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REPORT

Tracing natural groundwater recharge to the Thiaroye aquifer of Dakar, Senegal

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Abstract

Urban groundwater in Sub-Saharan Africa provides vital freshwater to rapidly growing cities. In the Thiaroye aquifer of Dakar (Senegal), groundwater within Quaternary unconsolidated sands provided nearly half of the city's water supply into the 1980s. Rising nitrate concentrations traced to faecal contamination sharply curtailed groundwater withdrawals, which now contribute just 5% to Dakar's water supply. To understand the attenuation capacity of this urban aquifer under a monsoonal semi-arid climate, stable-isotope ratios of O and H and radioactive tritium (^{3}H), compiled over several studies, are used together with piezometric data to trace the origin of groundwater recharge and groundwater flowpaths. Shallow groundwaters derive predominantly from modern rainfall (tritium >2 TU in 85% of sampled wells). δ^{18}O and δ^{2}H values in groundwater vary by >4 and 20‰, respectively, reflecting substantial variability in evaporative enrichment prior to recharge. These signatures in groundwater regress to a value on the local meteoric water line that is depleted in heavy isotopes relative to the weighted-mean average composition of local rainfall, a bias that suggests recharge derives preferentially from isotopically depleted rainfall observed during the latter part of the monsoon (September). The distribution of tritium in groundwater is consistent with groundwater flowpaths to seasonal lakes and wetlands, defined by piezometric records. Piezometric data further confirm the diffuse nature and seasonality of rain-fed recharge. The conceptual understanding of groundwater recharge and flow provides a context to evaluate attenuation of anthropogenic recharge that is effectively diffuse and constant from the vast network of sanitation facilities that drain to this aquifer.

Keywords Urban groundwater · Groundwater recharge · Environmental isotopes · Semi-arid regions · Sub-Saharan Africa

Introduction

Over the last half century, rates of urban population growth in Sub-Saharan Africa have been the highest among the world's regions (UNDESA 2017). In 2010, the urban population of Sub-Saharan Africa was estimated to be 294 million; by 2030, this is projected to grow to 621 million. Such rapid urbanisation presents serious challenges to the provision of universal access to safe water and sanitation by 2030 outlined in United Nations' Sustainable Development Goal (UN SDG) 6. A recent overview of urban water-supply sources in 10 African cities (Foster et al. 2018) reveals that urban groundwater represents a substantial, strategic freshwater resource to meet rising demand under accelerating rates of urbanisation and reduced river-intake due to pollution and climate change. As also recognised by Adelana et al. (2008), there is a critical need to manage groundwater storage as a strategic reserve, used conjunctively with surface-water sources, to improve security of urban water supplies.

Like other large conurbations in tropical West Africa, the city of Dakar (Senegal) experienced rapid population growth in the 1970s that coincided with the onset of Sahelian drought; its population increased sharply from just over half a million

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inhabitants in 1972 to 3 million inhabitants in 2009. Dakar and its periphery on the Cap Vert peninsula (Fig. 1) represent 54% of the total urban population of Senegal and cover an area of 550 km^2 corresponding to 0.3% of the nation's land area (ANSD 2013). The unconfined Thiaroye aquifer comprising unconsolidated Quaternary sands lies beneath an area of suburban Dakar that features considerable groundwater resources, which during the 1970s and 1980s contributed up to 47% of the freshwater supply to Dakar. Suburban areas overlying this aquifer include Pikine, Guediawaye and Thiaroye (Fig. 1), and possess an estimated population of 1.6 million inhabitants in 2012 (ANSD 2013).

Since 2000, groundwater abstraction from the Thiaroye aquifer has declined drastically as nitrate concentrations in production boreholes rose. During the mid to late 1980s, nitrate concentrations of between 80 and 285 mg/L were observed (Collin and Salem 1989; SONEES 1989). By the turn of the twenty-first century, nitrate concentrations in the Thiaroye aquifer of up to 500 mg/L were recorded (Cissé Faye et al. 2004; Mandioune et al. 2011) and traced to faecal sources using stable isotopes ratios of O and N in nitrate (Re et al. 2010; Diedhiou et al. 2012). The substantial reduction in urban groundwater abstraction since the millennium has led to rising groundwater levels which outcrop as seasonal lakes and cause recurrent flooding in the suburban areas of Pikine, Guediawaye and Thiaroye (Fig. 1b).

Isotopic tracers such as the stable-isotope ratios of oxygen ($^{18}O/^{16}O$) and hydrogen ($^{2}H/^{1}H$) as well as radioactive tritium (^{3}H) can constrain both the origins of groundwater recharge and residence time of groundwater (Clark and Fritz 1997). Stable-isotope ratios of O and H in groundwater are considered to be transported conservatively in shallow aquifers where the evaporation and water–rock interactions are limited (Gat 1996). Consequently, comparisons between isotopic signatures in rainwater and groundwater can be used to trace sources of rain-fed recharge (e.g. Kumar et al. 2011; Parisi et al. 2011; Jasechko and Taylor 2015; Karami et al. 2016). Tritium with a half-life of 12.3 years can be used roughly to constrain whether groundwater derives primarily from precipitation that fell before the "bomb pulse" of the early 1960s resulting from thermonuclear atmospheric testing (i.e. pre-modern) or after the bomb pulse (i.e. modern).

This study seeks to improve an overall understanding of rain-fed (natural) groundwater recharge and flow regimes in the now highly contaminated Thiaroye aquifer of Dakar in order to better understand the attenuation capacity of this urban aquifer. Specifically, the study applies isotopic tracers to: (1) identify the origin and sources of the shallow groundwater; and (2) trace groundwater flow regimes (i.e. recharge and discharge). In addition, recently collated piezometric data from the Thiaroye aquifer are used to support analyses and interpretations derived from isotopic tracers and quantify recharge.

Study area

The study area is located on the Cap Vert peninsula east of central Dakar between the extreme westward side of the peninsula that is characterized by the uplift of Quaternary sedimentary deposits (105 m) and the Thies plateau (127 m) towards the east (Fig. 1a). This low-lying area features Quaternary sand dunes trending in a SW–NE direction and *niayes*, interdunal depressions that are currently dominated by agricultural activities (Fig. 1b). Lakes occur along the northward coast and most of them are seasonally dry except for the hypersaline Retba Lake. Urban mapping from aerial photography (1942, 1966, 1978) and satellite images (1972, 1986, 1995, 2006, 2009, 2010) shows that urbanisation occurred after the Sahelian drought that started in the 1970s, which was characterised by rapid growth in informal settlements and substantial reductions in natural or cultivated vegetative land cover (Sow 2009). The peninsular climate of Cap Vert is semi-arid with low mean annual precipitation ranging between 450 and 500 mm, which occurs exclusively during rainy season between July and October; mean daily temperatures range between 21 and 29 °C and high evapotranspiration ranges from 1,800 to 2,100 mm/year.

The Thiaroye aquifer is part of the Senegalese sedimentary basin and covers an area of about 300 km^2 from Dakar to Kayar in the Senegal northeastern coastal zone. Unconsolidated Quaternary sands overlie Eocene-aged marl and clay formations which outcrop in the south. Quaternary deposits consist largely of clayey sands, coarse sands and aeolian sands from the Ogolian dunes edified during the last glacial period (Hebrard 1966). The thickness of the sediments varies from 5 m in the southeastern edge to 75 m towards the north-west strongly related to the morphology of the marl basement. Hydraulic conductivity (K) of the unconfined Thiaroye aquifer ranges from 10^{-3} and 10^{-5} m/s (OMS 1972; Cissé Faye et al. 2001) and specific yield is estimated to be approximately 20% from pumping tests and laboratory column tests (Martin 1970; Diedhiou et al. 2012). Aquifer transmissivity varies between 10^{-1} and 10^{-3} m^2/s (OMS 1972).

