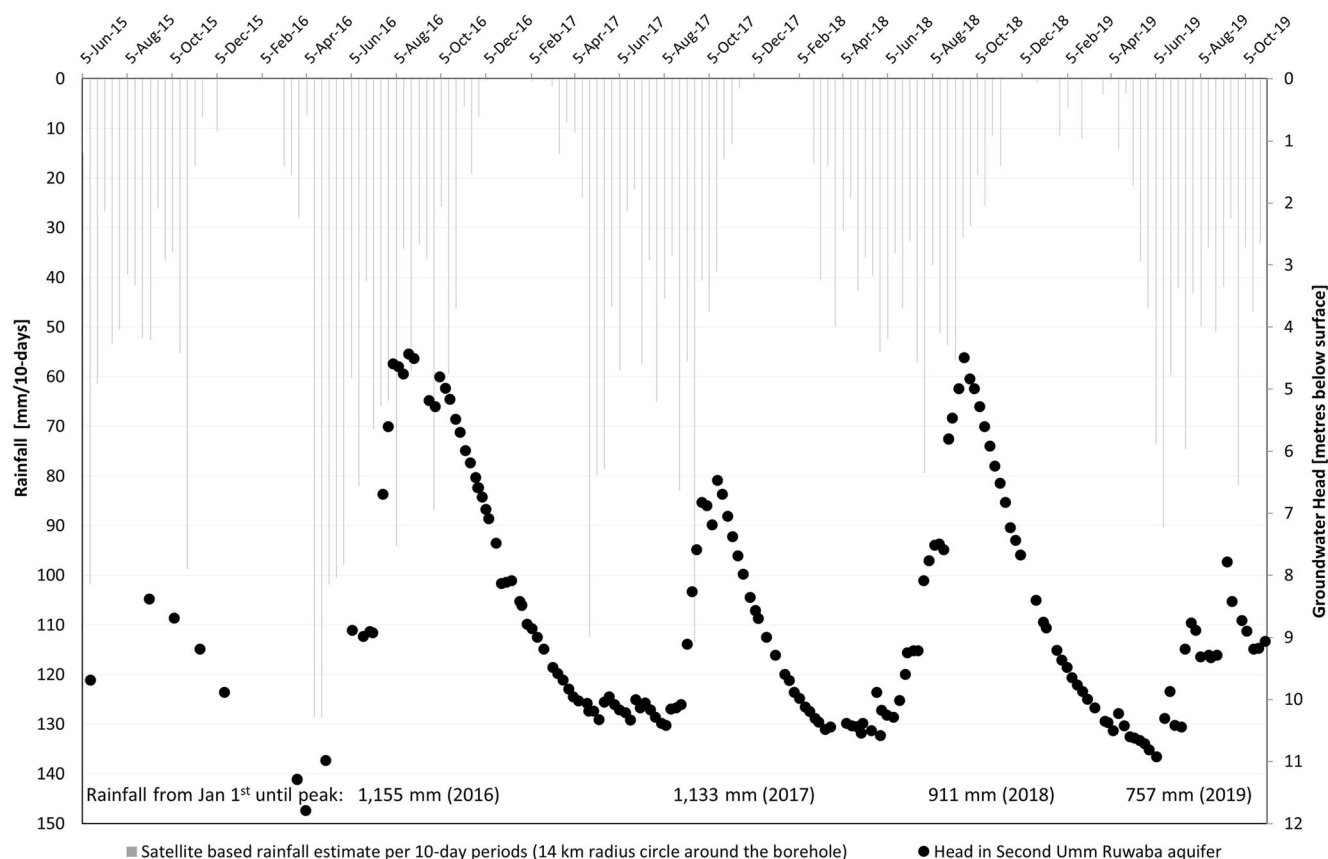
## Discussion

### Groundwater occurrence

The small proportion of surveyed groundwater points that tap the phreatic aquifer of the Umm Ruwaba area (6.8%) are hand-dug wells and shallow (<30 mbs) boreholes; and are mainly concentrated in zones near the Basement Complex boundary and along the Bahr el Jebel River (Fig. 3). During the survey, the population near these water points reported that many of them provide less water or even dry up during the

second half of the dry season. The high mean (2003–2005) wet season groundwater recharge of 30–300 mm/year for South Sudan is mostly used by direct evapotranspiration from this and other shallow aquifers (Bonsor et al. 2010). In addition, a modest downward recharge to the second aquifer (discussed in the following) and possibly some groundwater flow to discharge areas occur.

In most of the confined second Umm Ruwaba aquifer, the head is relatively shallow (<25 mbs) and the transmissivity is fair (median 8.4 m<sup>2</sup>/day, Fig. 4a). A storage coefficient of  $0.5 \times 10^{-3}$  to  $1.0 \times 10^{-3}$  (Table 1) and observed seasonal head variations of 1–7.5 m (Figs. 3 and 6) give a mean estimated recharge of 0.1–7.5 mm/year. Therefore, despite a mean annual rainfall of over 1,000 mm/year (discussed in the preceding) and regular wet seasons floods that can cover up to a third of the surface area of Lakes State in relatively wet years (EMM 2019), the mean annual recharge is modest (about 1% of the rainfall) due to the mostly confined nature of the aquifer. The relatively large head gradient (Fig. 3) and the low salinity (Fig. 2d) in the zones where the second Umm Ruwaba aquifer borders the Basement Complex areas indicate a relatively fast through-flow of groundwater due to local groundwater recharge. The few pockets (Fig. 2a, 3.1% of the drilling logs discussed in the preceding) where the second aquifer is unconfined provide



