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Research Paper

On-site sanitation density and groundwater quality: evidence from remote sensing and *in situ* observations in the Thiaroye aquifer, Senegal

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ABSTRACT

In rapidly urbanising low-income towns and cities, there remains an absence of scientific evidence and regulatory structures to sustain the quality and quantity of groundwater used for low-cost water supplies and to reconcile this with continued use of the subsurface for low-cost sanitation. Here, we analyse the relationship between the density of on-site sanitation and shallow groundwater quality in the Thiaroye aquifer of Quaternary sands in Dakar, Senegal. On-site sanitation was mapped using object-oriented classification and visual interpretation of high-resolution, optical satellite images and ground-truthing surveys. Groundwater quality was assessed over a three-year period (2017–2019) from a network of 61 sources comprising boreholes, dug-wells, hand tubewells and piezometers. More than 253,000 on-site sanitation facilities are identified over an area of 520 km^2 with densities ranging from 1 to 70 per hectare. A moderate, statistically significant linear relationship ($r^2 = 0.55$, $p \ll 0.01$) is found between the density of on-site sanitation facilities and nitrate concentrations in sampled groundwater sources. Groundwater contamination beyond the WHO drinking-water guideline value (50 mg/L) occurs where densities of on-site sanitation facilities exceed 4 (±4) per hectare, a threshold commonly surpassed in peri-urban areas underlain by the Thiaroye aquifer of Dakar.

Key words | faecal contamination and remote sensing, groundwater quality, on-site sanitation density, urban and peri-urban area, water supply

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HIGHLIGHTS

- Here, we conduct the first city-scale analysis in sub-Saharan Africa of the relationship between the density of on-site sanitation (generally unimproved) and shallow groundwater quality.
- These provisional results have important implications not only for urban planning in areas dominated by the use of on-site water and sanitation facilities, but also for other dense settlements such as refugee and IDP (internally displaced peoples) camps.

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INTRODUCTION

Groundwater is a climate-resilient source of freshwater in sub-Saharan Africa (Cuthbert *et al.* 2019), playing a vital role in sustaining improved access to safe water in pursuit of United Nations Sustainable Development Goal 6 – water and sanitation for all by 2030. The strategic importance of groundwater in urban areas lies additionally in: (1) its lower vulnerability to contamination relative to surface waters reducing treatment costs, and (2) its capacity for phased investment (Adelana & MacDonald 2008; Foster *et al.* 2018; Olago 2019). The last two decades have witnessed substantial growth in the use of groundwater in towns and cities across sub-Saharan Africa, both alone (e.g. Dodoma, Tanzania) and in conjunction with surface water (e.g. Cape Town, South Africa; Dar es Salaam, Tanzania) (Taylor *et al.* 2004a; Lapworth *et al.* 2017; Gaye & Tindimugaya 2019; Olivier & Xu 2019). The distributed nature of groundwater enables individuals to construct private, on-site groundwater sources (e.g. boreholes, shallow wells, and protected springs). The proportion of urban dwellers in sub-Saharan Africa served by piped water supplies has declined over the last three decades (Tucker *et al.* 2014; Foster & Chilton 2017), whereas the proportion of on-site sources or self-supply has risen considerably (Healy *et al.* 2018).

Increased use of the urban groundwater commons in sub-Saharan Africa is constrained quantitatively by competitive abstraction (Diouf 2012) and qualitatively by seawater intrusion in coastal aquifers (e.g. Diouf 2012; Comte *et al.* 2016) and use of the shallow subsurface to contain faecal waste through on-site sanitation (Kulabako *et al.* 2007; Taylor *et al.* 2009; Kiptum & Ndambuki 2012; Okotto *et al.* 2015; Nayebare *et al.* 2020; Sorensen *et al.* 2020). For the latter, the risk to groundwater quality derives from faecal effluent, rich in organic nitrogen (urea: $CO\ (NH_2)_2$), chloride, and pathogenic microorganisms, that drains from on-site sanitation (e.g. pit latrines, septic tanks) into the surrounding soil. Mineralisation of this organic nitrogen (i.e. nitrification) then produces substantial concentrations of nitrate in the leachate (e.g. Harman *et al.* 1996; Buss *et al.* 2005). In most cities in sub-Saharan Africa, conventional sewerage serves only a small proportion of the urban population so that on-site sanitation is the dominant form of provision (Morella *et al.* 2008; UNICEF and WHO 2015). Conjunctive use of the subsurface to provide a source of safe water and repository of faecal effluent requires careful management, supported by effective policies and informed by science (Olago 2019).

Research to date has focused on protecting groundwater sources from faecal contamination in African towns and cities, and is dominated by local-scale analyses evaluating setback (safe) distances between 'source', on-site sanitation facility, and 'receptor', an individual groundwater-fed waterpoint (e.g. ARGOSS 2001; Howard *et al.* 2003; DEW POINT and DFID 2007; Mbaka *et al.* 2017). Such approaches are better suited to rural or low-density settlements where individual sources and receptors can be readily identified. Far fewer studies (e.g. Wright *et al.* 2012; Templeton *et al.* 2015) have examined the relationship between the density of on-site facilities from multiple locations and groundwater quality sampled from multiple receptors. Templeton *et al.* (2015) used a numerical model to estimate the impact of faecal effluent from pit latrines on nitrate concentrations in shallow groundwater that was informed by observations from three cities in West Africa including Abidjan (Ivory Coast), Abomey-Calavi (Benin), and Dakar (Senegal). Wright *et al.* (2012) conducted ground-based mapping of pit latrines and shallow wells over an area of $\sim 4\ \mathrm{km}^2$ in Kisumu (Kenya) and found the number of pit latrines within a radius of 100 m correlated significantly ($p = 0.004$) with nitrate concentrations sampled from shallow wells.