Sampling and analytical procedure

Rainwater and groundwater sampling and monitoring

Monthly rainwater samples were collected between June and October 2008 at eight meteorological stations (Fig. 1). Aliquot fractions of daily rainfall samples from 30/06 to 31/08/2008 (sample 1) and from 01/09 to 21/10/2008 (sample 2) were analysed for both stable isotope ratios of O and H and ^{3}H (details in the subsequent text). In all, 39 groundwater samples were collected between March 2007 and October 2008 from

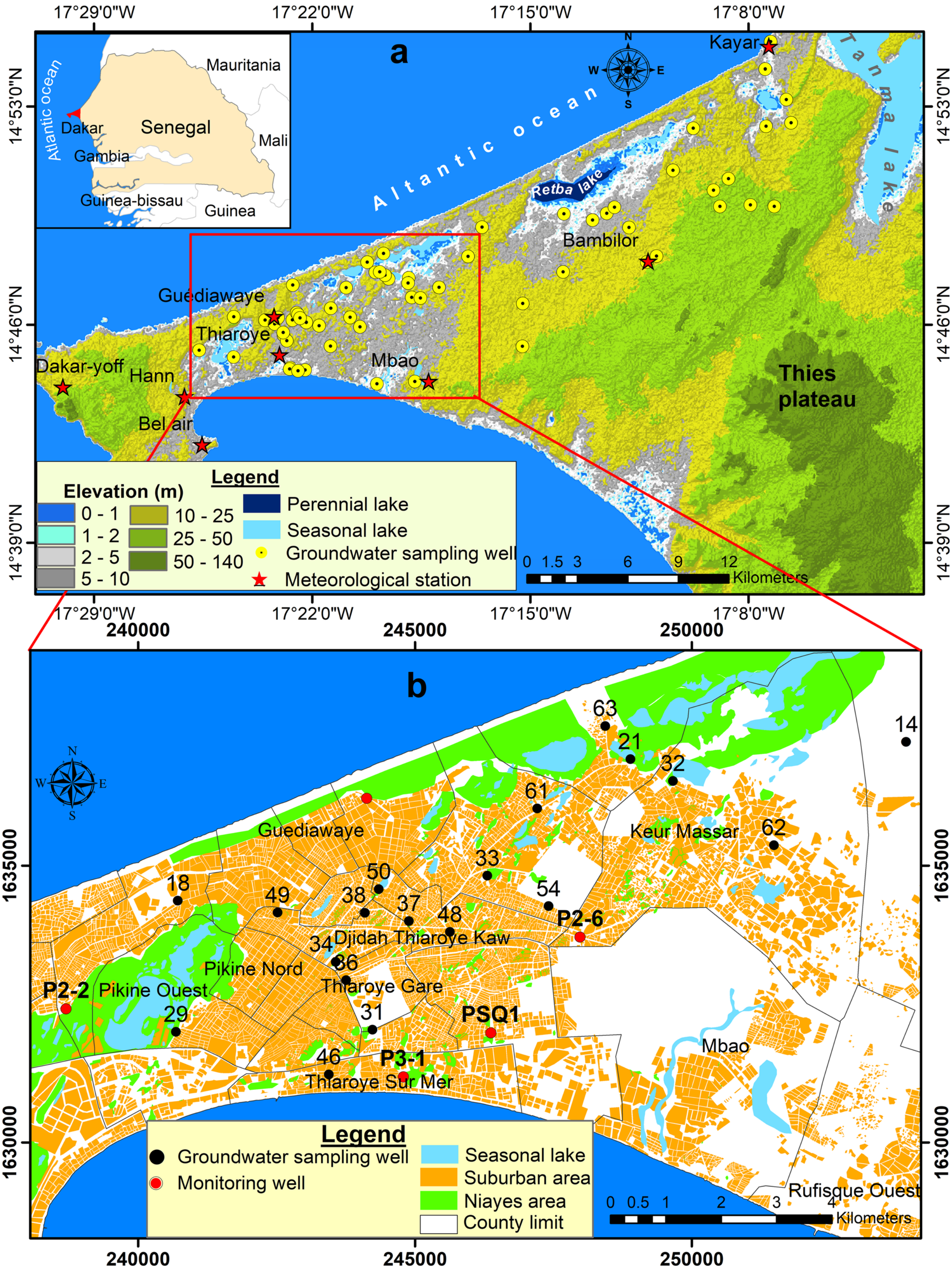

Fig. 1 Maps of **a** the city of Dakar on the Cap Vert peninsula and **b** Thiaroye suburb showing the locations of "niayes" (interdunal depressions colored green) and employed monitoring networks and meteorological stations

Table 1 Stable-isotope ratios of O and H and rainfall depth from eight meteorological stations in the Thiaroye aquifer in 2008

Station	ID	Month	Precipitation (mm)	δ^{18}O [‰]	δ^{2}H [‰]	^{3}H [TU]
Dakar-Yoff	DKYSI	June	10.5	−4.34	−25.6	2.1
		July	42.6			
		August	149.6			
	DKYS2	September	220.8	−7.33	−48.5	2.4
		October	6.4			
Dakar-Hann	DKHS1	July	45.5	−5.37	−33.4	2.4
		August	113			
	DKHS2	September	115.5	−6.89	−44.5	2.8
		October	13.5			
Bel–Air	BELS1	July	65.4	−4.58	−27.1	2.4
		August	134.6			
	BELS2	September	106.7	−6.24	−39.8	1.9
		October	7.8			
Thiaroye	THARS1	July	278	−4.75	−30.5	2.0
		August	154			
	THARS2	September	143.0	−5.76	−36.5	1.9
		October	10.0			
Guediawaye	GUEDS1	August	78.5	−4.49	−27.6	2.6
	GUEDS2	September	166.5	−6.50	−43.9	2.5
Mbao	MBAOS1	July	76.2	−4.81	−28.8	2.0
		August	175.6			
	MBAOS2	September	30.6	−6.39	−40.9	1.5
Bambilor	BAMBS1	July	65.9	−3.93	−25.4	2.2
		August	147.3			
	BAMBS2	September	18.0	−7.08	−47.3	2.7
		October	6.0			
Kayar	KAYS1	July	58.0	−4.84	−30.8	2.0
		August	160.0			
	KAYS2	September	109.0	−7.62	−51.4	2.3

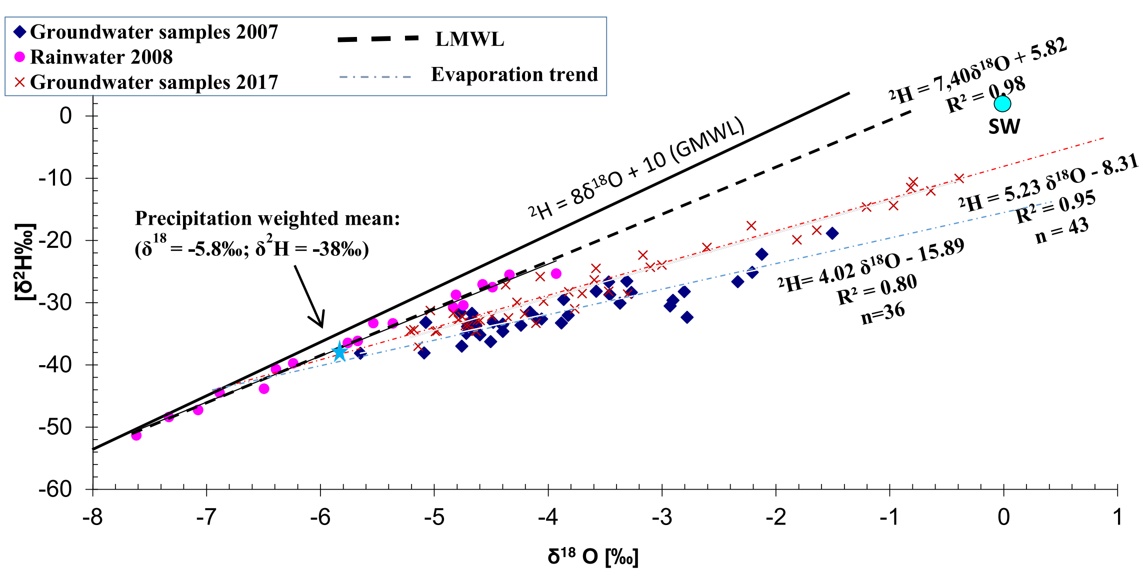

Fig. 2 δ^{2}H vs. δ^{18}O values of groundwater collected in 2007 and 2017 and rainwater compared to the Global Meteoric Water Line (GMWL; Craig 1961)

