Research Paper

Nexus between sanitation and groundwater quality: case study from a hard rock region in India

S. Murty Bhallamudi, R. Kaviyarasan, A. Abilarasu and Ligy Philip

ABSTRACT

Groundwater quality in the towns of Namakkal and Erumaipatti in India was studied to understand the nexus between surface sanitation and groundwater quality in hard rock regions. In total, 32 wells, both shallow open and deep bore wells, were monitored over a two-year period. The presence of fecal coliforms (FCs) up to 600 CFU/100 mL in wells as deep as 100 m showed that bacteriological contamination had reached deep aquifers through fractures and fissures. Statistical analyses showed that bore wells located in Namakkal were bacteriologically more contaminated than those in Erumaipatti ($p = 0.017$ for FC) because of urbanization, the type of top soil and the shallow groundwater table. Wells in densely toileted areas of Namakkal were more contaminated than those located in open defecation areas. After replacing a soak pit with a septic tank, concentrations of FC and chemical oxygen demand (COD) in the leachate at a depth of 2.1 m reduced from 2,500 to 1,000 CFU/100 mL and from 200 to 50 mg/L, respectively, after 150 days of the construction of septic tanks. To improve the hygiene and sanitation, the provision of toilets along with on-site waste management systems, capable of achieving required effluent quality, are essential.

Key words | bacteriological contamination, groundwater quality, hard rock areas, sanitation

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INTRODUCTION

Poor sanitation is one of the main causes of diarrhea (WHO 2019). As part of the Sustainable Development Goals, the United Nations has set the target to achieve access to adequate and equitable sanitation and hygiene for all and end open defecation by 2030 (UNDP 2018). India has launched the Swachh Bharat Mission, which includes, among other goals, the elimination of open defecation by 2019 through large-scale toilet construction (MoHUA 2018). Improved sanitation includes flush toilets connected to either the sewerage systems or septic tanks, and pit latrines (Jenkins *et al.* 2015). Recently, the Joint Monitoring Program for water supply, sanitation hygiene (JMP) of the WHO/UNICEF (World Health Organisation (WHO) 2017) has estimated that around 0.9 billion people worldwide use toilets or latrines where excreta are disposed of *in situ*. In India, currently about 46.1% of urban households are connected to septic tank/flush latrines and 14.6% are connected to pit latrines. 13% of households have other latrines (night soil disposed into open drain; night soil removed by humans or animals), and 26.3% are without any latrines (Government of India 2011a).

A field study by Sunderrajan (2011) indicated that faulty design and implementation of on-site sanitation technologies in India are resulting in poor containment of wastewater and are increasing risk to drinking water quality. The study by Sunderrajan (2011) found that the bottom of the pit is left exposed to the soil. Recent studies have shown that excreta of approximately 29% of the population is managed properly and the amount of septage treated is less than 10% (CSE 2017; Krithika *et al.* 2017). Contaminants from on-site sanitation technologies can leach into the groundwater and affect its quality (van Ryneveld & Fourie 1997).

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Concerns regarding the effect of the sanitation technologies on the quality of groundwater are serious because, in India, about 50% of the urban water requirements and 85% of the rural domestic water requirements are met by groundwater (Megha *et al.* 2015). The ubiquity of on-site sanitation technologies can be expected to cause widespread pathogen contamination in adjacent wells (Hunt & Johnson 2017). Thus, it is important to understand the effect of sanitation on groundwater quality in order to protect the groundwater sources and to formulate appropriate policies.

There have been several studies on the nexus between sanitation and groundwater quality from different parts of the world (Dzwairo *et al.* 2006; Pujari *et al.* 2007; Lu *et al.* 2008; Vinger *et al.* 2012; Jangam *et al.* 2015). Hynds *et al.* (2014) reported that there is an increased likelihood of *Escherichia coli* being present in a well if the septic tank setback distance is around 32.8 m. Most of the earlier studies on the nexus between sanitation conditions and groundwater quality in India were conducted in either alluvial areas (NEERI 2005; Pujari *et al.* 2012) or hard rock areas with a shallow groundwater table (Pujari *et al.* 2012). Recently, a few studies were carried out in hard rock aquifers with a deep groundwater table (Shivendra & Ramaraju 2015; Quamar *et al.* 2018). Quamar *et al.* (2018) found that the geo-hydrological parameters and separation between the on-site sanitation technology and groundwater source are key parameters affecting groundwater contamination. Kumar *et al.* (2017) noted that the diversified hydro-geological settings in India make it difficult to understand the transport processes of contaminants in the groundwater. Therefore, more studies in different geographical regions are necessary (Rao *et al.* 2013).