**Fig. 6** Groundwater head monitoring of the second Umm Ruwaba aquifer in Rumbek (monitoring borehole location indicated as the blue dot within Rumbek shown on Fig. 3). Satellite-based rainfall estimates from USGS FEWSNET 2020



opportunities for recharge to occur. The groundwater head in the second Umm Ruwaba aquifer declines from southwest to northeast, from approximately 440 masl near the Basement Complex boundary to 390 masl at the start of the floodplains (about 25 km west of the Bahr el Jebel River; Fig. 3). Groundwater discharge is unlikely to occur here since the head is well below the surface (>10 mbs). Further east along the Bahr el Jebel, the head rises again to between 400 and 410 masl. A similar pattern in groundwater head occurs on the other side of the river at Bor (Fig. 3). Elevated heads along both sides of the Bahr el Jebel suggests that the river recharges the second aquifer. However, observed heads in the boreholes in Bor (just next to the river) are at least 5 m below the river bed (SMEC 2013c). Thus, river bed recharge is not keeping up with groundwater abstraction by the at least 55 (SMEC 2013c) mostly hand-pump-equipped boreholes in Bor. This is attributed to the confined nature of the second aquifer.

In the Basement Complex area, the groundwater potential varies over short distances and depends on the thickness, sandiness, and extent of the weathered top layer and/or fractures. The low transmissivity (Figs. 2 and 4b) indicates that the aquifer is generally clayey and/or not very fractured.

There are several areas within the second Umm Ruwaba and the Basement complex aquifers with anomalies in groundwater properties (head, transmissivity or salinity) that pose challenges for developing new boreholes (Fig. 2a). The main ones and their possible origins are discussed in the following.

- In the north at Maper, there is an area of approximately  $2.5 \times 2.5$  km where the head in the second Umm Ruwaba aquifer is below 350 masl, which is approximately 15 m lower than the regional head (Fig. 3). This area has a relatively high concentration of 30 hand-pump-equipped boreholes and one new (2018) water yard with a solar-powered pump. No larger motorised groundwater abstractions were observed here during the water points survey. A reliable supply of diesel for motorised pumps would have been very expensive due to the poor state of the untarred road to Maper and because the road is impassable during most of the wet season. The average aquifer transmissivity of five pumping tests from the area (Fig. 2c) is low ( $4.9 \text{ m}^2/\text{day}$ ). The MLU groundwater modelling tool that computes drawdowns in and near pumping wells using analytical solution techniques for well flow in a layered system (Hemker and Post 2020) was used to verify if this relatively dense network of handpumps (approximately 1 per  $0.2 \text{ km}^2$ ) in the low transmissivity zone of a confined aquifer could explain the observed trough in the groundwater head. Estimated aggregated groundwater abstraction from this area amounted to approximately  $196 \text{ m}^3/\text{day}$  (based on a 70% borehole functionality with each functional borehole serving on average 267 people (Fig. 2b) at an assumed water use of 35 L per person per day). Under a confined

aquifer storage coefficient of  $0.5 \times 10^{-3}$  (Table 1), the model showed that the abstraction would indeed be able to cause a significant drawdown after 15 years of pumping of 13.0 and 7.3 m at 1 and 2.5-km distance from the abstraction, respectively. Such a large drawdown would not be possible if the aquifer is unconfined.

- West and east of Nyang, in the hills of the Basement outcrop, there are two zones with a deep (50–85 mbs) groundwater level. The average aquifer transmissivity (five pumping tests) in the eastern zone that had the deepest groundwater level was  $3.7 \text{ m}^2/\text{day}$  (Fig. 2c). The abstraction from this zone is probably less than in Maper (previously discussed) because the surveyed water point density is lower here (just over 1 per  $1 \text{ km}^2$ , Fig. 3). There were no pumping test data for the zone west of Nyang (Fig. 2c). The low transmissivity combined with the uncertain lateral interconnectivity between local Basement Complex aquifers are the most likely explanations for the aquifer being depleted relatively quickly.
- In the southeast near Awerial, there is a zone where the groundwater of the second Umm Ruwaba aquifer was relatively saline (EC 800–4,670  $\mu\text{S}/\text{cm}$ , Fig. 2a,d). There were no known pumping tests in this area (Fig. 2c). The origin of the elevated salinity is uncertain, but could possibly be due to the resolution of evaporites.

### Borehole siting

The payams that are relatively poorly served in terms of groundwater (Fig. 2b and Fig. S1 of the ESM) are from a social perspective the obvious focus for siting new boreholes. Political pressure on siting new boreholes was high during the period when the underserved areas had not yet been mapped, as it took a relatively long time to survey existing boreholes under the challenging field conditions. The hydrogeological aspects of borehole siting within the two most exploited aquifers (second Umm Ruwaba and Basement Complex) are discussed in the following.

