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Case report

Groundwater pollution assessment in a coastal aquifer in Cape Coast, Ghana

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ABSTRACT

This work presents an assessment of the chemico-physical and microbial quality of water samples from hand-dug wells in the shallow aquifer of three communities neighbouring the University of Cape Coast, Ghana. Sanitary risk inspection was undertaken at each well location and the physical parameters including electrical conductivity, pH, Dissolved Oxygen (DO) and etc. were measured in situ via probes. Microbial groundwater quality was analysed using membrane filtration method. Samples of water were analysed for the pollution indicator anions including chloride and nitrate. In addition, the possible persistence of bacteria in groundwater environments in the absence of predator organisms were studied and results fitted with exponential, second-order polynomial and linear distribution models.

Sanitary risk inspection and microbial quality results indicate that all the wells were at risk and polluted with total coliforms from on-site sanitation. Twenty-five percent (7 out of 28) of the wells recorded DO concentration within acceptable limits of drinking water standards (> 5 mg/L). Average chloride concentration, 360.5 mg/L (range: 46 mg/L to 844 mg/L) and average electrical conductivity value of 1.5 mS/cm (range: 213 μS/cm to 2.7 mS/cm) were both higher than WHO recommended limits. Acidic conditions (pH < 6.5) were observed in water samples, indicating mineralisation of the aquifer. The high EC values and chloride content in groundwater were attributable to dry atmospheric aerosol deposition and possible mineral dissolution in the aquifer. Bacteria re-growth experiment results indicate that second-order polynomial distribution best describes bacteria inactivation rates in the absence of antagonist predators in our work. Extrapolation of time for complete inactivation of bacteria under groundwater environment ranged from 0.1 to 4 years indicating bacteria can persist in aquifers for long period of time. It was concluded that all the wells are at risk of pollution and polluted with faecal matter and atmospheric aerosols.

1. Introduction

In Sub-Saharan Africa (SSA) shallow groundwater remain an important source of water for the water needs of many rural and urban poor communities. The socio-economic conditions prevailing in many of these rural communities and peri-urban areas differ greatly from those of the urban centres and in most cases influence the choice of water source for various uses. The direct reliance on groundwater sources has been variously ascribed to irregular water supply and the inability of governments to expand water supply networks to these areas [1]. Liddle and co-workers [2] have described the situation as a systematic failure of the formal sector to provide piped water services. In addition, many inhabitants are unable to afford water utility bills [3] and therefore rely on free water from wells and boreholes [4]. Other factors making the groundwater resource consumption popular in the communities include the safety of groundwater from contamination, provision of groundwater facilities in close proximity to beneficiary communities [5] and the resilience of groundwater to the impacts of climate change [6] in parts of SSA [7]. Thus, supporting the crucial role groundwater resources will continue to play in the socio-economic development of SSA. In spite of the above importance, the susceptibility of groundwater to contamination has not received adequate attention in many areas of the World [8], especially in communities and settlements in SSA where groundwater remains the main source of water for various water needs including