In the present work, the authors have studied the groundwater quality in two towns in India, which are located in hard rock terrain, overlain by a weathered zone. Wells in these towns draw water from fractured rock aquifers, and the groundwater table varies from as shallow as 5 m below ground level (bgl) to 100 m bgl at some of the locations. The specific objectives of this study were to determine (i) are deep bore wells (up to 100 m bgl) as vulnerable to bacteriological contamination as bore wells in shallow aquifers? (ii) is there any effect of urbanization and the density of toilets on the concentration of contaminants in the groundwater? (iii) are the wells in open defecation areas more vulnerable to bacteriological contamination than wells in areas with soak pit-based toilets in a weathered rock region? and (iv) is it possible to reduce the contamination of aquifers by replacing pervious soak pits with impervious septic tanks? To answer these questions, 32 wells, both bore holes and shallow dug wells, were monitored for various water quality parameters over a period of two years. The microbial contamination of the unsaturated zone was also monitored before and after replacing a soak pit with a septic tank. The bacteriological quality was monitored in terms of fecal coliforms (FCs) and total coliforms (TCs).

MATERIALS AND METHODS

Study area

The study was carried out in the towns of Namakkal and Erumaipatti, located in Namakkal District (Supplementary Material S1) in the state of Tamil Nadu, India. The normal annual rainfall over the district varies from 491 to 1,283 mm with an average of 867 mm. The district enjoys a tropical climate. A brief description of the geo-hydrological conditions of the study area is given in Supplementary Material S2.

Field sampling from wells

In total, 12 existing wells in Erumaipatti and 20 existing wells in Namakkal town were chosen for monitoring. The locations for sampling wells were selected based on diverse sanitation conditions such as proximity to household septic tanks (8), proximity to public toilet systems and areas with open defecation (5), locations with significant open drainage system (4), locations with no drainage system but a high density of septic tanks (4), proximity to contaminated surface water bodies (2), and composting sites and sewage treatment plants (STPs) (4). Five of the wells were located in agricultural areas. Samples were taken from both open wells (13) and bore wells (19). The locations of the wells and the prevailing sanitation conditions in the vicinity of these wells are presented in Supplementary Materials S3 and S4, respectively. Groundwater samples were collected six times during a two-year period (November 2015, December 2015, April 2016, June 2016, December 2016, March 2017 and July 2017) from these wells.

Chemicals and glassware

The bacterial concentrations of groundwater and wastewater samples were determined by using Chromo cult plates procured from Sartorius Stedim Biotech, Germany. Stock solutions were prepared in Millipore water. All other chemicals were procured from Rankem, India. Sterilized tap water was used for experiments involving bacterial suspension and Millipore or double-distilled water was used in all other preparations. The glassware used in the present study was purchased from Borosil, India. All the glassware was rinsed in a chromic acid solution followed by a Millipore water rinse.

Analytical methods

Water samples collected from different wells were preserved at 4 °C and analyzed in the laboratory as per the standard method for the examination of water and wastewater suggested by the American Public Health Association (APHA 2012). Temperature, pH, electrical conductivity and total dissolved solids were measured *in situ* by using a multi-parameter meter (Eu-Tech, USA). Groundwater samples were collected in 2 L plastic containers and were analyzed for (i) FCs, (ii) TCs, (iii) total organic carbon (TOC), (iv) chemical oxygen demand (COD), (v) ammonia and (vi) nitrate. The detailed description of analytical methods for each parameter is described in the following sections. In India, FCs and TCs are the indicators most commonly used for testing the bacteriological quality (Quamar *et al.* 2018). TCs are used for drinking water and FCs are used for wastewater discharge standards (IS 10500, BIS 2012).

Organics

COD and TOC were determined for all the samples as per standard methods for the examination of water and wastewater (APHA 2012). COD was estimated using the closed reflux digestion (acid destruction at 150 °C for 120 min) method in a HACH COD digester (Model No. 45600, USA). TOC was measured using a TOC analyzer V600 series (Shimadzu, Japan). All analysis was completed within 48 h of sampling.

Nutrients and pathogens

Ammonia (NH_4-N) and nitrate (NO_3^--N) were analyzed after filtering the samples through a 0.45 μm Whatman glass fiber filter paper (APHA 2012). The concentration of ammoniacal nitrogen was determined with the indophenol method; nitrate nitrogen was determined using the 1 N HCl method. Coliforms were detected using a multiple tube fermentation technique to determine the most probable number (APHA 2012). The concentrations of FC and TC were also determined by colony forming units (CFUs) per 100 mL (APHA 2012). Collected water samples were diluted using sterilized water. Diluted samples were filtered using a 0.45 μm cellulose nitrate filter paper, followed by keeping the filter paper in a Chromocult medium and incubated for 48 h at 35 ± 2 °C.

Field sampling for leachate characteristics

Leachate characteristics in the vicinity of leach pits were monitored at two selected locations in Erumaipatti. At each location, three slotted PVC pipes were installed within 0.6 m of the leach pit/septic tank to collect leachate from different depths as shown in Figure S5 (Supplementary Material). Leachate seeped through the slots and accumulated in a collection cup at the bottom of these collection pits. The leachate was bailed out using a string attached to the collection cup and taken to the laboratory for analysis. Leachate was collected at approximately 15-day intervals, from August 2016 to August 2017, and was analyzed for (i) FC, (ii) TC, (iii) COD, (iv) ammonia and (v) nitrate. The purpose of this exercise was to determine the impact of the two different sanitation technologies on the contaminant loading and the attenuation of contamination in the leachate as it seeped through unsaturated soil layers. At the beginning of the study, both locations had leach pits receiving black water. During the study period, the leach pit at one of the locations was replaced by a septic tank (November 2016) to assess the reduction in concentrations of contaminants in the leachate.