Here, we conduct the first city-scale analysis in sub-Saharan Africa of the relationship between the density of on-site sanitation (generally unimproved) and shallow groundwater quality within an unconsolidated Quaternary sand aquifer in the Thiaroye area of Dakar (Senegal). To map the density of on-site sanitation facilities over an area of $\sim 520\ \mathrm{km}^2$, we apply an object-oriented classification and visual interpretation of high-resolution, optical satellite imagery (i.e. Quickbird, Geoeye, Orbview), supported by extensive ground-truthing surveys. The density of on-site sanitation facilities (generally unimproved) is then compared to observed concentrations of faecal contamination from solutes (nitrate) and bacteria (*Escherichia coli*) sampled from 61 shallow ground-water sources over three years (2017–2019) to assess their association (dependency). Key intended outcomes of this city-scale analysis include an improved understanding of the capacity of this unconsolidated sand aquifer to attenuate faecal effluent from on-site sanitation facilities and guidance concerning the carrying capacity of the aquifer to provide safe water and store faecal waste.

MATERIALS AND METHODS

Study area

The study area lies within the Thiaroye shallow aquifer on the Cap Vert Peninsula (Figure 1) and extends from the head of the Dakar peninsula to Kayar Township (longitudes 17°25′ to 17°17′ W and latitudes 14°49′ to 14°43′ N). The peninsular climate of Cap Vert is semi-arid with a short rainy season, which lasts from June to October. Mean annual rainfall is 410 mm (1961–1990) but exhibits substantial inter-annual variability with a low of 373 mm in 1979 and a recently recorded high of 550 mm in 2019; recent monitoring records feature gaps. Mean daily temperatures range between 19 and 29 °C; potential evapotranspiration ranges from 1,800 to 2,100 mm/year. The Thiaroye aquifer comprises unconsolidated Quaternary sands with intercalations of sandy clay in places. Its thickness varies between 5 m (southeast) to 40 m (west) and 75 m (northwest). Hydraulic conductivity (K) of the unconfined aquifer ranges from 10^{-3} to 10^{-5} m/s (Cissé Faye *et al.* 2001) and specific yield is estimated to be ~0.20 from pumping tests and laboratory column tests (Diédhiou *et al.* 2012).

The study area, located within the departments of Guédiawaye, Pikine, and Rufisque as well as part of the Thiès region (Figure 1), is home to more than 1.6 million people, 11% of the national population and 52.5% of the population of Dakar (ANSD 2016). It is bounded to the west, north and south by the Atlantic Ocean and to the east by the cliff of Thiès. Population densities can reach up to 9,589 people

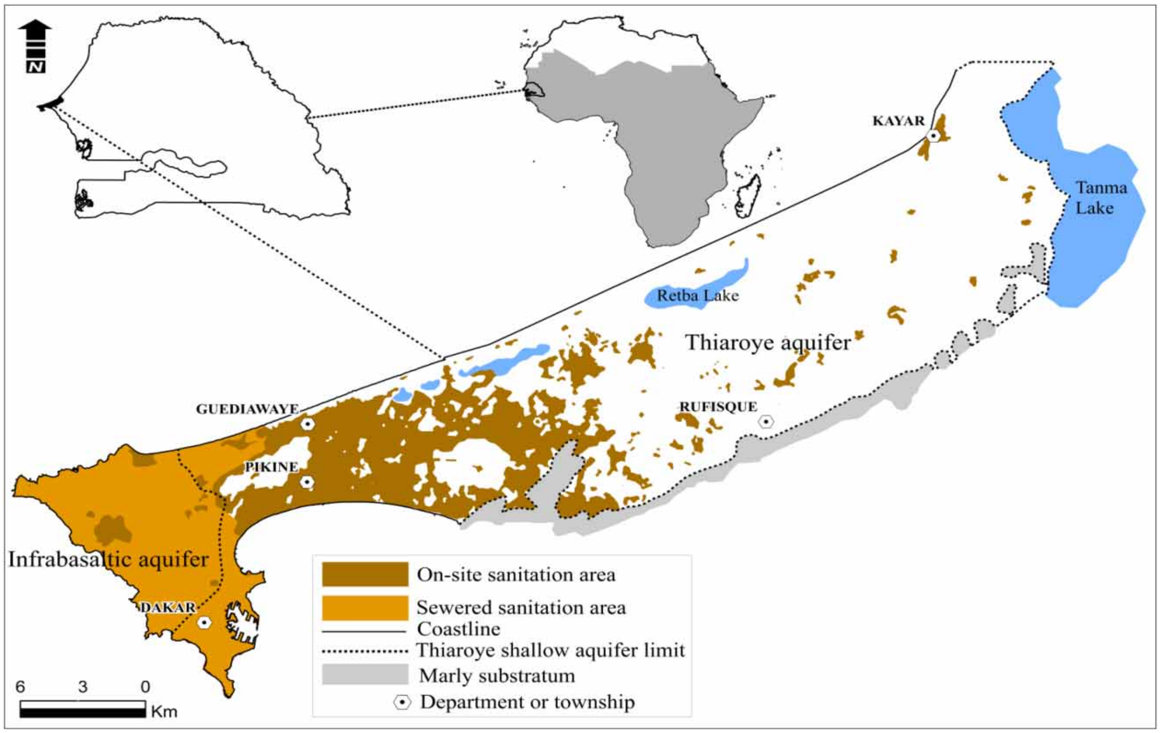

Figure 1 | Map of the Thiaroye and Infrabasaltic aquifers underlying Dakar on the Cap Vert peninsula showing areas of predominant sanitation facilities; inset maps provide the geographical context of Senegal and Cap Vert peninsula.

per km^2 with an average household size of 6 individuals. Sanitation provision in the study area derives from on-site systems that consist almost entirely of septic tanks; access to on-site sanitation is estimated to be ~95% (ONAS 2010). Faecal loading from septic-tank effluent has progressively contaminated the Thiaroye aquifer (Diédhiou 2011) from which abstraction for public water supplies has declined by 84% from 3.7×10^6 m^3/year in 1968 to 5.9×10^5 m^3/year in 2009 (Diouf 2012). Groundwater still supplies nearly 50% of the water withdrawn in Dakar for domestic purposes but because of the high faecal contamination, this groundwater is now almost entirely imported from deep aquifers outside of Dakar. Small-scale abstractions from the Thiaroye aquifer still occur via some boreholes, dug-wells and hand-tubewells. Previous studies examining stable-isotope ratios ($\delta^{15}N_{NO3}$, $\delta^{18}O_{NO3}$) trace high nitrate concentrations to faecal sources (Diédhiou 2011).