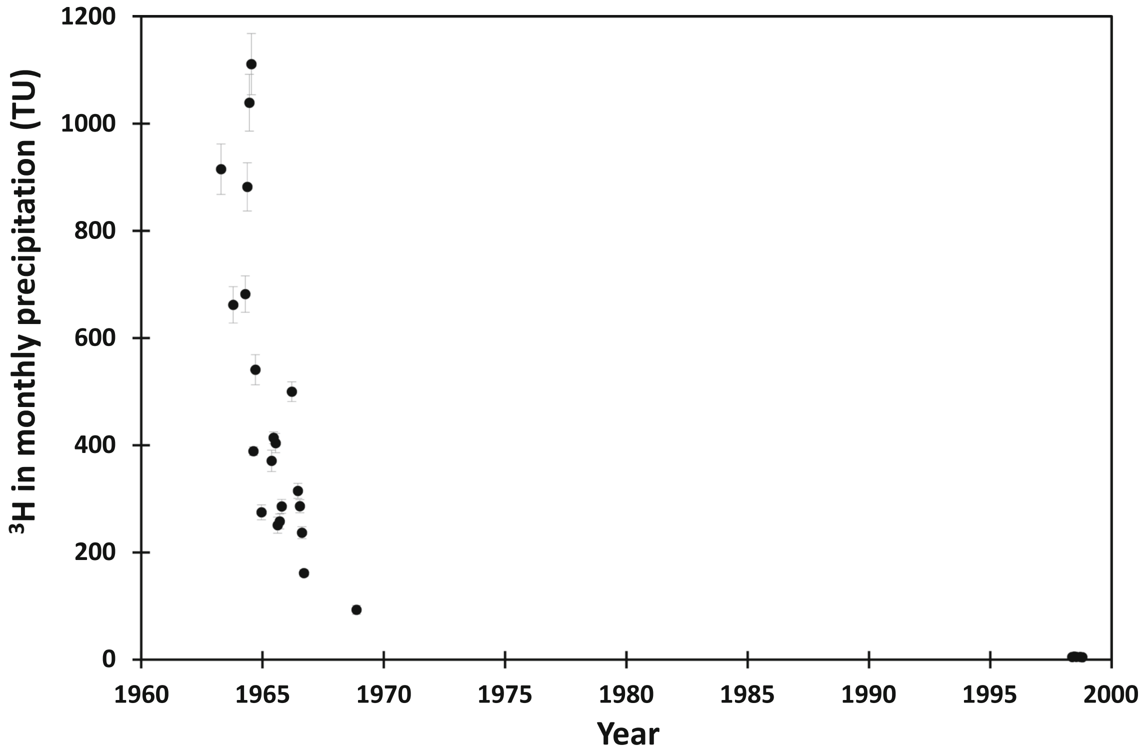

Fig. 3 Tritium activity in monthly precipitation at the IAEA monitoring station in Bamako, Mali, from 1963 to 1999 (IAEA GNIP); error bars represent analytical uncertainty

piezometers, hand-pumped wells, and production boreholes (Fig. 1). A total of 43 groundwater was also collected from many of the same locations during September 2017. All samples from piezometers and hand-pumped wells were collected after purging with submersible pump until consistent readings of pH and electrical conductivity (EC) were obtained. In continuously pumped production boreholes, this latter procedure was not necessary. Other in situ measurements such as temperature (T°) and alkalinity were also made at the wellhead. Samples were filtered (0.45-μm membrane) and analysed for $\delta^{18}O$, δ^2H and ^3H. Groundwater-level monitoring data were compiled from both low-frequency observations, collected using a dipper at two piezometers, P2-5 (1987–1991) and P2-3 (1998 to 2002), and high-frequency observations at two sites in 2010–2011 and three sites in 2017–2018—see electronic supplementary material (ESM).

Chemical and isotopic measurements

Stable-isotope ratios of O and H in samples collected between 2007 and 2008 were analysed at the Institute of Groundwater Ecology (IGE) and Helmholtz Center (Germany), respectively, using the standard CO_2 equilibration according to Epstein and Mayeda protocol (Epstein and Mayeda 1953) and zinc reduction techniques (Coleman et al. 1982). Groundwater samples collected in 2017 were analysed by a commercial laboratory, Elemtex Limited (UK). $\delta^{18}O$ and δ^2H compositions are reported in the conventional ‰ notation referenced to the V-SMOW. The analytical reproducibility is ±0.1‰ for the oxygen and ± 1.0 ‰ for deuterium. Tritium analyses were performed by electrolytic enrichment and analyzed with a liquid scintillation counting method and results are reported as tritium units (TU) with an analytical error of ±0.7 TU. Dating of groundwater by decay of tritium is based on the assumption that the tritium input to the recharging water is known and that the residual ^3H measured in groundwater is the result of radioactive decay alone.

Results

Isotopic composition of meteoric waters

Time-series records of the isotopic composition of rainfall in both Dakar and Senegal are limited and are derived from two sampling campaigns in 1981 and 2008. During the 2008 monsoon, 14 monthly values of the stable isotope ratios of O and H in rainfall derive from sampling twice (primarily July, September) at eight locations in the Thiaroye area of Dakar (Table 1). These data regress ($R^2 = 0.99$) along a local meteoric waterline (LMWL), $\delta^2H = 7.4 \cdot \delta^{18}O + 5.6$, that reflects the impacts of evaporative enrichment (e.g. lower slope) relative to a previously computed LMWL by Travi et al. (1987), $\delta^2H = 7.9 \cdot \delta^{18}O + 10$ ($R^2 = 0.97$), based on a set of seven monthly samples collected from rainfall stations across

Table 2 Chemical and isotopic composition of sampled groundwaters from the Thiaroye aquifer between March 2007 and October 2008