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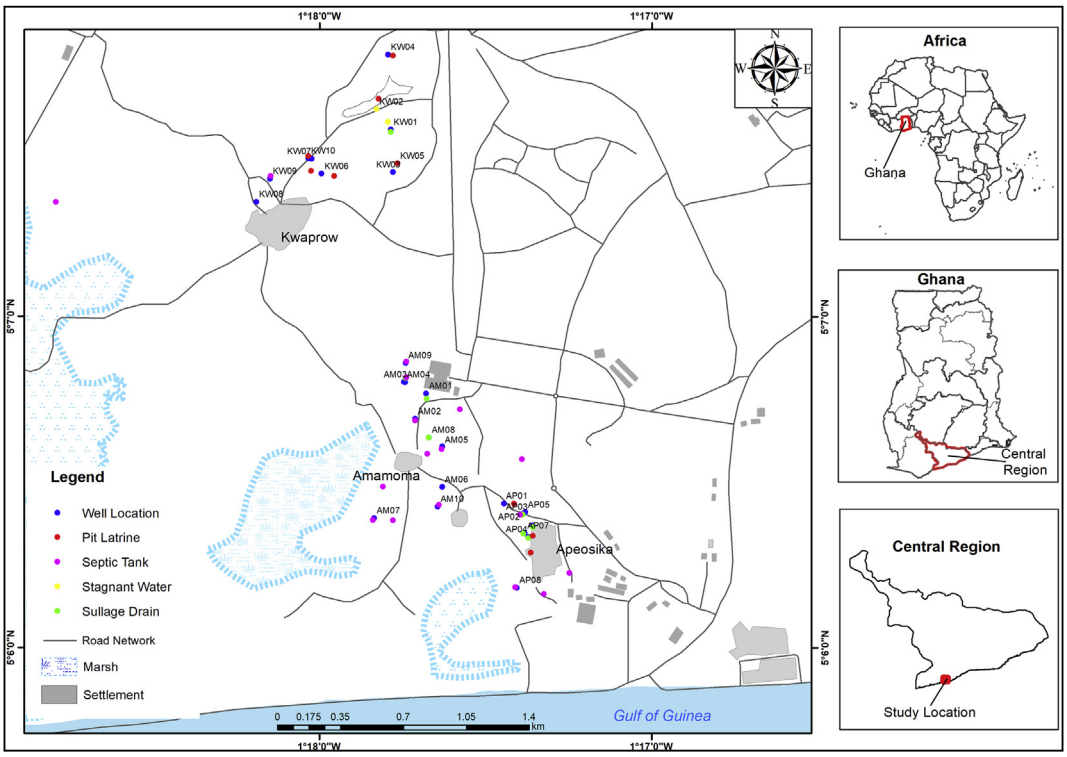

Figure 1. Location map (a) Area under study showing wells and potential sources of contamination (b) Central Region (c) Map of Ghana Showing the Central Region (d) Africa showing Ghana.

drinking. The general assumption that groundwater is safe from pollutants including pathogenic microorganisms is misleading, as recent research reports [1,9,10], indicate that water samples from groundwater sources in many parts of the world are polluted with faecal matter and faecal indicator anions e.g. nitrates and or chlorides [11,12,13,14]. Recent research have implicated on-site sanitation facilities such as pit latrines, leaking septic, waste water flowing on the surface and other improper waste disposal methods serving as point sources of groundwater contamination in many urban areas [15,16], peri urban [1] and rural areas [17,18] in SSA. In addition, faecal pollution of groundwater sources has been linked to infiltration of contaminated surface water [19]. Ferrante et al [20] has highlighted on the risk posed by some physico-chemical parameters to groundwater consumers and reiterated on the importance of safe and adequate distances between pit latrines and water sources.

Compounding the problem is the absence of regular monitoring of the drinking suitability of water from groundwater sources [21] together with the lack of conventional network sewage system for sewage treatment [22]. Bacteriological groundwater quality and groundwater chemistry play crucial roles in the intended use of groundwater. Regardless of the source, drinking water is expected to be free from high concentration levels of ions and chemicals that may pose public health threat to consumers [23]. In spite of this, there are shortfalls in knowledge with regards to quality of water from groundwater sources [7]. Efforts are continuously being made to improve the protection of wells and boreholes. In the absence of regular monitoring of wells, majority of the people who rely on groundwater sources for various uses in SSA may be at risk to the contraction of various diseases.

This work presents an assessment of drinking water suitability of water from wells dug in a coastal aquifer of three communities bordering the University of Cape Coast in Ghana. The vulnerability of these hand dug wells to pollution is assessed by the use of the sanitary risk method. Also, the possible persistence of *E. coli* in groundwater environments is studied.

2. Methods

2.1. The study area

Samples were taken from wells located within three communities; Amamoma, Apewosika and Kwaprow bordering the University of Cape Coast in the Cape Coast Municipality. Water samples were taken from 36 wells serving as the main source of water for the population in these communities (Figure 1). Cape Coast is an urban municipality in the central Region of Ghana and lies between 05°06′00″N and 01°15′00″W and bounded on the south by the Gulf of Guinea. The township is characterised by both formal communities and urban slums with a population of 169,894 [24]. The Kakum river drains the western part of the township and flows into the Gulf of Guinea with other minor streams flowing into wetlands, and in addition, the Fosu lagoon lies to the south of the township.