Mapping of on-site sanitation facilities

Mapping of on-site sanitation facilities began with the imposition of a grid in QGIS (v. 2.18.4) on the area underlain by Quaternary sands in the Cap Vert Peninsula. An object-oriented classification (Hájek 2012) of high-resolution satellite images (Quickbird, 6 December 2016) was then performed in Envi (v. 5.1) that required a lengthy (nine-month), painstaking supervision process informed by visual photo-interpretations and field surveys (10–17 March 2018). As individual on-site sanitation facilities such as septic tanks could not be identified directly, we employed the assumption that each house or, more specifically roof of a house, possessed one septic tank or pit latrine. Auxiliary images [Geoeye (November 10, 2012), Orbview (November 20, 2009)] were used to assist the interpretation of optical imagery and to select training samples and validation points for classification (Table 1). Through this approach we estimated the number of on-site sanitation facilities within a hectare (100 × 100 m) grid across the unsaturated zone of the shallow aquifer over a total area of 520 km^2 comprising 51,500 grids.

Classification of the Quickbird satellite imagery required preliminary processing (i.e. calibration, radiometric enhancement and geometric correction) and an object-oriented classification with segmentation process. Radiometric calibration of satellite imagery makes it possible to convert the digital signal recorded by the satellite into a physical variable such as radiance in order to discern objects and select learning samples. Radiometric enhancement stretches the histogram of the satellite image (coded to 8 bits) so that it extends across the whole range of radiometric responses (i.e. 1–255 patterns). An accuracy assessment was then undertaken to assess classification errors. For each of the 10 classes, 100 test pixels were created at points visually identified as the referenced class in the imagery and then compared with the corresponding location in the classified image for accuracy. The overall performance of the classification gives very satisfactory results with an overall accuracy of 93% and a Kappa index of the order of 0.93 (Table 2).

Table 1 | Optical satellite images used in the analysis of on-site sanitation density in the Thiaroye aquifer of Dakar

Type of satellite image and use	Acquisition date	Resolution (m)	Source
Classified and interpreted image (Quickbird)	December 6, 2016	0.6	Digital Gobe
Interpreted auxiliary image (Orbview)	November 20, 2009	1.6	Orbview
Interpreted auxiliary image (Geoeye)	November 10, 2012	0.6	Geoeye

The object-oriented classification was preceded by segmentation which allowed us to refine the object-oriented classification by reducing as much as possible spectral confusions. This process made it possible to map surfaces occupied by houses based not only on their spectral values but also on their morphological characteristics. As a result, the analysis was able to discriminate as best as possible areas occupied by the houses from areas not occupied by the houses. Ground-truthing field surveys were facilitated by consulting *cadastral* maps of each district community to obtain an overview of the average size of houses, usually 15 × 10 m, but occasionally 7.5 × 10 m. Field surveys were conducted along 10 well-distributed, validation grid transects (200 × 300 m) with the aid of GPS-marked boundaries. During these, the location of encountered houses and type of on-site sanitation facilities (e.g. septic tanks, pit latrines) were recorded; 1,267 houses were visited to validate mapping of on-site sanitation facilities.

Table 2 | Confusion matrix and Kappa index derived from the object-oriented classification of satellite imagery

Class value	**C_0**	**C_1**	**C_2**	**C_3**	**C_4**	**C_5**	**C_6**	**C_7**	**C_8**	**C_9**	**Total**	**U Accuracy**	**Kappa**
C_0	93	0	0	5	0	0	0	1	0	1	100	0.93	0
C_1	1	91	0	0	0	0	0	0	2	6	100	0.92	0
C_2	0	0	94	0	0	0	4	2	0	0	100	0.94	0
C_3	0	0	0	94	0	1	3	1	1	0	100	0.94	0
C_4	0	0	0	0	92	0	4	0	4	0	100	0.95	0
C_5	0	1	1	3	2	93	00	0	0	0	100	0.93	0
C_6	0	0	0	0	0	0	95	5	0	0	100	0.95	0
C_7	5	0	0	0	1	2	0	92	0	0	100	0.92	0
C_8	0	0	0	3	1	0	0	0	96	0	100	0.96	0
C_9	4	0	2	0	3	0	0	0	0	91	100	0.91	0
Total	103	92	97	105	99	96	106	101	103	98	1000	0	0
P Accuracy	0.90	1	0.96	0.90	0.95	0.96	0.89	0.91	0.93	0.92	0	0.93	0
Kappa	0	0	0	0	0	0	0	0	0	0	0	0	0.93

Sampling and analysis of indicators of faecal contamination (nitrate, *E. coli*)