The areas of head anomalies could be identified prior to drilling through borehole survey and pumping test data (Fig. 2a,c). VES taken inside and just outside the over-exploited low-transmissivity zone near Maper did not show a significant contrast, as the mean interpreted electrical resistivity at the depth of the second Umm Ruwaba aquifer was similar at around 60 Ohm-m for both inside (8 VES) and just outside (8 VES) the zone (EMM 2019). Although no VES were done in the slightly brackish groundwater zone (Fig. 2a,c), the contrast in electrical resistivity between an aquifer filled with slightly brackish (EC 800–4,670  $\mu\text{S}/\text{cm}$ ) and fresh (EC < 800  $\mu\text{S}/\text{cm}$ ) groundwater is probably also undetectable for VES due to larger contrasts caused by the lateral variation in clay content. Thus, the database on existing boreholes is more useful than VES for avoiding siting new low-abstraction and/

or slightly brackish hand-pump-equipped boreholes in the second Umm Ruwaba aquifer. Seven out of 276 (2.5%) of the newly drilled hand-pump-equipped boreholes in the second Umm Ruwaba aquifer were of low productivity. This is mainly attributed to poor local aquifer conditions (dynamic groundwater level  $> \sim 50$  mbs and/or transmissivity  $< 5 \text{ m}^2/\text{day}$ ). Unproductive boreholes outside the mapped areas with known poor aquifer conditions (Fig. 2a) were redrilled to minimise the chance of poor construction techniques as a cause.

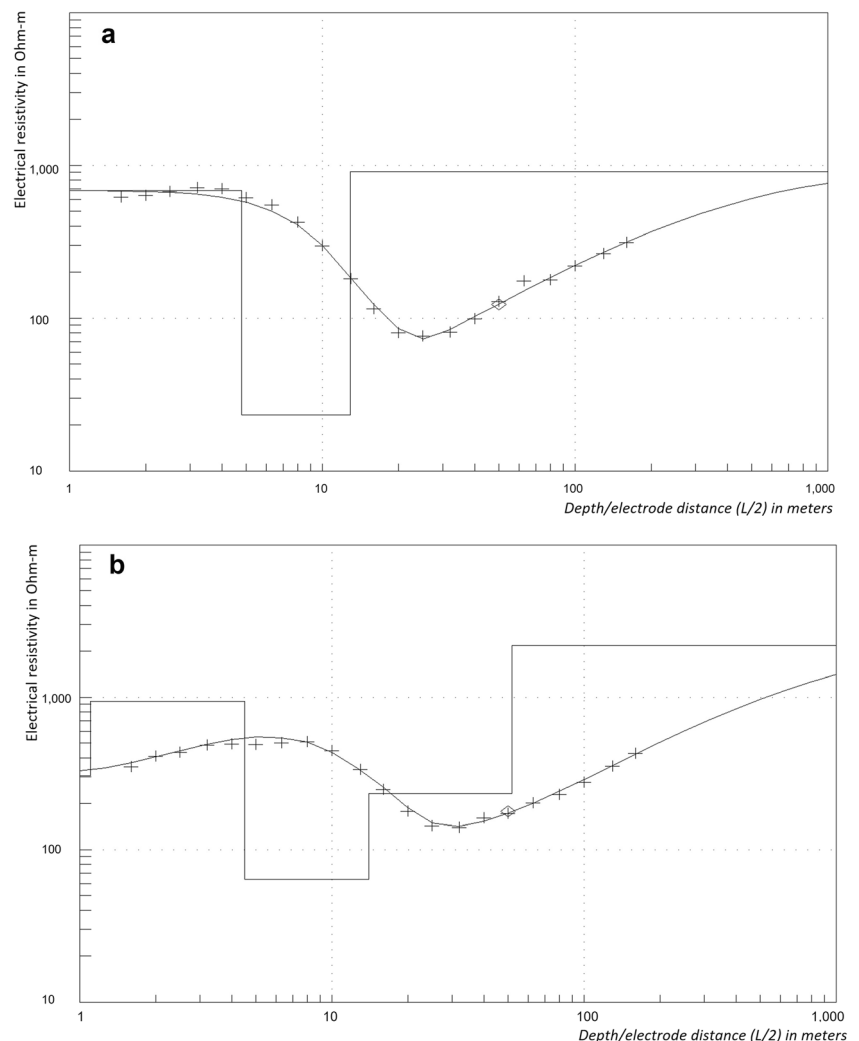
In the Basement Complex area and within the Umm Ruwaba Formation geological boundary, VES measurements were applied successfully to avoid drilling new boreholes at sites with shallow ( $< 30$  mbs) bedrock. This is because hard rock has a much higher electrical resistivity than the weathered Basement and the overlying sedimentary deposits. Figure 7 shows an example of two nearby (1.7 km apart) VES in the Basement Complex area. The modelled starting depth of the high-resistivity layer ( $\geq 900 \text{ Ohm-m}$ ) that has been interpreted as hard-rock is shallower at one site (13 mbs, Fig. 7a) than at another site (52 mbs, Fig. 7b). At the site with

deep interpreted hard-rock, a productive new hand-pump-equipped borehole was drilled. Similar as with the second Umm Ruwaba aquifer, VES were not successful (EMM 2019) at identifying locations where the Basement Complex aquifer had a very low transmissivity ( $< 4 \text{ m}^2/\text{day}$ ) and/or a deep dynamic groundwater level ( $> 50$  mbs). Due to the local nature of the Basement aquifer a deep groundwater level can be very local and can hence remain undetected more easily than in the Umm Ruwaba area during the borehole survey. Eight percent (4 out of 50) of the newly drilled hand-pump-equipped boreholes in the Basement Complex aquifer were of low productivity, attributed to poor local aquifer conditions (deep groundwater level and/or low transmissivity). In three cases, the first borehole drilled was dry.