Well No.	Well ID	Well type	Site	Depth [m]	T [°C]	pH	EC [μS/cm]	δ^{18}O [‰]	δ^{2}H[‰]	^{3}H [TU]
1	P02	DW	Déni B. Ndao	8.49	26.1	5.82	2,530	−3.31	−26.6	2.5
2	P109	DW	Santhiane	12.27	25.9	7.1	108	−4.51	−36.3	2.4
3	P128	DW	Wayambame	9.20	27.6	6.9	720	−5.09	−38.1	4.8
4	P202	DW	Kounoun	5.75	24.4	6.62	4,770	−3.27	−28.4	2.1
5	P209	DW	Bayakh	14.56	24.8	7.04	665	−4.64	−34.6	<0.8
6	P210	DW	Dar. B. Sylla	8.71	26.6	5,73	238	−4.16	−31.6	4.3
7	P215	DW	Golam	7	25,6	6.52	739	−4.64	−34.6	5.1
8	P232	DW	Kaniack	6.86	26.8	6.20	305	−4.49	−33.2	2.5
9	P234	DW	Kayar	1.51	26.7	7.40	2,000	−3.47	−26.7	3.5
10	P213	DW	K. Ab. Ndoye	4.36	28	5.90	3,169	−4.77	−31.6	–
11	P221	DW	Diender	10.72	27.3	6.79	826	−3.89	−33.5	–
12	P235	DW	Bambilor	5.07	24.5	7.29	3,180	−3.87	−29.5	2.1
13	P2–10	PZ	Gouy Guewel	8.77	28.9	6.90	1,993	−4,4	−33.5	1.1
14	P2–7	PZ	Tivao. Peulh	7.58	27.8	7.87	584	−3,58	−28.2	2.4
15	P2–9	PZ	Niaga Peulh	4.40	23.8	7.95	556	−2.21	−25.2	2.1
16	P2–5	PZ	Corn. Guedia	4.55	30.6	7.42	1,465	−1.51	−18,9	2.3
17	P2–6	PZ	Boune	3.27	26	6.46	1,497	−5.08	−33.2	2.1
18	P2–3	PZ	Crois. Bethio	13.59	29	8.21	690	−4.76	−37	3.5
19	P2–2	PZ	Cambérène	5.58	30.2	6.90	1,784	−4.35	−37	2.5
20	P2–8	PZ	Tivao. Peulh	5.59	26.1	7.90	649	−4.40	−34.7	<1.2
21	P3–4	PZ	Malika	0.76	27.7	9.92	198	−5.65	−38.2	–
22	P19	DW	Warouwaye	3.71	27.8	5.46	738	−4.67	−31.8	–
23	PS4	PZ	S. Mame Gor	6.97	24.2	5.56	608	−2.34	−26.7	2.3
24	PS5	PZ	Mbawane	4.96	24.2	7.97	418	−3.37	−30.1	2.0
25	PS6	PZ	S. Mame Gor	4.12	25.4	6.30	236	−2.91	−29.7	3.8
26	PS7	PZ	Kayar	1,69	31	7.55	607	−2.93	−30.6	5
27	PS10	PZ	Gouy Guewel	4.82	24.6	6.02	363	−2.78	−32.4	5.3
28	PS11	PZ	Gorom I	5.26	25.4	5.13	861	−2.81	−28.3	3.1
29	P1(Techno)	PZ	Technopole	1.31	22.9	6.80	1,772	−2.13	−22.3	1.5
30	P3–1	PZ	Thiaroyes/mer	2.22	26.4	6.62	1,060	−4.67	−32.8	1.3
31	P3–2	PZ	C. M. Thiar	1.2	24.7	6.31	1,797	−3.46	−28.8	3.0
32	Pts 58	DW	Mbeubeuss	3.70	25.9	5.2	1,766	−4.24	−33.7	2.3
33	P21	PZ	Yeumbeul	3.98	28	3.89	2,890	−4.10	32.6	2.2
34	Pz 4	PZ	Pikine	0.87	24.7	6.03	2,850	−4.06	−32.7	3.0
35	Pts 58 bis	DW	Mbeubeuss	9.73	26.8	5.52	556	−3.89	−33.3	2.9
36	F17	BH	Thiaroye	0.57	29.6	4.88	1,687	−4.64	−33.8	2.6
37	F19	BH	Thiaroye	5.34	28.6	4.83	2,100	−4.71	−33.9	2.1
38	F22	BH	Thiaroye	0.21	29.1	5.12	1,956	−4.72	−35.0	2.2
39	P120	DW	Wayabam	7.31	27	6.2	634	−4.41	−33.7	2.8
40	PS1	PZ	Sangalkam	7.35	26.2	6.7	141	−3.83	−32.1	4.1

DW dug well, *PZ* piezometer, *BH* borehole, *EC* electrical conductivity, δ^{18}O and δ^{2}H are with respect to Vienna Standard Mean Ocean Water (VSMOW)

Senegal (i.e. Mbour, Diafilon, Tambacounda, Richard-Toll) in July and August during the 1981 monsoon; the latter dataset is consistent with the Global Meteoric Water Line (GMWL; Fig. 2). Curiously, δ^{2}H and δ^{18}O values in sampled rainfalls from the Cap-Vert peninsula in September 2008 consistently show greater depletion in the heavy isotope of O and H, −2 and −15‰, respectively, relative to rainfalls sampled in July and August; such differences during the monsoon are not evident in the national-scale dataset of Travi et al. (1987). In the data from 2008, a relationship between rainfall amount and depletion in the heavy isotope of O or H, known as the "amount effect", is not evident.

Table 3 Chemical and isotopic composition of sampled groundwaters from the Thiaroye aquifer in September 2017

Well No.	Well ID	Well type	Site	Depth [m]	T [°C]	pH	EC [μS/cm	$\delta^{18}O$ [‰]	$\delta^{2}H$ [‰]
1	P02	DW	Déni B. Ndao	4.74	28.6	8.0	2,660	−3.60	−26.4
2	P109	DW	Santhiane	6.95	28.0	8.4	690	−4.64	−34.6
3	P128	DW	Wayambame	9.97	28.9	8.2	690	−5.21	−37.0
4	P202	DW	Kounoun	1.60	31.0	6.6	2,130	−3.70	−28.6
5	P209	DW	Bayakh	14.81	30.1	8.0	830	−4.79	−32.7
6	P210	DW	Dar. B. Sylla	9.21	29.6	8.0	448	−3.77	−31.0
7b	P215bis	DW	Golam	6.08	32.0	8.4	321	−4.63	−34.6
8	P232	DW	Kaniack	6.86	24.5	6.6	1,112	−4.35	−32.5
9b	P234bis	DW	Kayar	1.65	29.2	8.6	1,980	−4.38	−27.2
13	P2–10	PZ	Gouy Guewel	9.55	29.2	8.5	1,670	−5.21	−34.6
15	P2–9	PZ	Niaga Peulh	4.98	29.6	8.9	1,460	−4.50	−32.2
17	P2–6	PZ	Boune	2.25	29	8.0	3,850	−3.82	−28.3
23	PS4	PZ	S. Mame Gor	3.90	32.9	6.7	1,260	−4.73	−33.7
24	PS5	PZ	Mbawane	1.92	29.8	8.6	409	−4.60	−32.9
27	PS10	PZ	Gouy Guewel	4.20	29.7	8.3	664	−4.70	−33.7
28	PS11	PZ	Gorom I	4.30	29.4	5.2	230	−5.18	−34.4
30	P3–1	PZ	Thiaroyes/mer	1.32	28.1	8.7	2,290	−0.63	−12.1
32	Pts 58	DW	Mbeubeuss	3.50	28.3	7.2	2,540	−4.28	−29.9
35	Pts 58 bis	DW	Mbeubeuss	3.70	29.0	8.0	1,440	−2.61	−21.2
37	F19	BH	Thiaroye	1.40	29.0	7.5	2,430	−4.83	−31.7
38	F22	BH	Thiaroye	1.50	28.6	7.0	2,680	−4.11	−33.3
39	P120	DW	Wayambame	8.20	28.6	8.0	1,820	−4.99	−34.6
40	PS1	PZ	Sangalkam	4.50	29.3	8.4	1,540	−4.98	−34.6
48	F21	BH	Thiaroye	2.46	29.6	6.7	2,700	−4.62	−32.8
49	F30	BH	Thiaroye	1.94	30.0	8.6	1,130	−2.22	−17.6
50	F31	BH	Thiaroye	2.04	30.6	8.3	2,660	−4.07	−25.9
51	PTS/PD5	DW	K. Massar	3.90	28.7	8.1	2,010	−3.30	−28.6
52	PTS3	DW	K. Massar	1.10	28.7	8.5	2,280	−3.47	−28.2
53	PTS4	DW	K. Massar	1.80	27.8	8.7	1,560	−4.21	−31.8
54	PTS9	DW	Yeumbeul N.	3.80	29.0	7.7	2,020	−3.10	−24.3
55	PD1	MP	M. Gounass	–	31.5	8.4	970	−5.04	−31.3
56	PD2	MP	M. Gounass	–	30.0	7.9	2,720	−3.58	−24.5
57	PD3	MP	Yeumbeul S.	–	29.4	8.1	2,570	−3.18	−22.4
58	PTS14	DW	Yeumbeul S.	3.00	30.3	7.9	2,080	−4.04	−29.8
59	PTS2	DW	Djiddah T. K.	1.40	29.6	8.3	3,090	−3.00	−24.0
60	PTS01	DW	Tivaouane P.	6.20	29.2	9.1	660	−4.76	−32.2
62	PTS8	DW	Yeumbeul N.	2.60	29.6	8.8	3,260	−1.64	−18.4
63	PTS5	DW	Keur Massar	4.80	28.1	7.8	2,040	−1.20	−14.6
64	PD6	MP	Malika	–	30.1	7.8	1,780	−0.39	−10.1
65	PTS10	DW	Sicab Mbao	0.80	27.7	8.6	3,140	−0.82	−11.5
66	PTS12	DW	Sicab Mbao	−1.30	30.2	8.5	2,280	−0.97	−14.4
67	PTS15	DW	Mbao	0.50	30.6	9.7	2,530	−0.79	−10.6
68	PTS16	DW	Mbao	1.10	30.0	8.8	1,061	−1.82	−19.9