Sampling of indictors of faecal contamination (nitrate, *E. coli*) in groundwater was carried out over a three-year period (2017–2019) using a network of 61 wells including dug-wells, piezometers, hand tubewells and boreholes; wells range in depth from 3 to 14.8 m and are distributed across the shallow aquifer. The network considered the operability of groundwater sources (still in use by users), their distribution in the area under the influence of faecal contamination, and their remoteness from agricultural activities. The number of sources sampled before and after the monsoon each year varied due to changes in site access and field logistics: 48 in 2017, 55 in 2018, 38 in 2019 (Tables S2 and S3). Groundwater samples were collected in 250 mL HDPE bottles after purging each groundwater source (unless in constant use) and stored in a cold box for transport to laboratories. Sample bottles for bacteriological analysis were collected in sterilized bottles and, after sampling, kept in ice at temperatures of ~4 °C; all samples were transported to the laboratory within 1 hour of collection and analysed within 24 hours of collection. Analysis of nitrate and other major ions was conducted using a Dionex™ Aquion™ Ion Chromatography System (Thermo-Fisher Scientific, Waltham USA) following standard methods (Rice *et al.* 2017); *E. coli* counts were determined by fluorescence *in situ* hybridization using an ESCO 473 probe (Poppert *et al.* 2005) in which bacterial cells were fixed according to the method described by Wallner *et al.* (1996). For nitrate concentrations, only analyses with a charge-balance error (CBE) of less than 10% were correlated with on-site sanitation density; 98% of employed analyses had a CBE of <5%.

Analysis of the relationship between on-site sanitation density and groundwater quality

The relationship between the estimated density of on-site sanitation facilities and the quality of groundwater was assessed through correlations with both nitrate concentrations and *E. coli* counts observed in sampled groundwater sources. Correlation analyses were carried out on wells within the Thiaroye aquifer (520 km^2) that were remote from agricultural activity. Nitrate concentrations recorded during pre- and post-monsoon sampling in 2017, 2018 and 2019 were averaged to a mean value for the period from 2017 to 2019. For *E. coli*, results from three sampling campaigns (post-monsoon and pre-monsoon 2017, post-monsoon 2018) were integrated into a median value and classified into World Health Organization (WHO 1997) drinking-water quality risk categories: Very Low (0 cfu), Low (1–9 cfu), Medium (10–99 cfu), High (100–999 cfu) and Very High (1,000 + cfu).

Linear regression was employed to test for possible association (dependency) between nitrate contamination (independent variable) and the density of on-site sanitation facilities (dependent variable). A coefficient of determination (r^2) was used to indicate the strength of the linear regression. For *E. coli* counts, box plots showing the median, the interquartile range and the 5th and 95th percentile points were also used to assess its relationship to the estimated density of on-site sanitation facilities. Spatially, this comparison related the number of septic tanks and pit latrines in each 9 ha grid (i.e. 9 grids of 100 × 100 m) centered on the sampled waterpoint (i.e. shallow groundwater source).

Ethical considerations

Permission was sought and obtained from the Directorate of Water Resources Management and Planning (i.e. Direction de la Gestion et de la Planification des Ressources en Eau, Dakar) and the UCAD Research Ethics Committee before conducting the study; informed consent was also secured from owners and users of dug-wells and on-site sanitation facilities in advance of questions posed regarding the type of on-site sanitation employed, user-interface (e.g. squat versus sitting toilet) and frequency of emptying.

RESULTS

Mapping on-site sanitation facilities results

On-site sanitation mapping reveals the density of on-site sanitation facilities per hectare (Figure 2). In total, the analysis identified 253,014 septic tanks over an area of 520 km^2. Densities of on-site sanitation vary between 1 and 70 septic tanks and pit latrines per hectare (100 × 100 m), with an average density of 20 per hectare. Cartographic results were validated from ground-truthing (Figure 3(a)) which consisted of a census of the number of houses located within the 10 validation grids distributed over the entire