### Groundwater development

The groundwater development potential of the phreatic Umm Ruwaba aquifer is low because the survey showed that the boreholes provide less water or even dry up, especially during

**Fig. 7** Two nearby (1.7 km apart) vertical electrical soundings (VES) showing log-log plots of apparent resistivity against electrode distance (dots) and interpreted layer resistivity against depth (rectangular line): **a** VES site 1, **b** VES site 2. The starting depth of the high-resistivity hard-rock layer was shallower at site 1 (13 mbs) and deeper at site 2 (52 mbs). (Interpreted with Schlumberg for Windows, location shown in Fig. 3)



the second half of the dry season. Hence, it is no longer common to develop new boreholes in this aquifer.

Almost all new boreholes in the Umm Ruwaba area have been screened in the second (confined) aquifer which has mostly good enough transmissivity (Figs. 2c and 4a) to sustain hand pumps in towns like Rumbek and Yirol without significantly lowering the head (Fig. 3). From a groundwater development perspective, it is recommended to limit the borehole density and hence the abstraction from the low-transmissivity zones in this aquifer (Fig. 2a) because it becomes very difficult to operate and maintain hand-pump-equipped boreholes when the groundwater level drops below 50 mbs. The observed local groundwater troughs in or near more densely populated county capitals like Maper (Fig. 2a) indicate that the current yield (discussed in the preceding) is here already above its maximum for keeping the hand pumps operational. Analytical pumping test software like MLU or a simple groundwater model can be used for determining a maximum abstraction given a locally acceptable drawdown.

The groundwater development potential of the Basement Complex aquifer is generally poorer than for the second Umm Ruwaba aquifer due to its lower transmissivity (Fig. 4b) and large thickness variation over short distances (Fig. 7). The two zones with a low transmissivity and a deep groundwater level (Fig. 2a) are being avoided for new drillings due to a high concentration of dry and failed boreholes that were observed here during the survey (EMM 2019). During the survey the payam pump mechanic reported an outward migration of people during the dry season and long queues were observed at the boreholes that still function. The following strategy to augment the groundwater supply in these areas has been tested. First, the relatively most productive, or ‘least-worst’, existing borehole was identified based on recent and repeat pumping tests, and on the water depth. Then, one such hand-pump-equipped borehole (location on Fig. 2a, transmissivity  $4.3 \text{ m}^2/\text{day}$ , dry season water depth 56 mbs) had been successfully upgraded to a more productive solar-powered water yard.

Consuming untreated groundwater from the second Umm Ruwaba aquifer is not recommended in the zone with a relatively high salinity (EC 800 to over  $4,000 \text{ }\mu\text{S/cm}$ ), especially where the EC exceeds  $1,200 \text{ }\mu\text{S/cm}$  (Fig. 2a,d). Boreholes in the high salinity zone would also need to be given priority for further water quality testing by a certified laboratory especially considering the previously described outcome of the water quality survey in Eastern Equatoria State by Kut et al. (2019). Surface water from the Bahr el Jebel River also needs basic treatment (SMEC 2013c). A test drilling in the deeper third aquifer that is probably present in the area and/or rainwater harvesting could be considered to explore its suitability as an alternative source.

About a third of the water points in Lakes State (approximately 730) received support from the W4L Project in their operation and maintenance through the training of Water User Committees and a supporting network of private pump

mechanics. Monitoring field visits showed that the functionality of these water points increased from 71 to 85% towards the end of the support period (EMM 2019).

## Conclusions and recommendations

An extensive survey of all existing groundwater points helped to reduce political influence on the siting of new boreholes in Lakes State. Currently (2019) 33 out of the 54 payams in Lakes State, on average, still do not comply with the minimum water supply standard for South Sudan (500 people or less per functional public water point). The functionality of the surveyed public groundwater points in Lakes State was 71% which is between what has been reported earlier for South Sudan: 50–70% by RSS-MWRI (2011a) and 80% by Foster et al. (2020).

The Basement Complex and the unconsolidated sediments of the Umm Ruwaba Formation are the most extensive geological formations and are the most exploited for groundwater in South Sudan. For the Basement Complex, low aquifer transmissivity values, resulting from most pumping tests in Lakes State (median  $4.2 \text{ m}^2/\text{day}$ , mean  $9.6 \text{ m}^2/\text{day}$ ) and in Yambio and Torit towns, indicate that the aquifer is relatively clayey and/or not very fractured. In most of the Basement area, only moderately productive hand-pump-equipped boreholes can be developed. In contrast, Yei in Central Equatoria State has higher transmissivities ( $67,119$  and  $220 \text{ m}^2/\text{day}$ ) in the Basement Complex.

It is no longer common to develop new wells or boreholes in the phreatic or first Umm Ruwaba aquifer because they provide less water or dry up, especially during the second half of the dry season. This is most likely largely due to evapotranspiration by the vegetation cover.