Statistical methods

Paired comparisons using *t*-tests were made for hypothesis testing. A significance level (p) of 0.05 was used in testing the null hypothesis, i.e., it was concluded that a difference exists if $p < 0.05$. Pearson's correlation analysis was also carried out to determine if there was any correlation between the occurrences of contaminants in the wells. The statistical analysis was carried out using the IBM SPSS software, version 20.

RESULTS AND DISCUSSION

Ground water quality in the study area

Concentrations of FC in all the 32 wells during three samplings are shown in Figure 1. Concentrations of FC in all 32 wells during all the six samplings are shown in Figure S6(a) and S6(b) (Supplementary Material). Concentrations of TC in all the 32 sampling wells, during all the six samplings, are shown in Figure S6(c) and S6(d) (Supplementary Material).

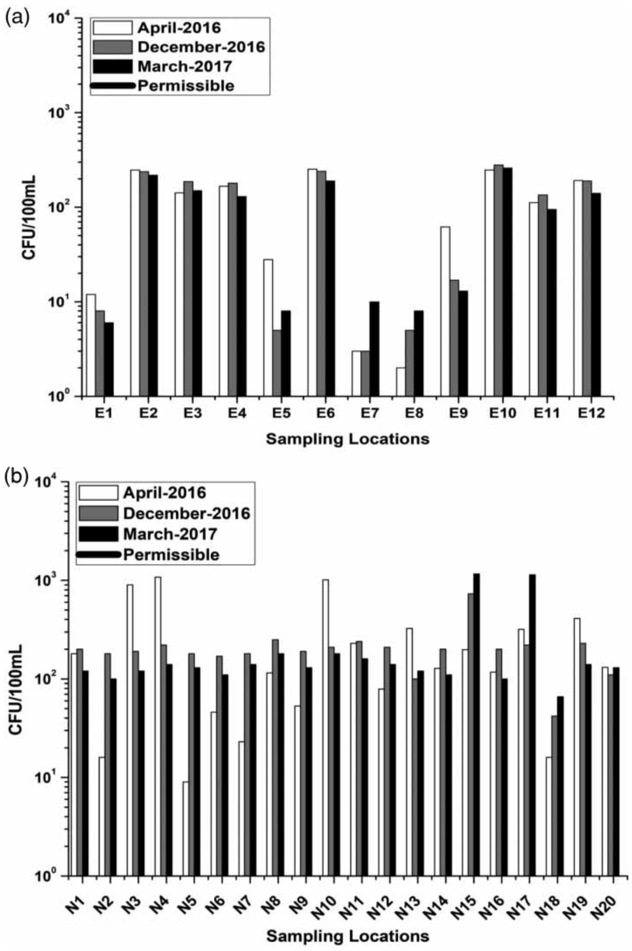

Figure 1 | FC concentrations in sampling wells: (a) Erumaipatti and (b) Namakkal.

All wells in Erumaipatti and Namakkal were contaminated with FCs and TCs irrespective of their location and whether they were bore wells or open wells. The permissible limit for FC concentrations is zero. FC concentrations reached 600 and 1,400 CFU/100 mL in bore wells in Erumaipatti and Namakkal, respectively. The groundwater table in Namakkal ranged from 5 to 20 m bgl, and both types of wells are drawing water from a shallow aquifer. FC concentrations in groundwater in Namakkal were in the range of 300–1,500 CFU/100 mL during the monsoon season (July–December) and varied from 100 to 1,100 CFU/100 mL during the summer season. Similar results were found for Erumaipatti. This marginal increase in concentrations during the monsoon season was due to the movement of pathogens along with rain water in the top soil layers which are up to 3 m in Erumaipatti and up to 4 m in Namakkal, and then movement through the fractured zone.

Some earlier studies have reported that on-site sanitation technologies did not have an effect on quality in places where the groundwater is drawn from deep and confined aquifers (NEERI 2005). Fractured rock aquifers with shallow water tables were contaminated more than alluvial formations (NEERI 2005). Recently, Quamar *et al.* (2018) reported that all the sampling wells were contaminated by on-site sanitation in highly weathered and fractured hard rock areas overlain by alluvial materials. In their study, the aquifers were confined, semi-confined or unconfined type, and the water table was 7–25 m bgl. In Namakkal, the hard rock formation is composed of charnockite and quartzofeldspathic gneiss. The thickness of the weathered zone ranges from 4 to 14 m, overlain by red loam soil. In Erumaipatti, the hard rock formation is composed of charnockite, granulites and hornblende biotite gneiss. The thickness of the weathered zone ranges from 3 to 30 m, overlain by clay loam soil. The groundwater level in the sampling wells in Namakkal varied from 5 m to 20 m bgl during the study period, while the groundwater level in sampling wells in Erumaipatti varied from 15 m to 100 m bgl. Nineteen samples from both these towns were taken from bore wells where the water level ranged from 20 m to 100 m bgl, and all of the samples contained FCs and TCs. FC concentrations in Erumaipatti ranged from 4 to 600 CFU/100 mL (average concentration = 141 CFU/100 mL). FC concentrations in Namakkal ranged from 15 to 1,600 CFU/100 mL (average concentration = 330 CFU/100 mL) in Namakkal. These results corroborate the findings of Quamar *et al.* (2018), indicating that the fractures in hard rock areas lead to higher aquifer vulnerability compared with the porous sandy formations in the alluvial settings. Water, even from bore wells as deep as 100 m bgl, was vulnerable to contamination from sanitation conditions if the wells are located in fractured rock aquifers. Shivendra & Ramaraju (2015) also found that preferential pathways (in the form of fractures) and continuous contamination from improper sanitation containment contaminate deep aquifers.