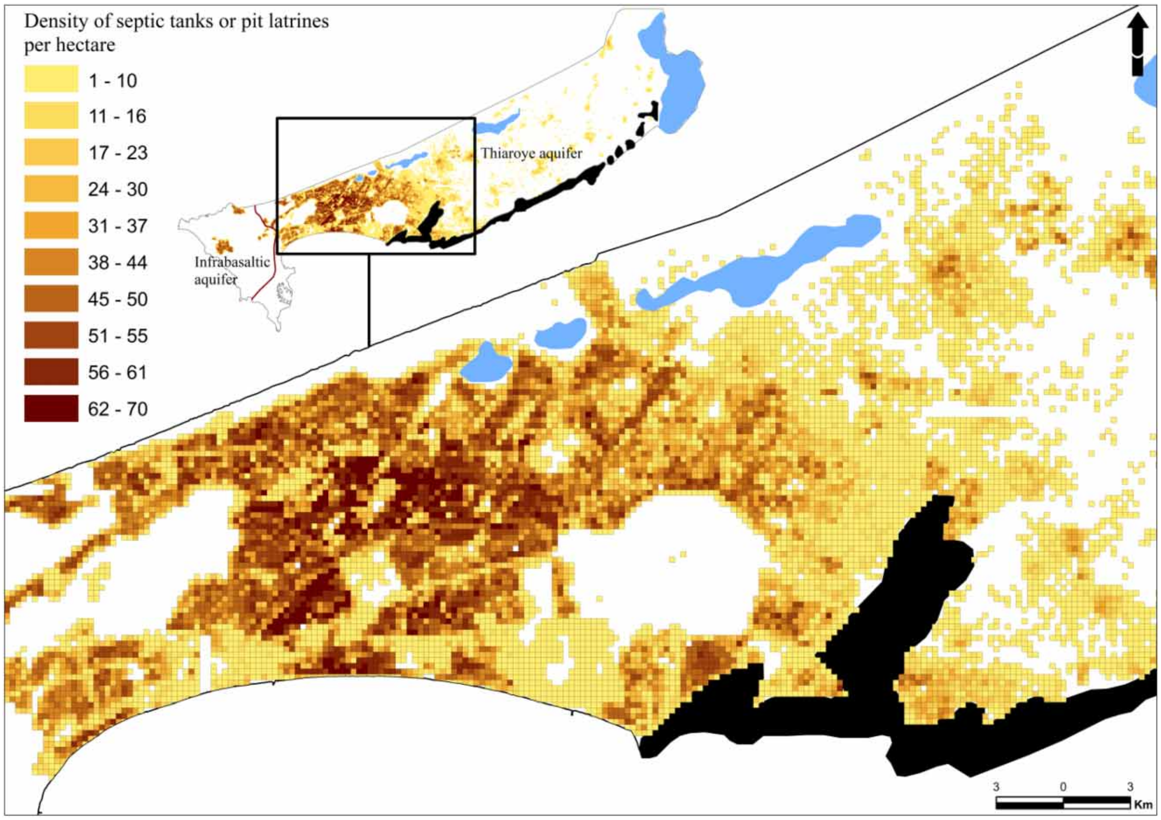

Figure 2 | Mapped density of on-site sanitation facilities (septic tanks, pit latrines) in the Thiaroye shallow aquifer estimated from Quickbird satellite image (acquired on December 6, 2016) and field surveys (10–17 March 2018); inset map shows the broader geographical context from Figure 1.

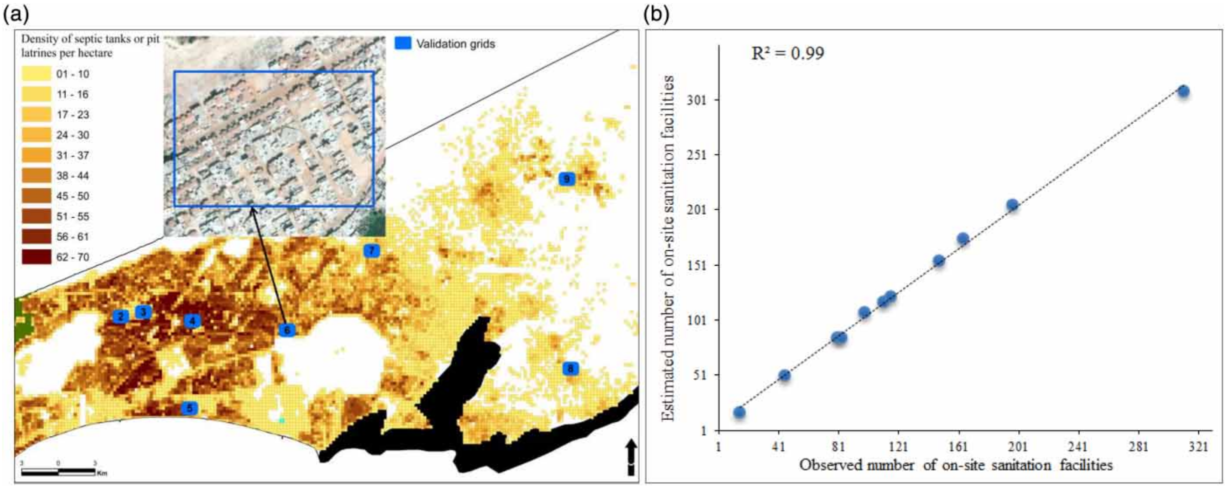

Figure 3 | (a) Map of validation grids for the estimation of on-site sanitation density from optical satellite imagery; (b) cross-plot of on-site sanitation facilities estimated from remote sensing and observed during ground-truthing surveys (10–18 March 2018) on 200 × 300 m grid.

aquifer surface. Employed validation grid sizes have a rectangular shape of 300 m length and 200 m width (Figure 3(a)). The results show a strong correlation between the number of on-site sanitation facilities determined from optical imagery and ground-truthing surveys (Figure 3(b)). Analysis of the results reveals that the grids of density of 1 on-site sanitation facility per hectare represent 10% of the total number of grids. Grids of density ranging from 2 to 20 on-site sanitation facilities represent 42% of the total grid size, whereas grids of density ranging from 20 to 70 on-site sanitation facilities account for 47% of the total grid size (Figure S1). Validation results reveal that the types of on-site sanitation systems encountered are almost entirely (98%) septic tanks. Toilet-user interfaces are mostly squat toilets (72%). Toilets are frequently associated with a shower in the same room or next door and separated by a partition. Validation results by ground-truthing reveal also that residents need to empty their on-site sanitation facilities every three years on average (Table 3).

Groundwater quality

Mean nitrate concentrations recorded in 2017, 2018, and 2019 vary considerably in space across the Thiaroye aquifer

Table 3 | Distribution and use of types of on-site sanitation facilities in the Thiaroye aquifer

Valida-tion grid	X [Center of the grid]	Y [Center of the grid]	District community	Septic tanks (%)	Pit latrines (%)	Mean number of users	Mean frequency of emptying (years)	Emptying by truck (%)	Emptying manually (%)
Grid 1	238560	1632570	Golf Sud	100	0	10–20	5	84	16
Grid 2	242530	1634140	Djida Thiaroye	100	0	10–20	4	92	8
Grid 3	242790	1633795	Medina Gounass	97	3	10–20	3	70	30
Grid 4	244890	1634001	Yeumbeul Sud	100	0	10–20	2	88	12
Grid 5	244793	1631188	Thiaroye Sur Mer	94	6	10–20	2	54	48
Grid 6	248000	1633700	Keur Massar	100	0	10–20	2	93	7
Grid 7	242790	1633795	Keur Massar	100	0	10–20	4	74	26
Grid 8	257326	1632464	Snngalkam	87	13	10–20	3	52	48
Grid 9	257203	1638573	Snngalkam	100	0	05–10	6	53	47
Grid 10	2571792	1650341	Kayar	97	3	20–30	3	52	48
Average				98	2	10–20	3	71	29

with values ranging from 3 mg/L to in excess of 500 mg/L (Figure 4(a)–4(c)). Higher nitrate concentrations are generally observed in the more densely populated areas on the western side of the Cap Vert peninsula underlain by the Thiaroye aquifer. In 32 of the 39 (82%) groundwater sources for which nitrate data are available, nitrate concentrations exceed the World Health Organization's guideline value of 50 mg/L for drinking water (Table S2). Curiously, high temporal variability in mean nitrate concentrations is also observed with a median coefficient of variation of 50%. Median *E. coli* counts in 61 groundwater sources from 2017 and 2018 for which data are available (Figure 4(d)) also exhibit high spatial variability with values ranging from 0 and 1,270 *E. coli* per 100 mL; 50% of sampled sources showed *E. coli* counts exceeding the WHO guide value of 0 (Table S3).