In Lakes State, the predominantly confined second Umm Ruwaba aquifer is estimated to receive a limited average recharge of 1 to 8 mm/year, which is mainly occurring from the Bahr el Jebel River and from the zones along the geological boundary with the Basement Complex. Unconfined conditions occur at 3.1% of the 196 drilling locations where direct recharge can take place. Weekly groundwater head monitoring of the aquifer (Rumbek, Lakes State) shows that there is a clear link between rainfall and groundwater recharge. The single-well aquifer transmissivity values for Lakes State boreholes (278 tests) are right-skewed (median  $8.4 \text{ m}^2/\text{day}$ , mean  $21.5 \text{ m}^2/\text{day}$ ) and generally below the literature values for South Sudan ( $25\text{--}60 \text{ m}^2/\text{day}$ ). Still, the aquifer transmissivity in Lakes State is generally good enough to sustain hand pumps in towns without significantly lowering the head. Zones with a very low transmissivity ( $<5 \text{ m}^2/\text{day}$ ) have also been mapped, and where a moderate density of hand-pump-equipped boreholes (1 per  $0.2 \text{ km}^2$ ) has been observed to be able to cause a drop in groundwater head of around 15 m. The resulting local groundwater troughs ( $<50$  mbs) in or near a more densely populated county capital, like Maper, indicate

that the current yield ( $\sim 196 \text{ m}^3/\text{day}$  from an area of  $\sim 6.3 \text{ km}^2$ ) is above its maximum for keeping the hand pumps operational. Historical maps (e.g. NCDWRWS-TNO-DGV 1989) show a groundwater trough in northeast South Sudan; however, data on this are scanty and the few recent groundwater heads measured near Bentiu and Malakal indicate that the extent of the trough may be less than originally sketched.

The third Umm Ruwaba aquifer is probably only present towards the centre of the basin where the formation is thick. Information from the few known boreholes with screens in this aquifer in northern South Sudan indicate a mean transmissivity of  $62 \text{ m}^2/\text{day}$ , a similar groundwater head as the aquifers above it, and mostly brackish water.

Geophysical (VES) measurements have been applied successfully for avoiding drilling new boreholes at sites where the depth of the hard rock is shallow. The database on existing boreholes is more useful than VES for avoiding siting new low-abstraction and/or slightly brackish hand-pump-equipped boreholes in the second Umm Ruwaba aquifer.

The following groundwater quality concerns have been identified: (1) In Eastern Equatoria State, the groundwater regularly exceeds the WHO drinking water limits for different chemical elements like cadmium, lead, and fluoride, and this is attributed to rock–water interaction (Kut et al. 2019). (2) Although the groundwater salinity is low ( $\text{EC} < 800 \text{ }\mu\text{S/cm}$ )

in most of Lakes State, there is a brackish zone ( $\text{EC } 800\text{--}4,670 \text{ }\mu\text{S/cm}$ ) within the second Umm Ruwaba aquifer in the southeast. The origin is uncertain, possibly it could be the resolution of evaporites. (3) In northeast South Sudan, a zone with brackish groundwater ( $2,300$  to over  $7,800 \text{ }\mu\text{S/cm}$ ) had been interpreted as being related to a buried saline lake (Salama 1997). More recent borehole information indicates that brackish groundwater is also present in the shallow and deeper aquifers in the northern part of South Sudan (Bentiu). (4) The oil production infrastructure in north and northeast South Sudan can lead to oil spills (Löw et al. 2021) and pollute the shallow aquifer; however, there is no accessible information on the scale of the pollution (UNEP 2018). Elaborate water quality data are scarce for most parts of the country and/or are of uncertain reliability due to the unclear certification status of local laboratories. The facilitation of the certification of at least one of the national laboratories would be a first step to addressing this information gap. Boreholes in the zones with an elevated salinity ( $>800 \text{ }\mu\text{S/cm}$ ) are recommended to be prioritised for a survey. Sustainably managing boreholes with poor water quality, for example, through the introduction of treatment technologies, will be a challenge, especially for public boreholes outside state capitals, given their poor accessibility, weak institutional capacity, and the limited life-span of donor-supported water projects.

## Appendix

**Table 3** Summary of outcomes of groundwater surveys for small towns in South Sudan from consultancy reports (locations of the towns on Fig. 1). *mbs* meters below surface; *ND* not detected

Geology	Town	Aquifer type	No. of boreholes /wells in area	Borehole depth [mbs]	Static Water Level [mbs]	Transmissivity [ $\text{m}^2/\text{day}$ ]
Umm Ruwaba possibly covered by Quaternary alluvium	Bor (near Nile)	Second aquifer (12 to $>150$ mbs), confined	$\sim 55$	40–110	17 (near river) to 58 ( $\sim 6.5$ km from river)	57 (27–77)
	Rumbek	Second aquifer (30 to $>90$ mbs), confined	$>100$	45–90	8–18	98 (15–264)
	Bentiu (near the 'groundwater trough')	First aquifer (0–32 mbs), unconfined	$>25$ (many unused)	30–40	12–15 (3 sites)	–
		Second aquifer (45– $\sim 150$ mbs), confined	–	–	–	Poor to medium
'possibly' Nubian	Wak Abil near Aweil	Third aquifer (154 to $>213$ mbs), confined	$\sim 12$	193–226	10–21 (10 sites)	62 (9–101)
		'Possibly' sandstone	9 (1 tested)	72	3	108
Quaternary on Basement Complex	Aweil	Alluvial, confined, bedrock at 30–60 mbs	$\sim 100$	30–70	Generally $<10$	1.2, 6.3 and 770
	Kuajok	Alluvial, confined, bedrock at 39–100 mbs	75	30–63	Generally $<11$	19 (6–44)
Basement Complex	Yambio	Weathered/fractured rock	$>150$	11–110	Generally $<15$ , deepest 28	7.6 (0.8–47.2)
	Torit		$\sim 100$	27–89	2–24	5 (1–26)
	Yei		$\sim 100$ , 3 newly drilled	38–82	Generally $<10$ , deepest 34	67, 119 and 220