Wells E2, E3 and E4 in Erumaipatti were located in areas used by people for open defecation. Also, public toilets and septic tanks with pervious bottoms were present in these locations. Well E6 was located where a badly maintained drain with a damaged bottom lining exists. Although bore wells E10, E11 and E12 were more than 60 m deep and were located away from open defecation and other known sources of pollution, the bacteriological contamination ranged from 60 to 600 CFU/100 mL. These wells are the main sources of water for communities. Wells E1 and E5 are located within 10 m distance from open drains. Concentrations of contaminants in wells E7 and E8 were low compared with concentrations in other wells and were in the range of 5–15 CFU/100 mL. Reasons for low concentrations in these wells are unknown. It can only be speculated that low concentrations could be due to local soil conditions.

In Namakkal, all wells contained FC and TC. In total, 42 samples were collected from wells (N1, N2, N3, N4, N5, N6 and N7), which are located in the vicinity of the pond area (Supplementary Material, Figure S3(b)). Out of these, FC concentration in 35 samples was more than 100 CFU/100 mL. FC concentrations ranged from 10 CFU/100 mL to as high as 1,100 CFU/100 mL, with an average value of 277 CFU/100 mL. It should be noted here that partially treated effluent from STP is discharged into the nearby pond. Namakkal has many unlined drainage channels carrying sewage and black water directly discharged from toilets. These channels also act as a continuous source of the contamination of groundwater. Well N15 was located in an area where there were no drainage channels. People in this location use soak pits for draining their gray and black water, and this well was located about 6 m from a soak pit. FC concentrations in this well also ranged from 700 to 1,500 CFU/100 mL. It may be summarized from the above results that besides on-site sanitation technologies such as pit latrines and septic tanks with pervious bottoms, contaminated ponds and unlined drainage channels receiving gray and black water directly from houses may cause widespread groundwater contamination. A similar conclusion was drawn in an earlier study by Shivendra & Ramaraju (2015).

Variations in COD, ammonia and nitrate concentrations for all the wells in Namakkal for three sets of samples are shown in Figure 2. Variations in COD, ammonia and nitrate concentrations for all the wells in Namakkal for all the six sets of samples are shown in Supplementary Material, Figure S7(a)–S7(c). The corresponding results for Erumaipatti are given in Supplementary Material, Figure S7(d)–S7(f).

Concentrations of COD, ammonia and nitrate in 50% of the wells were more than 30, 5 and 50 mg/L, respectively. The presence of FC and TC, along with concentrations of ammonia and nitrate more than the permissible limits, indicates that improper sanitation and wastewater management might be resulting in groundwater contamination in both Erumaipatti and Namakkal, as all the three pollutants are present in black water (Cabral 2010; Douagui *et al.* 2012). Pearson's correlation analysis was carried out to determine if there was any correlation between one contaminant and another in the wells located in Namakkal and Erumaipatti, and the results are presented in Supplementary Materials S8, Table S8(a) and S8(b). In the wells in Namakkal, the correlation coefficient between COD and nitrate, COD and ammonia, ammonia and nitrate and FC and TC is greater than 0.75. However, in the wells in Erumaipatti, the correlation coefficient between only FC and TC is greater than 0.75. It was noted that five out of 12 wells in Erumaipatti were located in agricultural areas. As per the Government of India census report (Government of India 2011b), Namakkal is classified as a Municipality while Erumaipatti is classified as Town Panchayat, which means that Erumaipatti is more rural than Namakkal. 49.2% of the