Relationship between on-site sanitation density and shallow groundwater faecal contamination

Groundwater sources with very high nitrate concentrations and *E. coli* counts generally but not exclusively correspond to areas with very high on-site sanitation densities. In areas where the density of on-site sanitation is lower, there is an associated decrease in nitrate concentrations in sampled groundwater (Figure 5(a)) but no consistent trend in *E. coli* (Figure 5(c)). A statistically significant relationship ($p \ll 0.01$) exists between mean (2017–2019) nitrate concentrations in shallow groundwater sources and on-site sanitation density in which 56% of the variation in nitrate is explained by the fitted regression with on-site sanitation density ($r^2 = 0.55$, Figure 5(b)). In contrast, no statistically significant relationship ($p = 0.42$) exists between median

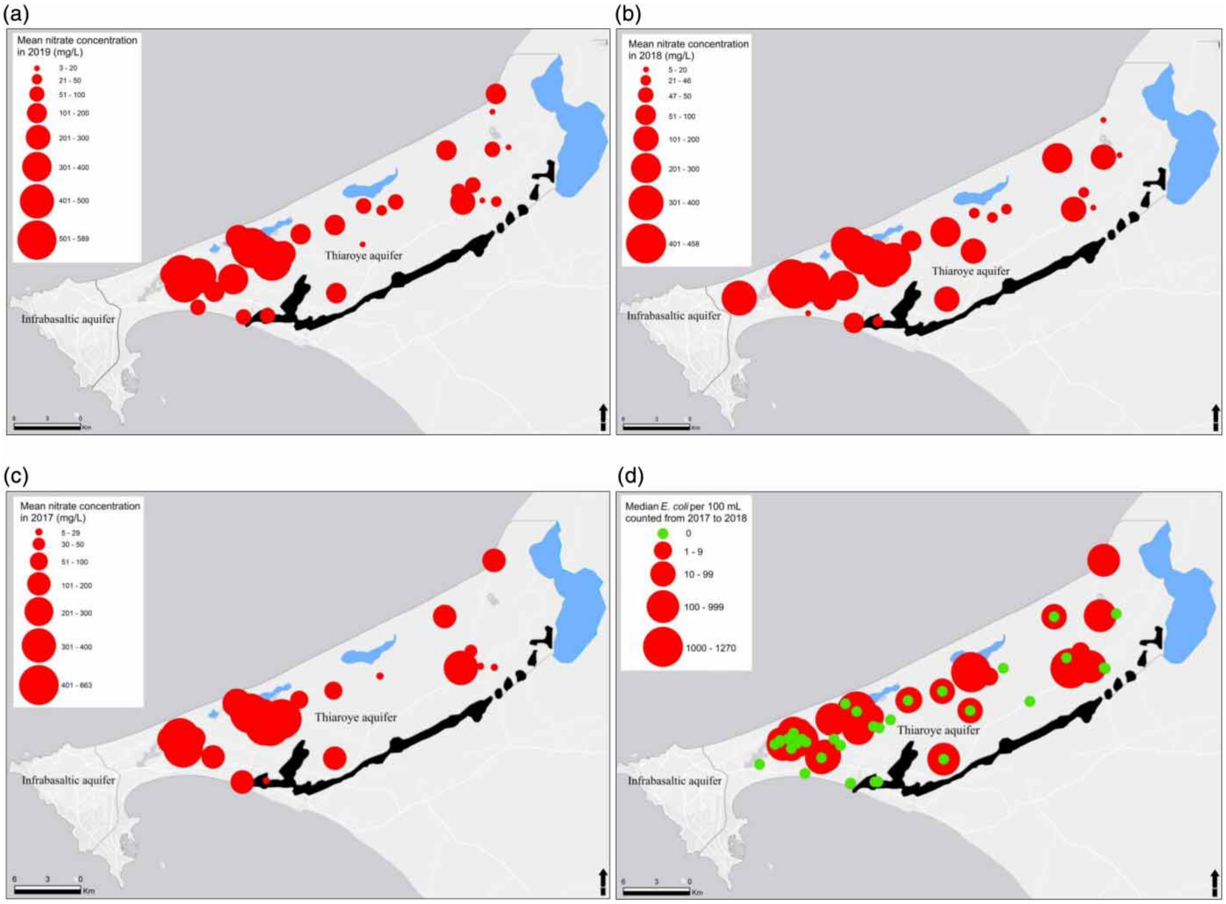

Figure 4 | Distribution of the mean nitrate concentrations (a – in 2019, b – in 2018, c – in 2017) and median *E. coli* counts (d – from 2017 to 2018) measured in the Thiaroye shallow aquifer of Dakar.