DW dug well, *PZ* piezometer, *BH* borehole, *EC* electrical conductivity, $\delta^{18}O$ and $\delta^{2}H$ are with respect to VSMOW

Tritium in rainfall sampled during the 2008 monsoon in Dakar ranges from 1.5 to 2.8 TU (Table 1) with a weighted-mean average composition of 2.3 TU. In the absence of long-term monitoring of tritium in rainfall in Dakar, approximation of

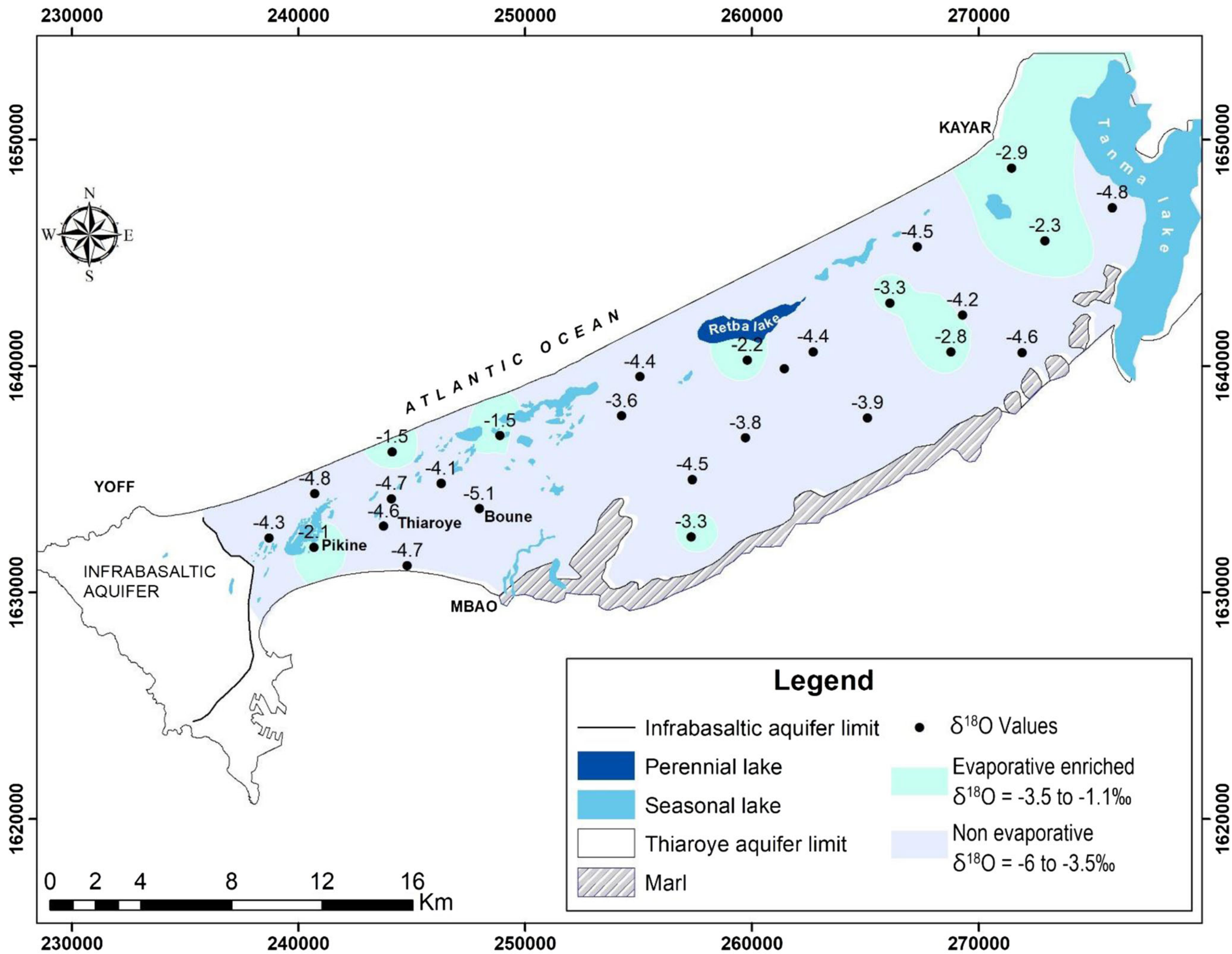

Fig. 4 Map of contoured values of $\delta^{18}O$ by krigging in groundwater from wells in the Thiaroye aquifer sampled in 2007 and 2008

the input signal since the bomb pulse in the early 1960s can be done using the most proximate station (Aranyossy and Gaye 1992), which for Dakar is Bamako (Mali). These long-term records of tritium activity in precipitation, compiled by the IAEA GNIP, from April 1963 to October 1998 are plotted in Fig. 3. Rough residence-time categories for rain-fed recharge can be identified by (1) considering the radioactive decay of tritium (i.e. half-life of 12.3 years) in precipitation that generated groundwater recharge over this input function from 1963 to 1998, (2) local observations from rainfall in Dakar in 2008 (Table 1), and (3) the 2008 sampling date for tritium values in groundwater. Groundwater that derives from predominantly "modern", post-bomb pulse rainfall would be expected to feature tritium activities of ≥2 TU. Assuming the pre-bomb pulse tritium content of precipitation in West Africa did not exceed 5 TU, groundwaters that derive predominantly from "pre-modern" (i.e. prior to the bomb pulse) rainfall, would be expected to have a tritium activity of <0.8 TU. Finally, more balanced mixtures of "modern" and "pre-modern" rainfall would be expected to have a tritium activity of between 0.8 and 2 TU.