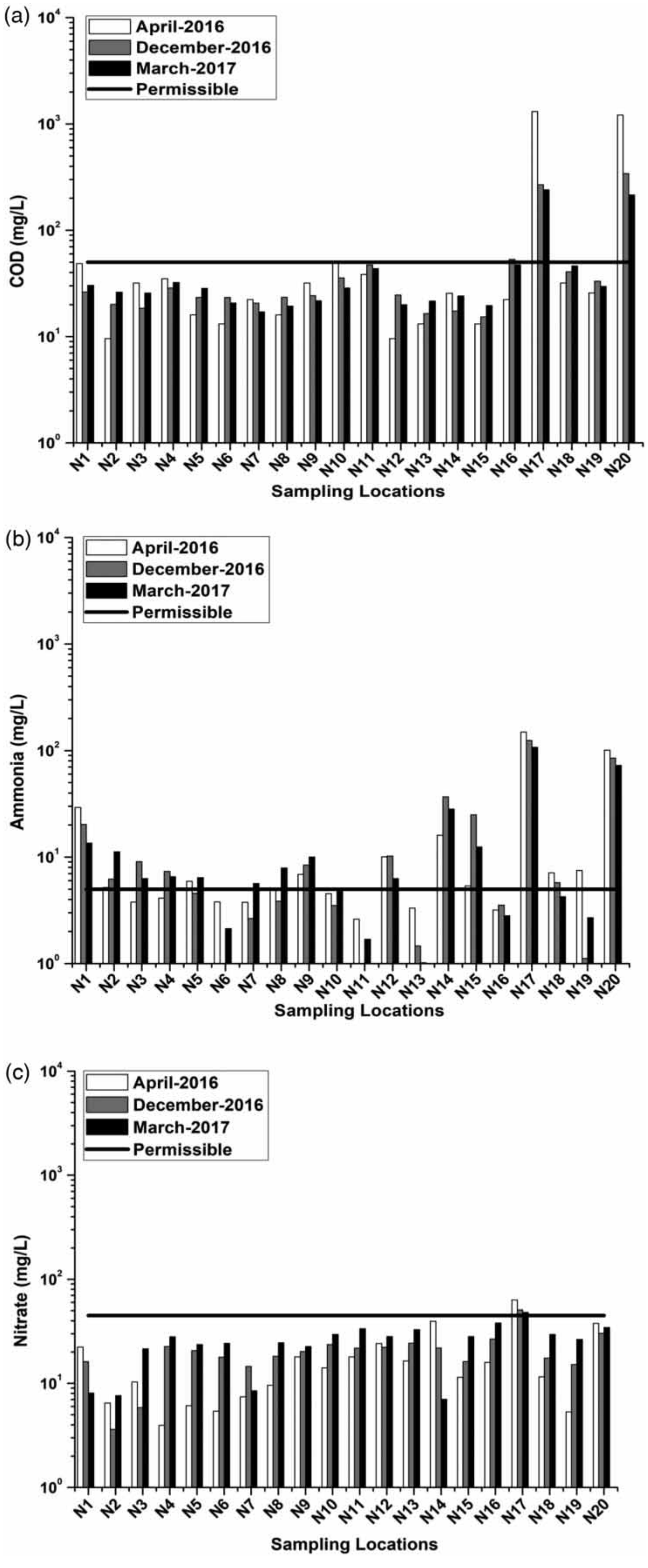

Figure 2 | Concentration of (a) COD, (b) ammonia and (c) nitrate in sampling wells in Namakkal.

population in Erumaipatti is engaged in agricultural-related activities as compared with only 2% of the population in Namakkal. We also found more cattle sheds in Erumaipatti than in Namakkal, although exact numbers were not counted. The cow dung could have contributed to the FC values measured. Similarly, the agricultural activity could be contributing ammonia and nitrate to aquifer, along with the leach pits and open defecation areas (Cabral 2010). Based on the data collected, it can be inferred that leach pits, open defecation and damaged drains carrying gray and black water are the major contributors to groundwater contamination in Namakkal, whereas in Erumaipatti, agricultural activity including cattle breeding and rearing is also responsible for groundwater contamination. To identify the actual contribution from each of the sources, detailed investigation into the presence of various microbial species is needed.

Water quality in Namakkal vs. water quality in Erumaipatti

The box plots for concentrations of FC, TC, COD, ammonia and nitrate in bore wells in Namakkal and Erumaipatti are shown in Figure 3.

A pairwise comparison was performed using the simple *t*-test to evaluate if the concentrations of contaminants in bore wells in Erumaipatti were statistically different from concentrations in bore wells located in Namakkal. Bore wells located in Erumaipatti and Namakkal showed statistically significant difference in water quality with respect to FC ($p = 0.016$) and TC ($p = 0.011$). Average FC and TC concentrations were higher in the bore wells located in Namakkal as compared with those located in Erumaipatti. Bore wells in Namakkal were bacteriologically more contaminated as compared with bore wells in Erumaipatti. The population of Namakkal is 55,145 with approximately 15,000 households, while Erumaipatti has a population of 12,085 with 2,954 households (Government of India 2011b). Based on the survey conducted, about 63% households in Erumaipatti had a toilet, while 90% of households in Namakkal had toilets. This difference could be the reason for the higher level of contamination of bore wells in Namakkal as compared with bore wells in Erumaipatti.