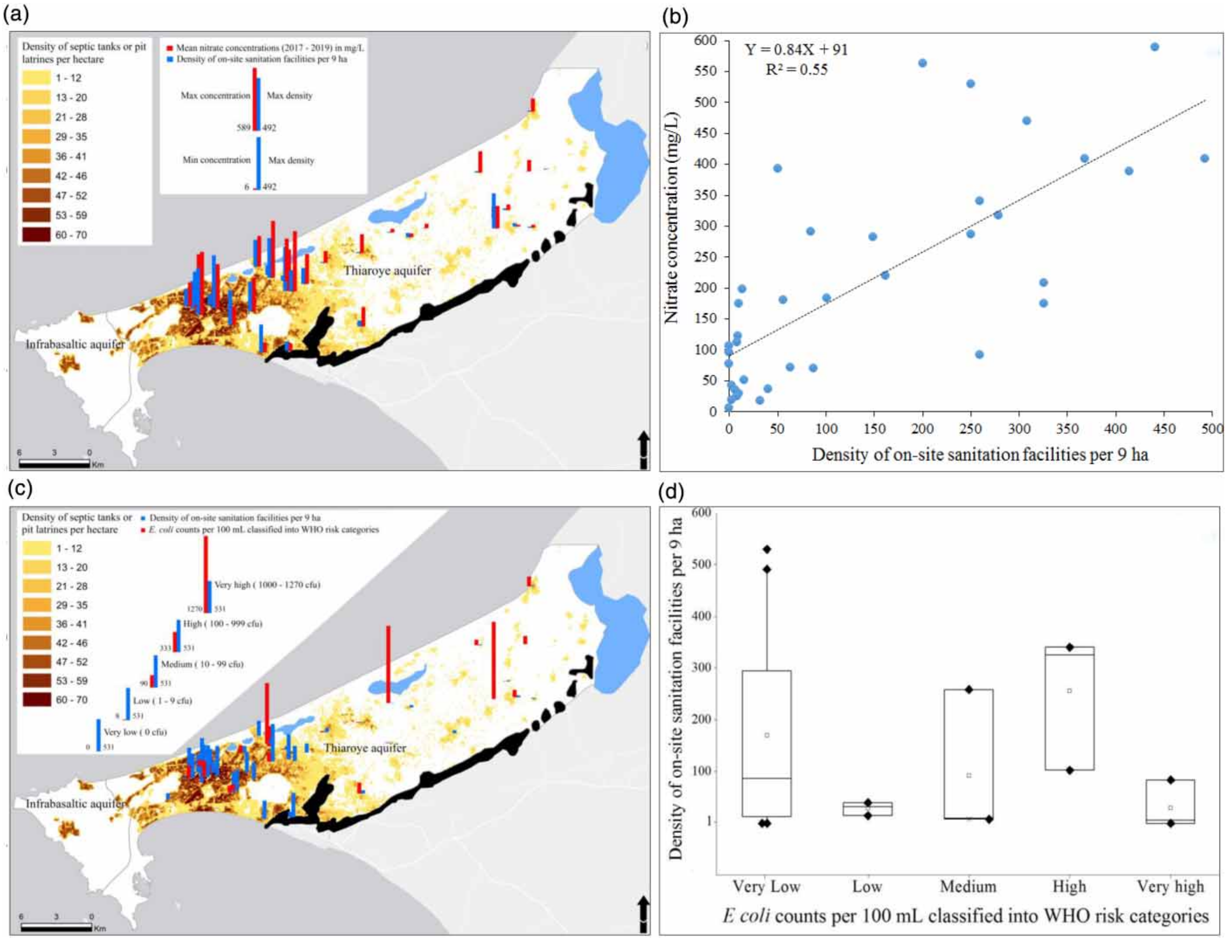

Figure 5 | Observed mean nitrate concentrations (a – from 2017 to 2019) and median *E. coli* counts according to WHO categories (c – from 2017 to 2018) in groundwater sources overlain on estimated density of on-site sanitation facilities; (b) linear correlations between these parameters; (d) Boxplots of *E. coli* count according to WHO (1997) drinking-water quality risk categories and density of on-site sanitation facilities. Box boundaries illustrate the 25th and 75th percentiles, the line within the box is the median, and the whiskers are the 10th and 90th percentiles.

E. coli counts and on-site sanitation density ($r^2 = 0.01$, Figure 5(c)). Further, grouping values of *E. coli* counts into WHO (1997) risk categories (Figure 5(d)) does not identify a general relationship between faecal bacteriological contamination and on-site sanitation density.

DISCUSSION

Previous studies mapping the density of on-site sanitation facilities in urban areas of sub-Saharan Africa have relied upon ground-based surveys over small areas of $\leq 7\ \mathrm{km}^2$ (Wright *et al.* 2012; Nkhuwa *et al.* 2015). Here, we employ an assumption, validated from ground-truthing surveys in Dakar, that each house or dwelling identified from high-resolution optical imagery (100×100 m grid) possesses an on-site sanitation facility where sewerage does not exist. Object-oriented classification of optical satellite imagery then enabled 253,014 on-site sanitation facilities comprising primarily septic tanks to be mapped over an area of 520 km^2. This process required a lengthy, painstaking supervision process based on visual photo-interpretations of classified and auxiliary images in which individual grids were checked for the validity of their identification/characterization of the number of dwellings (houses). This study represents one of the first large-scale assessments of the density of on-site sanitation facilities in an African city.