Isotopic composition of groundwaters

$\delta^{18}O$ and $\delta^{2}H$ values in sampled groundwater from the Thiaroye aquifer exhibit wide range of values that span >4 and >19‰, respectively, in datasets during two sampling periods in Table 2 ($\delta^{18}O$: −1.5 to −5.7‰; $\delta^{2}H$: −19 to −38‰; $n = 39$) and Table 3 ($\delta^{18}O$: −0.4 to −5.2‰; $\delta^{2}H$: −10 to −37‰; $n = 43$). Linear regression of both datasets generates slopes (3.9 ± 0.4, 5.2 ± 0.2) that are consistent with enrichment in the heavy isotope of O and H through evaporation ($\delta^{2}H = 3.9 \cdot \delta^{18}O - 16$, $R^2 = 0.77$; $\delta^{2}H = 5.2 \cdot \delta^{18}O - 8.3$, $R^2 = 0.95$). Both curves regress to the same isotopic composition on the LMWL ($\delta^{18}O$: −6.3; $\delta^{2}H$: −47‰), which is depleted relative to the weighted mean average composition of rainfall estimated from the limited dataset summarised in Table 1 ($\delta^{18}O$: −5.8; $\delta^{2}H$: −38‰). Neither curve connects with

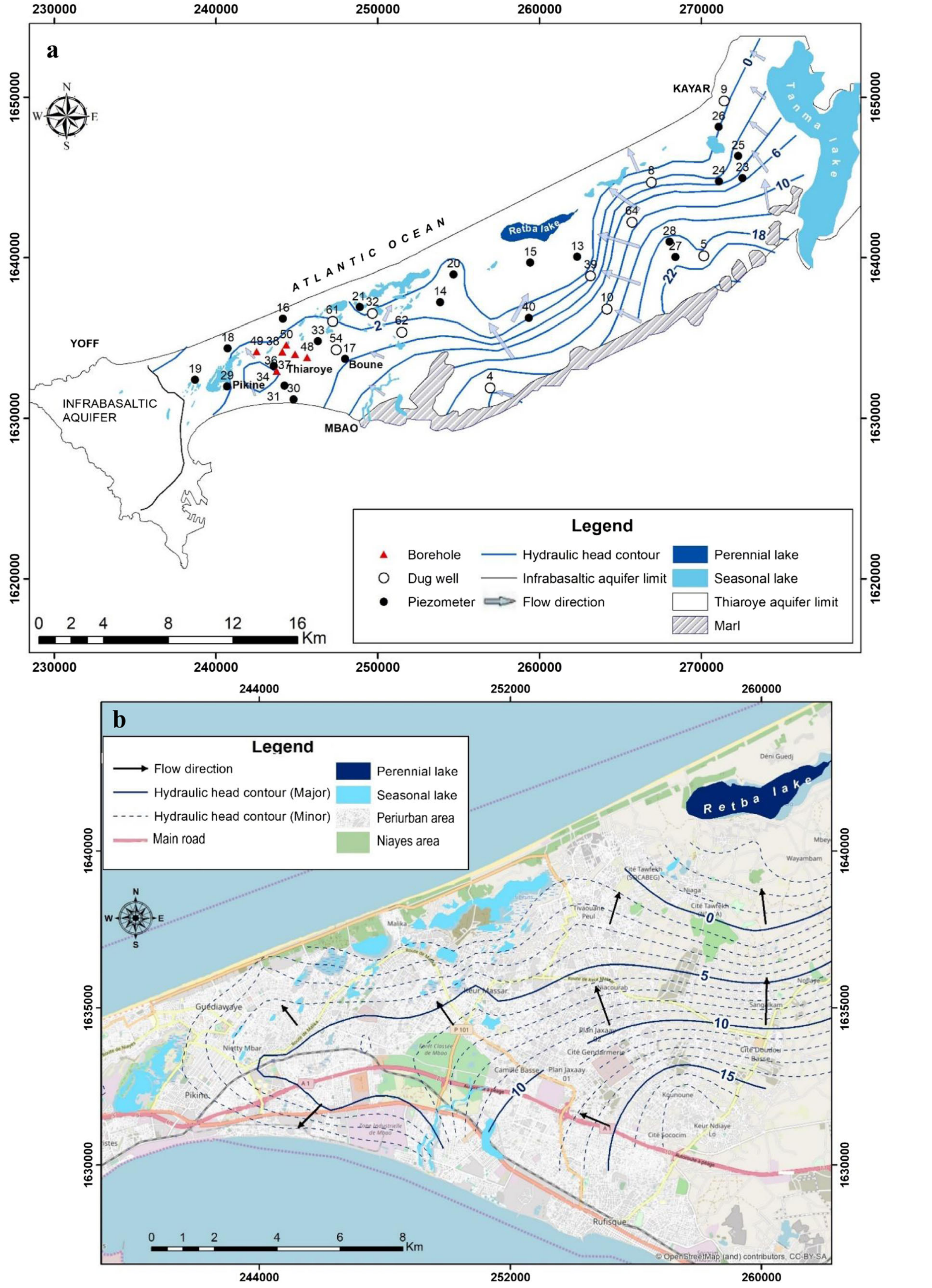

Fig. 5 Maps of hydraulic-head contours by kriging and expected flowpaths in the Thiaroye aquifer of Dakar in **a** March 2007 and **b** September 2017

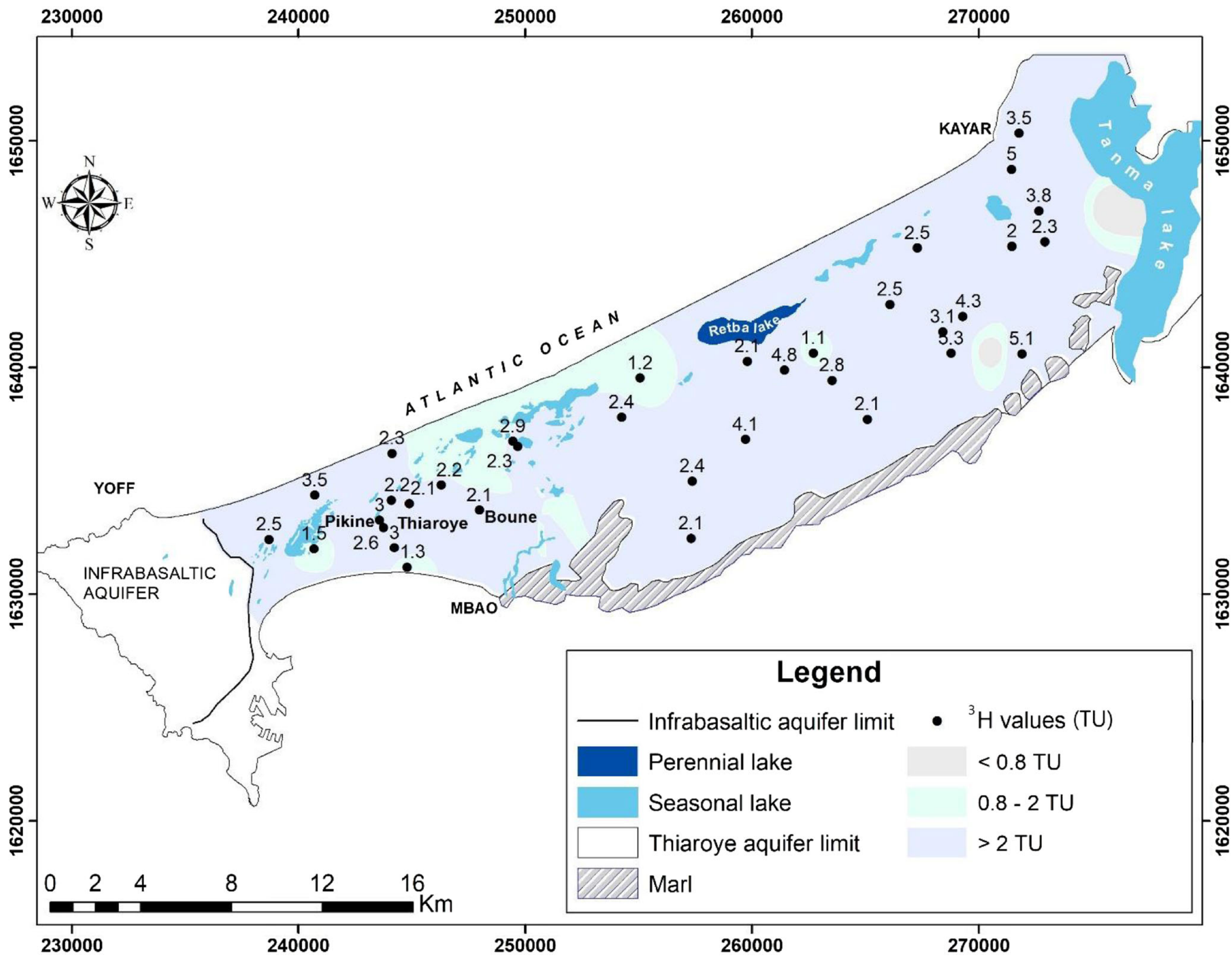

Fig. 6 Mapped of contoured tritium (^{3}H) activities (TU) by kriging in sampled wells from the Thiaroye aquifer in 2007 and 2008

seawater ($\delta^{18}O = 0‰$, $\delta^2H = 0‰$) as a potential end member (Fig. 2).