**Table 3** (continued)

Geology	Coliforms	Electrical conductivity [ $\mu\text{S}/\text{cm}$ ]	Chemical [mg/L]	Aquifer potential classification	Source
Umm Ruwaba possibly covered by Quaternary alluvium	Detected (2 out of 4)	366 (185–700)	Iron >0.5 (1 out of 4), nitrate >50 (2 out of 4)	Moderate	SMEC (2013c)
	Detected (2 out of 5)	163 (81–388)	Nitrate >50 (3 out of 5)	Moderate	SMEC (2013e)
	Detected (3 out of 6)	1,821 (785–4,050)	Sulphate 228 (55–360), nitrate >50 (4 out of 7), occasional trace elements (Cr, Ur)	Poor	SMEC (2013b)
	—	—	—	—	—
‘possibly’ Nubian	ND	1,416 (724–3,730)	Manganese 1.3–8.6, sulphate 515 (53–2,120), occasional trace elements (Al, Fe), ‘very hard’	Moderate	
	Detected	138	Bromide 3.3, nitrate 143	Moderate to good	SMEC (2013a)
Quaternary on Basement Complex	Detected (4 out of 5)	239 (52–541)	Aluminium >1.7 (3 out of 5), iron >0.5 (4 out of 5), manganese >0.4 (1 out of 5)	Moderate	
	Detected (3 out of 7)	199 (48–946)	Aluminium 0.8–8.7 (6 out of 7), bromide >0.5 (2 out of 7), iron >0.5 (5 out of 7), manganese >0.4 (2 out of 7)	Moderate	SMEC (2013d)
Basement Complex	Detected (5 out of 5)	<600	Nitrate >40 (2 out of 5), occasional trace elements (Al, Fe)	Poor	SMEC (2013g)
	Detected (3 out of 5)	1,259 (319–3,980)	Manganese >0.4 (2 out of 5), nitrate >50 (3 out of 5)	Poor	SMEC (2013f)
	Detected	<400	—	Moderate to good	Gauß Ingenieure (2018)

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## Declarations

**Conflict of interest** The corresponding author states that there is no conflict of interest.

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## References

- Abdalla OAE (2008) Groundwater discharge mechanism in semi-arid regions and the role of evapotranspiration. *Hydrol Process* 22: 2993–3009
- Abdelsalam MG (2018) The Nile’s journey through space and time: a geological perspective. *Earth Sci Rev* 177:742–773
- AfDBG (2013) South Sudan: an infrastructure action plan. A Program for Sustained Strong Economic Growth. African Development Bank Group (AfDBG), Abidjan, Côte d’Ivoire