Shallow groundwater across the Thiaroye aquifer of Dakar shows high levels of faecal contamination consistent with previous studies (e.g. Tandia *et al.* 1999; Diédhiou *et al.*

2012; Cissé Faye *et al.* 2019; Sorensen *et al.* 2020). Despite high levels of contamination, the aquifer remains an important source of water for self-supply due to limited access to piped water. Inter-annual variability in recorded nitrate concentrations in shallow groundwater (Figure 4(a)–4(c), Table S2) is substantial as indicated by a median co-efficient of variation in mean nitrate concentrations (2017–2019) of 50%. As systematic analytical errors are not expected (all but one analysis of solute concentrations has a CBE of <5%), other factors may explain this variability in nitrate including water-table depth and the risk of episodic flooding of septic tanks; median depth to the water table at sampling locations is 3.3 m despite guidelines specifying a minimum vertical distance of 3 m (Gabert *et al.* 2012). *E. coli* counts (Table S3) and associated drinking-water quality risk categories vary substantially in space and inconsistently with nitrate concentrations. Effluent pathways are expected to differ as faecal bacteria are particles, not true solutes, and often sample different pathways in the subsurface from their source to a receptor such as a pumping well (Taylor *et al.* 2004b). The observed correlation association between nitrate concentrations in shallow groundwater and the density of on-site sanitation facilities is statistically significant but moderate, explaining 55% of the observed variation in nitrate. Other factors that may contribute to observed nitrate concentrations include the lithology of the unsaturated zone, septic-tank functionality, household size, and greywater discharges.

The statistically significant association between faecal effluent loading from on-site sanitation and nitrate concentrations suggests that shallow groundwater retains the 'signature' of constant faecal loading from overlying on-site sanitation facilities comprising primarily septic tanks. In Thiaroye area of Dakar, local hydrogeological conditions have, in part, facilitated this. The intergranular nature of the Quaternary sand aquifer including its high effective porosity (~0.30; Diedhiou 2011), have promoted accumulation of pollutants over time. This process has been aided by relatively low hydraulic gradients (0.001–0.003; Cissé Faye *et al.* 2019), driving groundwater flow, that are associated with the cessation of intensive groundwater abstraction from the Thiaroye aquifer due to the excessive faecal contamination. This termination of pumping has reduced sub-horizontal hydraulic gradients in the shallow aquifer, which combined with local boundary conditions for drainage controlled by sea-level, restricts groundwater flow. In addition to seasonal diffuse recharge from rainfall (Cissé Faye *et al.* 2019); the widely distributed and constant nature of faecal effluent loading from the vast network of unimproved on-site sanitation facilities comprises an additional diffuse 'recharge' flux.

The moderate, statistically significant correlation between nitrate concentrations in groundwater sources and on-site sanitation density (Figure 5(b)) provides a rough, empirically derived estimate of the capacity of the Quaternary sand aquifer to attenuate faecal loading. Switching the dependent and independent variables (i.e. $Y =$ on-site sanitation density; $X =$ groundwater nitrate concentration), the regression model (Figure 5(b)) becomes $Y = 0.66X + 1.75$. Applying the WHO drinking-water guideline value of 50 mg/L and accounting for the fact that the regression model is for on-site sanitation densities per 9 ha, the linear relationship suggests (with large error) that this threshold nitrate concentration is exceeded where the number of septic tanks (or pit latrines) exceeds 4 (±4) per hectare. Notwithstanding the uncertainty in this estimate, the result suggests that for many areas of the Thiaroye aquifer, particularly to the west in Guédiawaye and Pikine (Figure 1) with the highest density of on-site sanitation facilities, the ability of the Thiaroye aquifer attenuate faecal loading from on-site sanitation has long been exceeded with high nitrate concentrations first detected in the early 1980s. This finding is consistent with the subsequent shift around the year 2000 in the withdrawal of groundwater locally from the Thiaroye aquifer to the importation of groundwater from beyond the Cap Vert peninsula for the water supply of Dakar (Cissé Faye *et al.* 2019).

Additional work is required to replicate and extend these analyses in other aquifer environments, urban settings, and types of on-site sanitation facilities. As the proportion of dwellers reliant upon on-site sources has risen considerably over the last few decades (Healy *et al.* 2018), our results provide a tentative marker of a threshold density of on-site sanitation facilities for urban planning and water safety plans with a similar hydrogeological context in low-income urban and peri-urban areas as well as refugee and IDP (internally displaced peoples) camps dominated by use of on-site water and sanitation facilities. As the finite capacity of the subsurface to conjunctively attenuate faecal effluent and provide safe water has been exceeded in many areas of the Thiaroye aquifer, sanitation options that will reduce faecal loading to underlying groundwater are restricted to sewerage or on-site dry (no-flush) toilet systems (e.g. earth auger toilet). Recent research in the Thiaroye area (Eggleton 2018) indicates that implementation of new technological solutions such as dry toilets needs to consider cost, cultural attitudes, and the viability of supply chains to promote uptake by user communities.

CONCLUSIONS

On-site sanitation facilities have been mapped over an area of 520 km^2 in densely populated, low-income areas of Dakar (Senegal) using an intensely supervised, object-oriented classification of optical satellite imagery (QuickBird). Employing the assumption, supported by ground-truthing surveys, that each identified dwelling possesses one on-site sanitation facility, >253,000 on-site sanitation facilities were mapped with densities ranging from 1 to 70 septic tanks or pit latrines per hectare. The density of on-site sanitation facilities comprising primarily septic tanks (~98%) is correlated with the magnitude of faecal contamination (nitrate) observed in shallow groundwater within unconsolidated Quaternary sands.

The analysis highlights the risk posed by dense networks of on-site sanitation facilities to shallow groundwater quality. Urban areas with high densities of on-site sanitation facilities and associated loading of faecal effluent to the subsurface, exhibit greater faecal pollution from solutes (nitrate). The moderate, statistically significant association between faecal nitrate and the density of on-site sanitation facilities suggests that densities exceeding 4 (±4) septic tanks per hectare in the Thiaroye shallow aquifer pose a risk to human health. As many areas underlain by the Thiaroye aquifer of Dakar have on-site sanitation densities that exceed the threshold, our results highlight the health risk posed by self-supply options employing shallow wells. Replication of the analytical approach employed here to other conurbations in sub-Saharan Africa is recommended to better understand the attenuation capacity of urban aquifer systems in different contexts and to inform use of low-cost sanitation systems restricting faecal effluent.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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