The spatial distribution of stable isotope ratios of O in groundwater (Fig. 4) shows that signatures more enriched in the heavy isotope (^{18}O) occur proximate to ephemeral (seasonal) and perennial surface waters and wetlands (niayes) that represent groundwater discharge zones along the northern coast of the peninsula. Contours of hydraulic head from datasets amassed in 2007 and 2017 (Fig. 5) generate flowlines that are consistent with the general flow of groundwater from south to north towards the seasonal lakes and wetlands as well as the perennial saline Retba Lake. Tritium activity in groundwater (Fig. 6) shows a much less uniform distribution with pockets of predominantly modern groundwaters with higher tritium activities (≥3.5 TU) found within areas of high hydraulic head (Fig. 5). Predominantly pre-modern groundwater or mixtures of groundwater derived from modern and pre-modern rainfall are observed adjacent to seasonal and perennial surface waters.

Observed hydrological responses to monsoonal rainfall

Daily and hourly observations of groundwater levels in the Thiaroye aquifer exist for several monitoring wells (e.g. see P3-1, PSQ1, P2-6, P2-5 and P2-2 in ESM) but are of limited duration (i.e. 2010–2011, 2017–2018). Longer time-series observations, albeit of lower frequency, exist for a small number of piezometers (Fig. 7). In all hydrographs, pronounced seasonality is evident with sharp rises during the rainy season and recessions during the subsequent dry season. Application of a simple water-table fluctuation (WTF) model (e.g. Healy and Cook 2002; Cuthbert 2010) in which recharge is computed as a scalar of rainfall with a variable time lag and discharge is estimated from dry-season recessions, is able to represent well (i.e. Nash-Sutcliffe Efficiencies range from 0.60 to 0.62) piezometric observations over a 5-year period for the two sites (P2-5, P2-3) in Fig. 7. Monsoonal (seasonal) recharge estimated from the WTF method and by applying a S_y of 0.20 for the

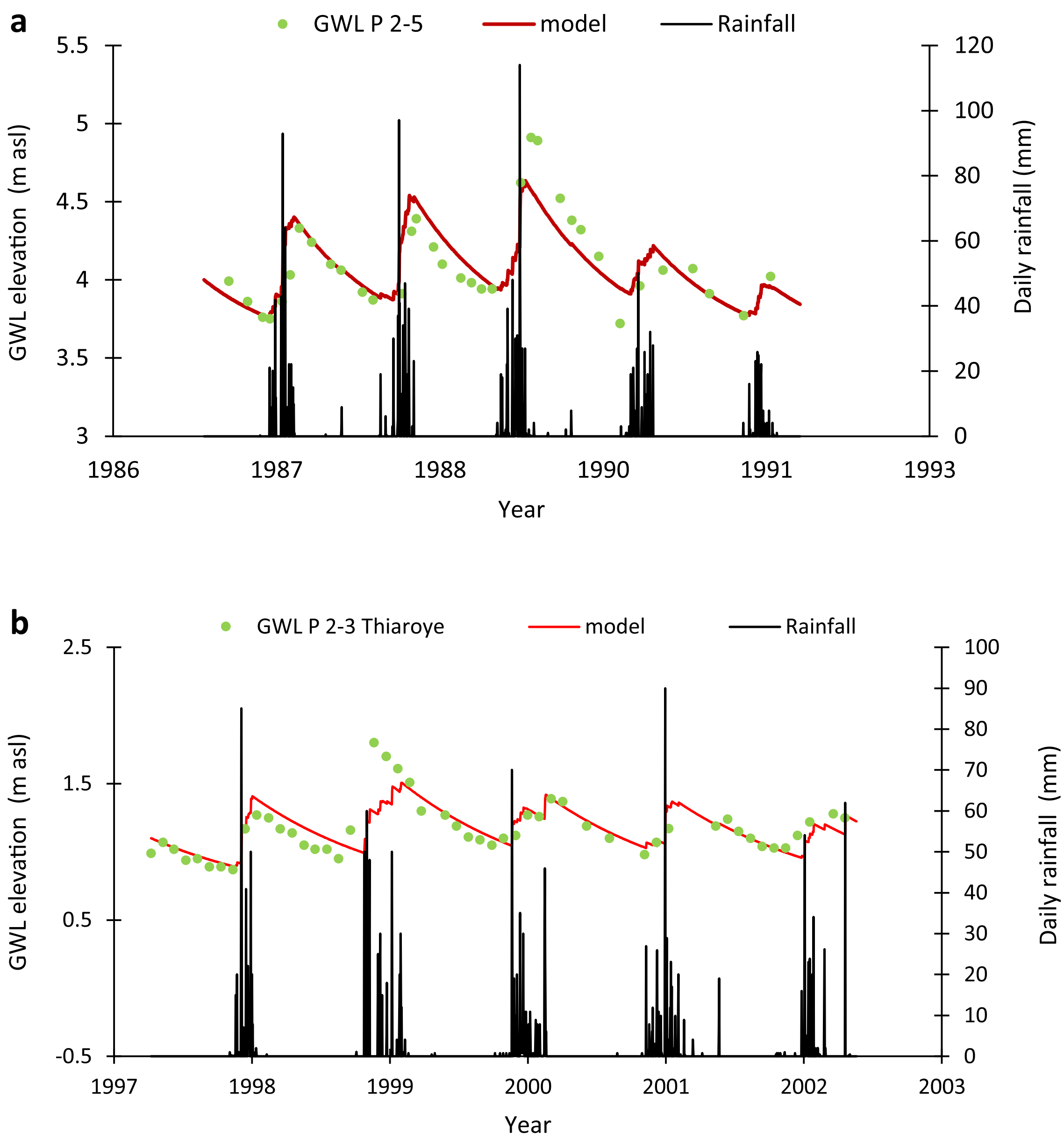

Fig. 7 Daily rainfall, observed (green dots) and simulated (red line) groundwater levels (GWL) at piezometers: **a** P2-5 (RMSE = 0.18 m, NSE = 0.6) from 1987 to 1991, and **b** P2.3 (RMSE = 0.12 m, NSE = 0.62) from 1998 to 2002

shallow unconsolidated sands of the Thiaroye aquifer, varies from 44 to 251 mm (1987–1991) and 100 to 171 mm (1998–2002).

Discussion

Tracing the origin of rainfall generating groundwater recharge

Shallow groundwaters sampled from the Thiaroye aquifer over two periods in 2007 and 2017 derive predominantly from modern rainfall (i.e. post-1963 bomb pulse) with tritium values exceeding 2 TU in 85% of sampled wells. Stable-isotope signatures in groundwater regress to a value on the LMWL that is depleted in heavy isotopes ($\delta^{18}O$: −6.3; $\delta^{2}H$: −47‰), relative to the weighted mean average composition of local rainfall ($\delta^{18}O$: −5.8; $\delta^{2}H$: −38‰). Limited observations of stable isotope ratios in rainfall for Dakar (Table 1) do not show an "amount effect" (i.e. depletion in the heavy isotope as a function of rainfall amount) observed across the tropics (Jasechko and Taylor 2015) but reveal a bias in the timing of recharge to isotopically depleted rainfalls observed during the latter part of the monsoon (September).