Annual rainfall varies from 1000 to 2000 mm [25] between April and June. Like other parts of Ghana, the area is characterised by wet and dry seasons. Two wet periods occur in the area; first wet period is between May and June and the second from September to October; Dry periods are between December and March.

The geology of the area comprises of the Sekondian formation which is made up of Palaeozoic sedimentary rocks: sandstones interbedded with shales [26] and the basin type granitoids [27]. The rocks contain shale and clay mixed with gravels. According to Dapaah-Siakwan and Gyau-Boakye [28] the sedimentary rocks were intruded by igneous activity including block faulting, the result is a complex of granite, metamorphic rocks: gneiss and schist. Groundwater occurrence in the area is controlled by secondary discontinuities including faults, fractures joints and weathered rocks [29].

2.2. Sanitary risk inspection and measurements of physical parameters

Field work was conducted to undertake sanitary risk inspection, measure physical quality parameters of well water and to take samples

Table 1. Well depth, depth to water surface, risk assessment and bacteriological quality results.

Well ID	Well Depth (m)	Depth to Water table (m)	Risk score (-)	Remarks (-)	*E. coli* (# cells/100 mL)	TTC (# cells/100 mL)
AM01	4.92	3.22	2	Low	20	343
AM02	5.55	4.15	5	intermediate	1	364
AM03	3.83	2.63	6	intermediate	20	79
AM04	3.81	2.61	7	High	0	401
AM05	6.18	5.88	4	Intermediate	43	406
AM06	2.70	1.1	7	High	0	188
AM07	2.41	0.61	9	Very High	4	10
AM08	5.67	4.37	4	Intermediate	26	56
AM09	3.02	1.92	5	intermediate	112	412
AM10	5.34	4.74	5	intermediate	23	409
AM11	5.16	3.76	8	High	116	460
AM12	4.41	1.91	6	intermediate	5	108
AM13	4.98	3.88	6	intermediate	13	138
KW01	5.29	4.79	6	intermediate	0	329
KW02	4.36	-	5	intermediate	300	469
KW03	5.48	4.38	5	intermediate	175	495
KW04	3.47	3.37	8	High	151	471
KW05	6.44	5.14	4	intermediate	0	1
KW06	4.40	3.6	7	High	0	300
KW07	3.10	2.2	4	Intermediate	0	10
KW08	3.93	3.13	8	High	0	300
KW09	5.78	5.78	5	intermediate	300	314
KW10	3.28	2.48	4	intermediate	0	377
KW11	6.52	4.72	4	intermediate	36	760
AP01	1.31	0.31	6	intermediate	5	137
AP02	8.68	5.38	6	intermediate	2	3
AP03	3.01	2.71	5	intermediate	3	73
AP04	6.13	5.33	6	intermediate	0	450
AP05	4.45	3.45	6	intermediate	3	303
AP06	2.44	0.64	6	intermediate	75	395
AP07	5.13	4.43	6	intermediate	0	153
AP08	1.96	1.26	6	intermediate	0	50
AP09	4.79	1.59	6	intermediate	2	65
AP10	1.96	1.26	6	intermediate	5	83
AP11	8.35	4.15	6	intermediate	144	408
AP12	7.80	7.4	6	intermediate	0	54

for chemical and microbial quality analyses. Field work was conducted in the dry season. Sanitary risk assessment involved the physical inspection of wells, identification of potential sources of microbial pollution and the measurement of well depths and depth to the water surface in wells from the ground surface. The risk assessment method followed procedures and methods used by Howard et al. [30] and Lutterodt et al. [1], and involved identification of specific information for assessment of risk to microbial pollution of the wells [31]; these included 11 risk factors such as pit latrine within a distance of <10 m from the wells, nearest pit latrine uphill, protective fencing missing or absent, collection of spilt water in the apron area and etc. The specific diagnostic information (risk factors) that were 'Yes' (risk present) for the source in question were then summed up to produce a risk score on a scale of 1–11. The scores were further grouped into very high for a total score of 9–11, high for 6–8 and score ranges of 3–5 and 0–2 were, respectively, assigned intermediate and low risk. Details of procedures used to assess risk posed by 11 commonly identified factors to contamination of the wells can be found in a British Geological Survey (BGS) report [31].