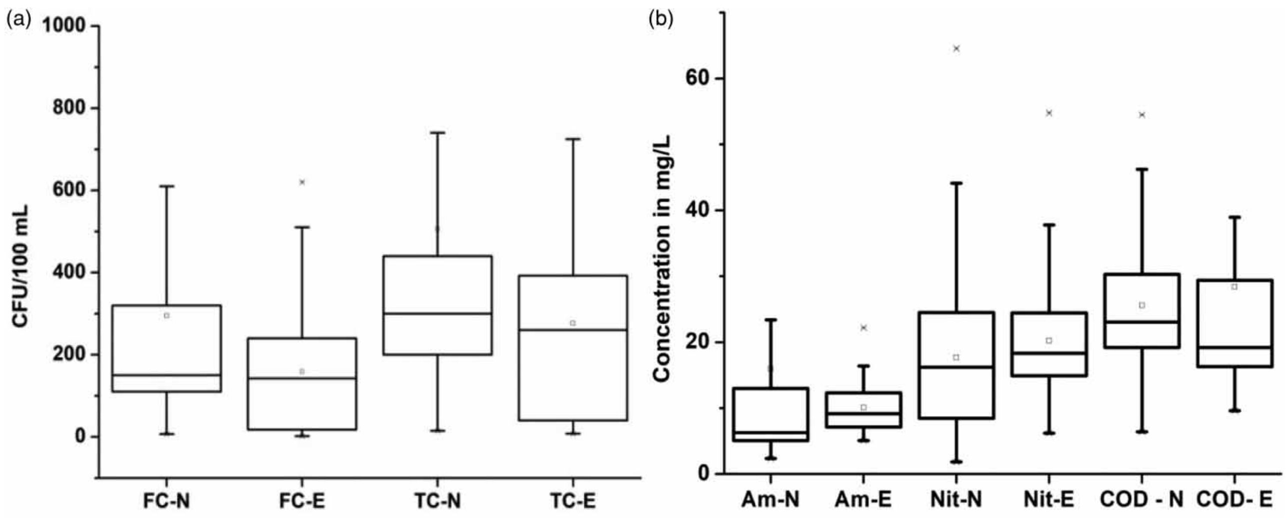

Figure 3 | Comparison of contaminant concentrations in bore wells in Erumaipatti and Namakkal (FC-N: fecal coliform in Namakkal; FC-E: fecal coliform in Erumaipatti; TC-N: total coliform in Namakkal; TC-E: total coliform in Erumaipatti; Am-N: ammonia in Namakkal; Am-E: ammonia in Erumaipatti; Nit-N: nitrate in Namakkal; Nit-E: nitrate in Erumaipatti; COD-N: COD in Namakkal; COD-E: COD in Erumaipatti).

There was no difference between COD ($p = 0.095$), ammonia ($p = 0.101$) and nitrate ($p = 0.253$) concentrations in bore wells of Erumaipatti as compared with concentrations in bore wells in Namakkal. Simple *t*-tests were carried out taking (a) all samples, (b) samples only for the monsoon season and (c) samples for only the summer season. There was a statistical difference in FC and TC concentrations in bore wells of Namakkal and Erumaipatti only for samples taken during the monsoon season. There was no difference for samples taken during the summer season. The above result may be because of the way contaminant leaching occurs in the monsoon season due to rain water infiltration and its dependence on: (i) characteristics of top soil, (ii) depth to the groundwater and (iii) geology of the area. The groundwater table varied from 15 m to 100 m bgl in Erumaipatti, while it varied from 5 m to 20 m bgl in Namakkal. The depth to groundwater table and the type of top soil (clay loam in Erumaipatti and red soil in Namakkal) could also have had a bearing on the extent of the effect of sanitation conditions on the groundwater quality.

Effect of surface sanitation conditions on the water quality

Although 90% of houses in Namakkal had toilets, people practiced open defecation in certain areas. Moreover, the interviews with septic tank constructors in Namakkal indicated that most toilets were connected to soak pits and not to septic tanks with a concrete lined bottom. In both towns, there is no proper sewerage system and wastewater flows in leaking, open channels. There is an STP in Namakkal; however, it was not functioning properly at the time of study, and the partially treated wastewater was being discharged into a large pond.

The box plots for FC and TC concentrations in bore wells located in areas of open defecation and in other areas in Erumaipatti and Namakkal are shown in Figure 4. A pairwise comparison was made using the simple *t*-test to evaluate if FC and TC concentrations in bore wells located in areas of open defecation in Namakkal differed from FC and TC concentrations in bore wells located in other areas in Namakkal (surrounded by toilets and leaking open drains). There was a statistically significant difference in the fecal contamination in wells located in the densely toileted area as compared with those in the open defecation area ($p = 0.019$), in Namakkal town. Wells located in toileted areas were more contaminated than those located in the open defecation area. Namakkal is situated in a place having weathered and fractured rocks with 1–4 m of top red soil. During open defecation, the amount of water available to transport the FC and TC through this soil layer is less (<250 mL) than the toilets which use flush water