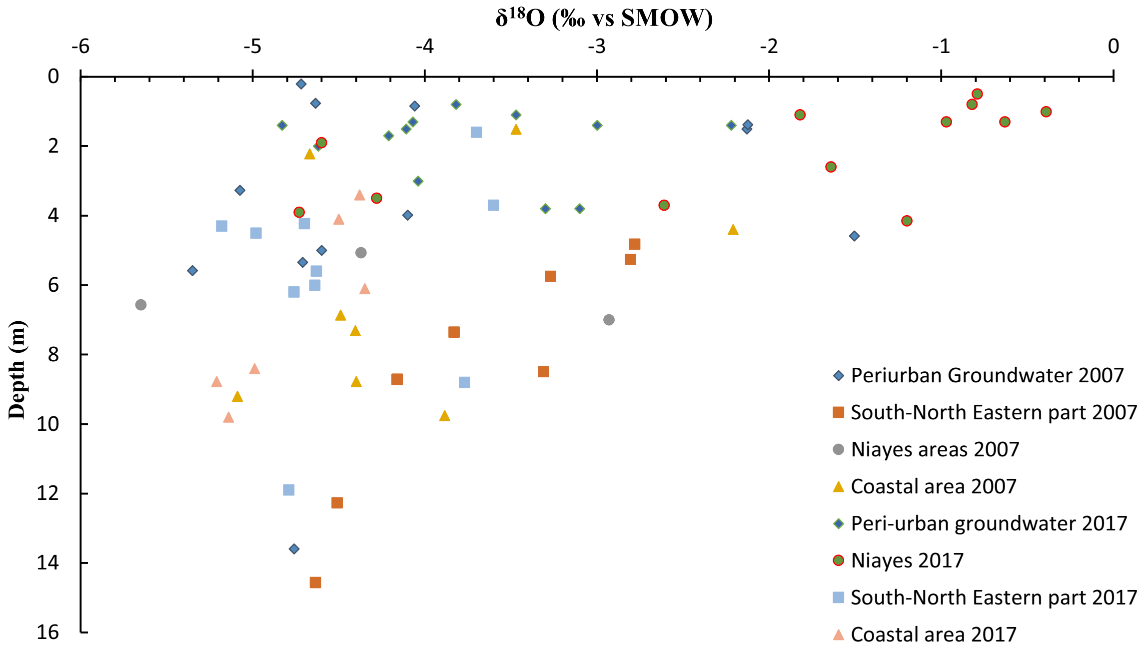

Fig. 8 Depth to water table in metres below surface versus $\delta^{18}O$ in shallow groundwaters from the Thiaroye aquifer in 2007 and 2017; greatest enrichment in ^{18}O is observed on shallow groundwaters in niayes (i.e. interdunal wetlands) proximate to seasonal lakes in the coastal groundwater discharge area of the Thiaroye aquifer

Tracing groundwater flow

$\delta^{18}O$ and $\delta^{2}H$ values in groundwater vary by over 4 and 20‰, respectively, reflecting substantial variability in evaporative enrichment commonly observed in the Sahel (Fontes et al. 1991). Whether this evaporative enrichment reflects surface ponding prior to recharge (i.e. focused recharge) or potentially direct evaporation from a shallow water table after diffuse recharge remains an open question. Piezometric observations of limited duration at multiple locations (Fig. 7; ESM) exhibit seasonal responses to rainfall during the monsoon that are consistent with diffuse recharge (Cissé Faye et al. 2001; Antea-Senagrosol 2003; PROGEP-ADM 2011). Further, groundwater flowpaths indicated by contours of hydraulic head from piezometric observations (Fig. 5) depict groundwater flow from recharge areas in the northeast and southwest to discharge areas featuring seasonal lakes and wetlands (niayes) along the northern shore of the Cap Vert peninsula (Fig. 8; Table 4). The conceptual model of groundwater flow is further supported by the observed distribution of tritium values in groundwater, whereby higher tritium activities (≥3.5 TU) coincide with zones of higher hydraulic head and discharge areas are characterised by lower tritium and hydraulic head values (Fig. 5).

Natural versus anthropogenic groundwater recharge

Superimposed on the processes of natural groundwater recharge and flow in Dakar characterised by isotopic tracers and piezometric data, is the loading of faecal effluent from the vast network of on-site sanitation facilities, primarily septic tanks that exist above the Thiaroye aquifer. Recent mapping of septic tanks in the Thiaroye area of Dakar reveals: (1) densities ranging from 1 to 70 tanks per hectare, and (2) strong correlations between

Table 4 Characteristics of the stable isotopic composition of groundwaters in the Thiaroye Aquifer

Equation	*n*	Data range (‰)		Mean composition (‰)		Spatial distribution
		Min ($\delta^{18}O$, $\delta^{2}H$)	Max ($\delta^{18}O$, $\delta^{2}H$)	$\delta^{18}O$	$\delta^{2}H$	
$\delta^{2}H = 4.85 \cdot \delta^{18}O - 10.65$	27	(−5.35, −37.2)	(−0.82, −11.50)	−3.86	−28.9	South-western part: peri-urban groundwater
$\delta^{2}H = 3.95 \cdot \delta^{18}O - 15.36$	14	(−5.21, −38.1)	(−2.21, −25.2)	−4.37	−32.6	Northern coastal zone
$\delta^{2}H = 2.82 \cdot \delta^{18}O - 20.37$	24	(−4.01, −33.7)	(−0.34, −10.10)	−2.88	−25.0	Niayes zones
$\delta^{2}H = 2.90 \cdot \delta^{18}O - 19.12$	19	(−5.18, −36.3)	(−2.78, −26.40)	−4.12	−31.8	South–north eastern part

septic tank density and nitrate concentrations. In contrast to the observed seasonality in natural groundwater recharge, anthropogenic recharge via effluent from on-site sanitation is perennial. The contributions of such loading may not be well recorded in piezometric observations as these rely upon temporal imbalances to trace recharge 'pulses', not effectively steady-state loading, to the subsurface (e.g. Healy and Cook 2002). By tracing the natural groundwater recharge and flow to the Thiaroye aquifer, this research informs improved conceptual and numerical models of the Thiaroye aquifer to evaluate its capacity to provide a freshwater supply while hosting a vast network of on-site sanitation systems.

Conclusion

A combination of environmental isotopic (^{18}O, ^{2}H, and ^{3}H) tracers shows that shallow groundwater of the unconfined Thiaroye aquifer in the rapidly growing conurbation of Dakar (Senegal) derives primarily from modern rainfall following the bomb pulse of atmospheric tritium that began in 1963. Shallow groundwater within this Quaternary sand aquifer is biased to isotopic compositions depleted in ^{18}O and ^{2}H relative to the weighted mean isotopic composition of observed rainfall. Limited, local evidence from the Cap Vert peninsula of Dakar on which the Thiaroye aquifer is situated, suggests that rain-fed recharge occurs preferentially during the latter part of the monsoon when soil-moisture deficits are expected to be lower. Further data are required to confirm whether the observed bias to rainfall depleted in the heavy isotope reflects the timing of monsoonal rainfall or its intensity arising from the "amount effect", a characteristic of rainfall observed across the tropics. The distribution of observed tritium in groundwater is consistent with groundwater flowpaths to seasonal lakes and wetlands (niayes), defined by piezometric records. Piezometric data further confirm the diffuse nature and seasonality of rain-fed recharge. The conceptual understanding of groundwater recharge and groundwater flow derived from this analysis provides a vital context to evaluate attenuation of anthropogenic recharge (effluent) that is effectively diffuse and constant from the vast network of on-site sanitation facilities that drain to this urban aquifer.

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