Physical quality parameters, such as Temperature and Electrical Conductivity (EC), and pH were, respectively, measured using a conductivity meter Cond340i (WTW GmbH, Weilheim Germany) calibrated at 25 °C and a pH meter pH340i (WTW GmbH, Weilheim Germany). Dissolved oxygen (DO) and salinity were analysed using the Oakton Waterproof PCD 650 Multi-checker (Eutech Instruments Europe B.V., Nijkerk Netherlands).

2.3. Measurements of chemical pollution parameters

Nitrate, phosphate, sulphate and chloride in water samples from the wells were analysed to assess the pollution status of the wells. To do this, 250 mL of well water was collected in sterile polypropylene bottles and by means of a syringe 25 ml of sample was filtered through 0.45 μm cellulose acetate filter paper (Carl Roth GmBH + Co, KG, Karlsruhe, Germany) into scintillation vials. Samples were then stored in a cool box and transported to the water quality laboratory of the Water Research Institute of the CSIR and then stored at -20 °C until analyses were conducted using ICS-5000 detector/Chromatography Module Model DC-5 (Dionex corporation, Sunnyvale, CA, USA). In order to avoid sampling stagnant water, all wells were sampled late morning when the communities have reached their maximum water abstraction.

2.4. Microbial quality assessment and E. coli re-growth experiments

Bacteriological water quality assessment followed previously used methods [32]. To do this, 100 mL of water sample from hand dug wells was collected in sterile polypropylene bottles and pressed through an 0.45μm cellulose acetate filter paper by means of a syringe. The filter was

Table 2. Physical and chemical quality of water samples from wells.

Well ID	Chloride (mg/L)	Phosphate (mg/L)	Nitrate (mg/L)	Salinity (mg/L)	Temp (°C)	pH (-)	EC (μS/cm)	DO (mg/L)
AM01	217	0.7	0.4	391.1	29.9	4.9	1027	1.9
AM02	122	0.4	9.2	219.9	29.3	5.9	912	6.8
AM03	251	0.3	16.3	453.4	28.9	5.7	1359	4.9
AM04	239	0.1	4.4	432.1	28.6	5.1	1108	3.3
AM05	150	0.3	19.8	273.4	29.1	6.1	989	6.5
AM06	81	0.3	14.5	146.7	28.9	4.4	329	8.2
AM07	145	0.2	23.2	261.9	28.8	5.2	1018	6.3
AM08	124	0.1	10.1	224.6	31.1	5.2	1123	5.9
AM09	164	0.2	14.1	296.3	28.7	5.8	676	2.6
AM10	141	0.3	12.8	254.1	28.5	5.4	688	2.0
KW01	294	0.3	22.9	528.6	29.4	5.7	1537	3.2
KW02	388	0.2	48.4	700.5	29.9	5.0	2109	3.1
KW03	534	0.6	9.7	964.7	32.8	6.2	2470	3.6
KW04	844	0.2	3.1	1523.0	32.1	6.0	3975	3.5
KW05	541	1.2	44.4	974.0	31.6	6.3	2688	3.4
KW06	366	0.5	1.3	661.5	32.3	6.8	1886	4.1
KW07	211	0.4	4.4	383.2	31.2	6.1	1854	6.6
KW08	262	0.4	41.6	472.9	32.2	6.4	1408	4.3
KW09	320	0.2	8.4	578.2	28.8	6.5	1631	2.5
KW10	46	0.2	4.0	81.3	32.0	6.5	213	6.6
AP01	558	0.6	0.9	1006.0	29.7	4.3	2481	2.8
AP02	253	0.2	14.1	455.4	29.0	4.9	1364	2.1
AP03	227	0.9	37.2	407.6	29.6	5.1	1176	2.5
AP04	235	0.2	5.3	426.9	29.7	5.3	1093	5.1
AP05	231	0.4	35.9	414.2	30.1	5.5	1158	3.2
AP06	248	0.2	37.3	446.3	29.1	4.1	1095	2.4
AP07	456	0.2	40.1	823.8	28.5	4.0	2080	2.0
AP08	398	0.3	39.5	715.3	29.0	4.9	1836	1.6