- Basheer M, Elagib NA (2019) Performance of satellite-based and GPCC 7.0 rainfall products in an extremely data-scarce country in the Nile Basin. *Atmos Res* 215:128–140
- Bonsor HC, Mansour MM, MacDonald AM, Hughes AG, Hipkin RG, Bedada T (2010) Interpretation of GRACE data of the Nile Basin using a groundwater recharge model. *Hydrol Earth Syst Sci Discuss* 7:4501–4533
- Coffel ED, Keith B, Lesk C, Horton RM, Bower E, Lee J, Mankin JS (2019) Future hot and dry years worsen Nile Basin water scarcity despite projected precipitation increases. *Earth's Future* 7:967–977
- EMM (2019) Water resources development in Greater Lakes State and its sub-basins: fourth Progress Report. Euroconsult Mott MacDonald (EMM), Programme between the Government of the Republic of South Sudan and the Embassy of the Kingdom of the Netherlands in South Sudan, supported by the Ministry of Foreign Affairs, Juba, South Sudan
- Engström E, Balfors B, Mörtberg U, Thunvik R, Gaily T, Mangold M (2015) Prevalence of microbiological contaminants in groundwater sources and risk factor assessment in Juba, South Sudan. *Sci Total Environ* 515–516:181–187
- Engström E, Mörtberg U, Karlström A, Mangold M (2017) Applying spatial regression to evaluate risk factors for microbiological contamination of urban groundwater sources in Juba, South Sudan. *Hydrogeol J* 25:1077–1091
- FAO (2011) Land cover atlas of the Republic of South Sudan. Food and Agriculture Organization of the United Nations, Rome
- Foster T, Furey S, Banks B, Willets J (2020) Functionality of handpump water supplies: a review of data from Sub-Saharan Africa and the Asia-Pacific region. *Int J Water Resour Dev* V36(5):855–869
- Gauß Ingenieure (2018) Yei urban water supply and sanitation project. Borehole Completion Report. Report to the Republic of South Sudan, Ministry of Electricity, Dams, Irrigation and Water Resources, Juba, South Sudan
- Gaye CB, Tindimugaya C (2019) Review: challenges and opportunities for sustainable groundwater management in Africa. *Hydrogeol J* 27: 1099–1110
- GMRD (1981) Geological map of the Sudan. Geological and Mineral Resources Department (GMRD), Khartoum, Sudan
- Golden Software (2016) Strater 5, superior well log, borehole & cross section plotting, user's guide. Golden Software, Golden, CO
- GoSS (2007) Water policy. Government of Southern Sudan (GoSS), Juba, South Sudan
- GRAS (1995) Accompanying geological notes to the 1:1,000,000 scale geological atlas of the Republic of the Sudan, Wau and Juba sheet notes. Ministry of Energy and Mining, Geological Research Authority of the Sudan (GRAS), Juba, South Sudan
- GRAS (2004) Geological map of the Sudan. Ministry of Energy and Mining, Geological Research Authority of the Sudan (GRAS), Khartoum, Sudan
- Harris I, TJ Osborn, P Jones and D Lister (2020) Version 4 of the CRU ts monthly high resolution gridded multivariate climate dataset. *Sci Data*. <https://doi.org/10.1038/s41597-020-0453-3>
- Hemker CJ, VEA Post (2011) Schlumbg for Windows, V2.20, interpretation of resistivity soundings with Schlumberger or Wenner Configuration. Software Package, Amsterdam
- Hemker CJ, VEA Post (2020) MLU for windows, aquifer test analysis for unsteady-state flow in multiple-aquifer systems. Microfem, Amsterdam, The Netherlands
- Hurst HE, Black RP (1943) The Nile Basin, volume VI, monthly and annual rainfall totals and number of rainy days at stations in and near the Nile Basin. Government Press, Cairo
- Institute of Hydrology (IH) (1981) Malakal water supply, a study of the water resources of the Malakal area. Institute of Hydrology, Wallingford, UK
- IOM (2018) Borehole report. In: South Sudan, upper Nile, Fashoda – Dethuok, Abruoc, 18FAS002. International Organisation for Migration (IOM), Grand-Saconnex, Switzerland
- JICA (2014) The project for comprehensive planning and support for urgent development on social economic infrastructure in Malakal town, the Republic of South Sudan. Final report, Japan International Cooperation Agency (JICA), Tokyo
- Kebede S, Abdalla O, Sefelnasr A, Tindimugaya C, Mustafa O (2017) Interaction of surface water and groundwater in the Nile River basin: isotopic and piezometric evidence. *Hydrogeol J* 25:707–726
- Krause J (2019) Stabilization and local conflicts: communal and civil war in South Sudan. *Ethnopolitics* 18(5):478–493
- Kuol LBD (2020) South Sudan: the elusive quest for a resilient social contract? *J Interv State Build* 14(1):64–83
- Kut KMK, Sarswat A, Bundschuh J, Mohan D (2019) Water as key to the sustainable development goals of South Sudan: a water quality assessment of eastern Equatoria state. *Groundw Sustain Dev* 8:255–270
- Lasagna M, Bonetto SMR, Debernardi L, Luca DAD, Semita C, Caselle C (2020) Groundwater resources assessment for sustainable development in South Sudan. *Sustainability* 12:5580
- Löw F, Stieglitz K, Diemar O (2021) Terrestrial oil spill mapping using satellite earth observation and machine learning: a case study in South Sudan. *J Environ Manag* 298
- MacAlister C, Pavelic P, Tindimugaya C, Ayenew T, Ibrahim ME, Meguid MA (2012) Overview of groundwater in the Nile River basin, chap 7. In: Awulachew SB, Smakhtin V, Molden D, Peden D (eds) *The Nile River Basin*. Routledge, Milton Park, Abingdon, UK
- MacDonald A, Davies J, Calow R, Chilton J (2005) Developing groundwater, a guide for rural water supply. ITDG, Rugby, UK
- Mohamed Y, Savenije HHG (2014) Impact of climate variability on the hydrology of the Sudd wetland: signals derived from long term (1900–2000) water balance computations. *Wetl Ecol Manag* 22: 191–198
- Mohamed YA, Savenije HHG, Bastiaanssen WGM, van den Hurk BJJM (2006) New lessons on the Sudd hydrology learned from remote sensing and climate modelling. *Hydrol Earth Syst Sci* 10:507–518
- NBI (2016) Nile Basin water resources atlas. Nile Basin initiative (NBI), Entebbe, Uganda
- NCDRWRS-TNO-DGV (1989) Hydrogeological map of Sudan. National Corporation for Development of Rural Water Resources Sudan (NCDRWRS) and TNO Dienst Grondwater Verkenning (DGV), Delft, The Netherlands
- Omer AM (2002) Focus on groundwater in Sudan. *Environ Geol* 41:972–976
- Petersen G (2008) The hydrology of the Sudd, hydrologic investigation and evaluation of water balances in the Sudd swamps of Southern Sudan. PhD Thesis, Ecology Centre, University of Kiel, Kiel, Germany
- Petersen G, Fohrer N (2010) Flooding and drying mechanisms of the seasonal Sudd flood plains along the Bahr el Jebel in southern Sudan flooding and drying of the Sudd flood plains in southern Sudan. *Hydrol Sci J* 55(1):4–16
- Petersen G, Bast H, Fohrer N (2008) Estimation of ungauged Bahr el Jebel flows based on upstream water levels and large scale spatial rainfall data. *Adv Geosci* 18:9–13
- RSS-MWRI (2011a) Water, Sanitation & Hygiene (WASH) sector strategic framework. The Republic of South Sudan (RSS), Ministry of Water Resources and Irrigation (MWRI), Juba, South Sudan
- RSS-MWRI (2011b) Procedures and criteria for: allocation, installation, construction, rehabilitation, maintenance and delivery of water, sanitation and hygiene (WASH) facilities and services. The Republic of South Sudan (RSS), Ministry of Water Resources and Irrigation (MWRI), Juba, South Sudan