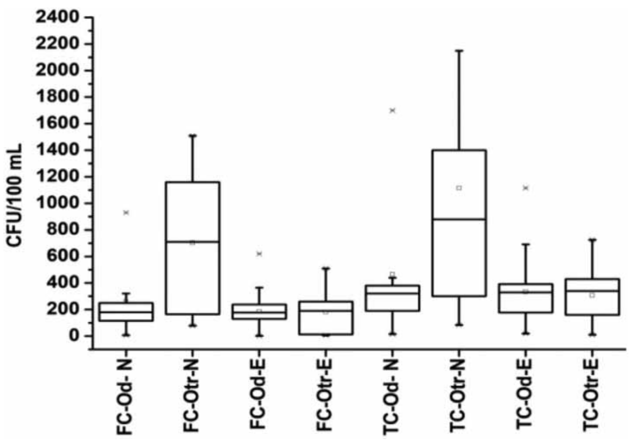

Figure 4 | Comparison of bacterial concentration in wells located in open defecation vs. other locations (FC-od-N: fecal coliform in wells located in the open defecation area in Namakkal; FC-Otr-N: fecal coliform in wells located in non-open defecation areas in Namakkal; FC-Od-E: fecal coliform in wells located in the open defecation area in Erumaipatti; FC-Otr-E: fecal coliform in wells located in non-open defecation areas in Erumaipatti; TC-Od-N: total coliform in wells located in the open defecation area in Namakkal; TC-Otr-N: total coliform in wells located in non-open defecation areas in Namakkal; TC-Od-E: total coliform in wells located in the open defecation area in Erumaipatti; TC-Otr-E: total coliform in wells located in non-open defecation areas in Erumaipatti).

(5,000 mL). Moreover, as mentioned earlier, most of the toilets are connected to soak pits. As a result, the percolation of FC/TC was greater in areas having toilets.

There was no statistical difference in water quality in wells depending on where they are located within Erumaipatti ($p = 0.922$ for FC). Bore wells in Erumaipatti were equally contaminated whether they were located in open defecation areas or in other locations. To identify the actual contribution from each of the sources (leach pits, open defecation, agricultural activity, cattle, etc.), a detailed investigation into the presence of various microbial species is needed.

The box plots for COD, ammonia and nitrate concentrations in bore wells located in areas of open defecation and in other areas in Erumaipatti and Namakkal are shown in Figure S9 (Supplementary Material). Ammonia and nitrate concentrations in bore wells located in densely toileted areas in Namakkal were higher than those in wells located in open defecation areas.

Monitoring of quality of leachate in unsaturated soil layers

Presently, most toilets in the study area are connected to soak pits without an impervious bottom. Therefore, it was hypothesized that the use of septic tanks in place of soak pits would better protect the groundwater quality. This hypothesis was tested by monitoring the quality of leachate in the field coming out of a leach pit and a septic tank. Soil pits were dug at two locations in the study area to collect leachate from nearby septic tanks and analyze for the quality of water seeping into the pits. These two locations were (i) a newly installed septic tank in Erumaipatti (Location I) and (ii) a location in Erumaipatti with an existing leach pit (Location II). FC and TC concentrations in the leachate collected from the soil pits in Locations I and II are presented in Figures 5 and 6, respectively.

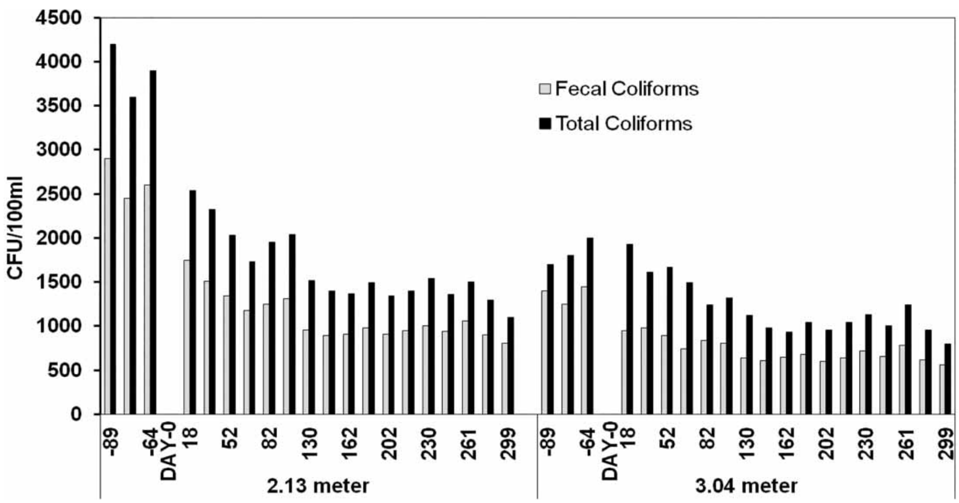

Figure 5 | Variation in concentrations of FC and TC in the leachate at Location I.

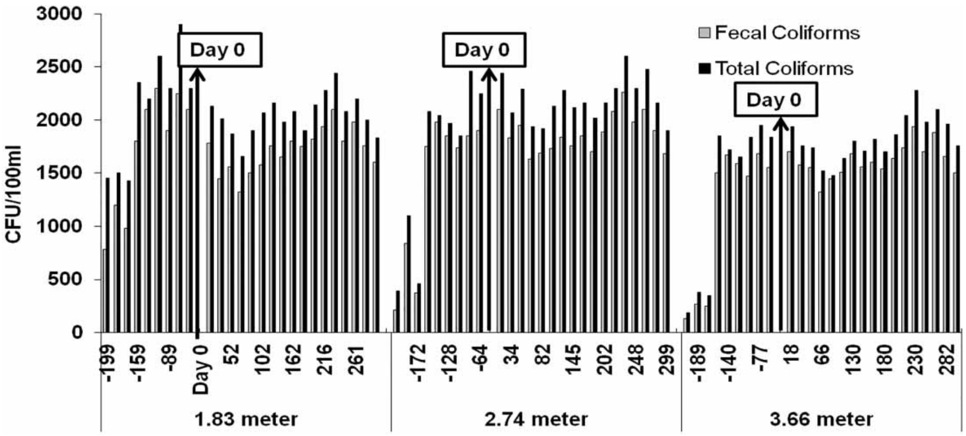

Figure 6 | Variation in concentrations of FC and TC in the leachate at Location II.