- Rueskamp H, Arik J, Stieglitz K, Treskatis C (2014) Effect of oil exploration and production on the salinity of a marginally permeable aquifer system in the Thar Jath-, Mala- and Unity oilfields, southern Sudan. *Zbl Geol Paläont Teil I*:95–115
- Salama RB (1976) Ground water resources of Sudan. Rural Water Corporation, Khartoum, Democratic Republic of the Sudan
- Salama RB (1987) The evolution of the River Nile. I: Bahr El Arab rift, the Sudd buried saline lake. *J Afr Earth Sci* 6:899–913
- Salama RB (1994) The Sudanese buried saline lakes. *Geol Soc Am Spec Pap* 289
- Salama RB (1997) The rift basins of Sudan. In: Selley RC, Hsu KJ (eds) *African basins: sedimentary basins of the world*, vol 3. Elsevier, Amsterdam, pp 99–143
- Senay GB, Velpuri NM, Bohms S, Demissie Y, Gebremichael M (2014) Understanding the hydrologic sources and sinks in the Nile Basin using multisource climate and remote sensing data sets. *Water Resour Res* 50:8625–8650
- Senden WJMK (1989) Hydrogeological map of Sudan, explanatory notes. TNO Institute of Applied Geosciences, the Netherlands and National Corporation for Development of Rural Water Resources, Khartoum, Sudan
- Shahin M (1985) *Hydrology of the Nile Basin*. Elsevier, Amsterdam
- SMEC (2013a) Water resources assessment study report: Aweil town—northern Bahr el-Ghazal State. SMEC, multi donor trust fund, report, Ministry of Water Resources and Irrigation, Juba, South Sudan
- SMEC (2013b) Water resources assessment study report: Bentiu town—Unity State. SMEC, multi donor trust fund, report, Ministry of Water Resources and Irrigation, Juba, South Sudan
- SMEC (2013c) Water resources assessment study report: Bor town—Jonglei State. SMEC, multi donor trust fund, report, Ministry of Water Resources and Irrigation, Juba, South Sudan
- SMEC (2013d) Water resources assessment study report: Kuajok town—Warrap State. SMEC, multi donor trust fund, report, Ministry of Water Resources and Irrigation, Juba, South Sudan
- SMEC (2013e) Water resources assessment study report: Rumbek town—Lakes State. SMEC, multi donor trust fund, report, Ministry of Water Resources and Irrigation, Juba, South Sudan
- SMEC (2013f) Water resources assessment study report: Torit town—Eastern Equatoria State. SMEC, multi donor trust fund, report, Ministry of Water Resources and Irrigation, Juba, South Sudan
- SMEC (2013g) Water resources assessment study report: Yambio town—Western Equatoria State. SMEC, multi donor trust fund, report, Ministry of Water Resources and Irrigation, Juba, South Sudan
- SNV (2010) The livestock sector in southern Sudan. SNV the Netherlands Development Organization, The Hague
- SSCCSE (2009) 5th Sudan population and housing census 2008. Southern Sudan Centre for Census, Statistics and Evaluation (SSCCSE), Juba, South Sudan
- Sutcliffe J, Brown E (2018) Water losses from the Sudd. *Hydrol Sci J* 63(4):527–541
- UNEP (2018) South Sudan first state of environment and outlook report 2018. United Nations Environment Programme (UNEP), Nairobi, Kenya
- UNICEF (2008) Southern Sudan water quality guidelines (proposed). UNICEF, Juba, Sudan
- UNICEF (2020) Water, sanitation and hygiene (WASH) in South Sudan briefing note: October–December 2020. UNICEF, Juba, Sudan
- United Nations (2022) The World. <https://www.un.org/Depts/Cartographic/map/profile/world.pdf>. Accessed February 2022
- USGS FEWSNET (2020) United State Geological Survey (USGS) Famine Early Warning Systems Network (FEWSNET) Data Portal, <http://earlywarning.usgs.gov/fews>. Accessed January 2020
- World Bank (WB) (2013) Republic of South Sudan: the rapid water sector needs assessment and a way forward. World Bank, Washington, DC
- World Bank (WB) (2021) Data: South Sudan. The World Bank. <https://data.worldbank.org/country/SS>. Accessed March 2021
- Yassin AA, Khalil FA, El Shafie AG (1984) Explanatory note to the geological map at the scale of 1:2,000,000 of the Democratic Republic of the Sudan. Ministry of Energy and Mining, Geological and Mineral Resources, Khartoum, Sudan

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