COD, ammonia and nitrate concentrations are presented in Figure S10 (Supplementary Material). It can be seen from Figure 5 that the average FC concentration at a depth of 2.1 m was 2,650 CFU/100 mL before the construction of a septic tank, and it reduced to 1,000 CFU/100 mL 299 days after the construction of a septic tank. The FC concentration at a depth of 3.3 m reduced from 1,500 to 750 CFU/100 mL. A similar trend was observed for TC, COD and TOC concentrations. After the construction of the septic tank, contaminant concentrations in the leachate passing through the soil layer below the on-site treatment technology were reduced considerably. At a depth of 2.1 m, the COD concentration reduced from an average value of 200 mg/L before the installation of the septic tank to a value of 50 mg/L after the construction. TOC concentration reduced from an average value of 45 mg/L before the installation of the septic tank to a value of 15 mg/L after the construction.

Conversely, results from pits located within 0.6 m from an existing leach pit in Erumaipatti (where the intervention was not made) (Figure 6) indicated that the contaminant concentrations in the leachate were of the same order of magnitude throughout the study period. Thus, the reduction in the contaminant concentrations in the leachate was likely due to the installation of the septic tank. Box plots for FC, TC, ammonia, nitrate and COD concentrations at a depth of 2.1 and 3.04 m before and after October 2016 (when the intervention was made) are presented in Figure S11 (Supplementary Material) for Location I. Paired comparisons were made using the *t*-test to compare the quality of leachate in soil pits before and after the construction of the septic tank. The pairwise comparison using the simple *t*-test showed that, after the construction of the septic tank, statistically there was significant reduction in concentrations in the leachate with respect to FC ($p = 0.0003$), TC ($p = 0.0002$), COD ($p = 0.0003$), ammonia ($p = 0.003$) and nitrate ($p = 0.0003$) at a 2.1 m depth. Similarly, there was a significant reduction in contaminant concentrations in the leachate with respect to FC ($p = 0.001$), TC ($p = 0.006$), COD ($p = 0.00001$), ammonia ($p = 0.003$) and nitrate ($p = 0.001$) at a depth of 3.3 m. Conversely, leachate at Location II in Erumaipatti showed the same level of FC, TC, COD, ammonia and nitrate concentrations throughout the study period. These results indicate that it is possible to significantly reduce the contaminant concentrations in the leachate from on-site sanitation technologies by replacing soak pits with impervious septic tanks. However, there was still some residual bacteriological concentration in the leachate. Therefore, it should be noted that if the thickness of top soil and weathered zone is not sufficient, the contamination may reach the groundwater eventually unless there is a piped collection system to transport effluent from the septic tank to a subsequent treatment stage in order to achieve the desired effluent quality.

CONCLUSIONS

Groundwater quality in two towns in India, Namakkal and Erumaipatti, was studied to gain insights into the nexus between surface sanitation and groundwater quality in hard rock areas. All wells, irrespective of whether they were deep bore wells or shallow open wells, irrespective of where they were located, were contaminated with FC, TC ammonia, nitrate and COD. The maximum FC concentrations reached 600 and 1,400 CFU/100 mL in some of the bore wells in Erumaipatti and Namakkal, respectively. COD, ammonia and nitrate concentrations in 50% of the wells were more than 30, 5 and 50 mg/L, respectively, indicating that the contamination could be due to improper sanitation. Bacteriological contamination of wells in Namakkal was higher than in Erumaipatti due to urbanization, the type of top soil and the shallow groundwater table. It was found through statistical tests that wells in densely toileted areas in urbanized Namakkal, where the groundwater table was also high, were more contaminated than those located in the open defecation area ($p = 0.019$ in t-test). Replacing a pervious bottom soak pit with a septic tank reduced the FC, TC, COD, ammonia and nitrate concentrations in the leachate collected from soil pits located within 0.6 m of the soak pit. FC and COD concentrations in the leachate reduced from an average value of 2,500 to 1,000 CFU/100 mL and from 200 to 50 mg/L, respectively, at a depth of 2.1 m. Results from this study indicate that the policy for the eradication of open defecation should not only focus on the construction of toilets but should also emphasize the installation of on-site sanitation technologies that are capable of achieving the required effluent quality. Results from this study also indicate that groundwater quality can only be protected if overall sanitation conditions are improved in a holistic way.

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SUPPLEMENTARY MATERIAL

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