then placed on Chromocult agar (Merck, Whitehouse Station, NJ) plate, and then transported to the molecular microbiology Laboratory at the School of Biological Sciences, University of Cape Coast and incubated at 37 °C for a day. The number of thermo-tolerant coliform bacteria cells were then counted.

The purple coloured colonies on the Chromocult agar plates allowed for the detection, selective counting and isolation of *E. coli* from other types of bacteria species (e.g. Enterobacter and salmonella) growing on the agar plates. A sterile toothpick was used to pick a single colony of *E. coli* from the agar plates and inoculated in 5 ml of Nutrient Broth (Hi Media Laboratories, Vadhani, India) in a test-tube followed by incubation at 37 °C for 24 h. Pure culture was stored in a refrigerator at 5 °C and transported to the T-GroUP field laboratory in Dodowa, Accra for bacteria regrowth assessment.

To assess the possibility of *E. coli* re-growth and/or their persistence in groundwater environment in the absence of predators as a worst-case scenario, six selected namely (AS8, AS9, FS3. FS4, KS01, and KS02) *E. coli* strains (pure cultures) chosen from wells with range of different chemical concentrations and parameters (Nitrate, Phosphate, and Chloride) from the minimum to maximum were selected and re-grown in nutrient broth and washed in groundwater samples. To do this, 25 ml of nutrient broth was inoculated with 1ml of each of the pure culture formed, from isolation of single colonies and incubated for 24 h at 37 °C to obtain a cell concentration of $\sim 10^9$ cells/ml. Bacteria were washed and centrifuged (2885 × g in an ALC PK 120), Cologno Monzese (MI), Italy three times in filtered groundwater samples abstracted from the wells in which individual bacteria strains were isolated. The washed cells were then re-suspended in filtered groundwater samples from the respective wells from which the strains were isolated. Cells were diluted to obtain an approximately cell suspension of 10^6 cells/ml. Samples were then stored in a sterile brown opaque bottle followed by plating 100μL on Chromocult agar at 2–5 days intervals. Plates were stored at room temperature (similar to the measured groundwater temperature in the area) between 18-24 h followed by counting of cells. The re-growth experiments were conducted over a period of 32 days.

2.5. Data analyses

All statistical analyses were performed using IBM SPSS Statistics version 25 (IBM corp., Armonk, NY, USA, 2019). Correlation analysis was performed to reveal the possible association between all parameters studied (chemico–physical, microbial quality, total coliforms (TTC) and *E. coli*, risk score, well depth, depth to water table). Exponential, linear and polynomial distributions were used to fit the results of bacteria re-growth (relation between number of cells and time) experiments. Goodness of fit was evaluated using the coefficient of determination (R^2). In case $R^2 > 0.9$, the fit was considered excellent. For $0.8 \leq R^2 \leq 0.9$, the fit was considered good, and when $R^2 < 0.8$, the fit was considered weak. The Chick-Watson model [33] in equation [1] below was used to estimate and extrapolate the bacteria die-off coefficient k_d (per day) and the time (t) in days needed for complete bacterial inactivation (no *E. coli* cells in water samples), respectively.

$$C(t) = C_0 e^{-k_d t} \quad (1)$$

C(t) is the measured *E. Coli* cell suspension (# cells/mL) at time t and C_0 the initial cell suspension and k_d (per day) is the decay rate constant.

3. Results

3.1. Sanitary risk inspection and microbial quality

Sanitary risk inspection scores and bacterial suspension (Total coliforms and *E. coli*) in 100 mL of well water samples are presented in

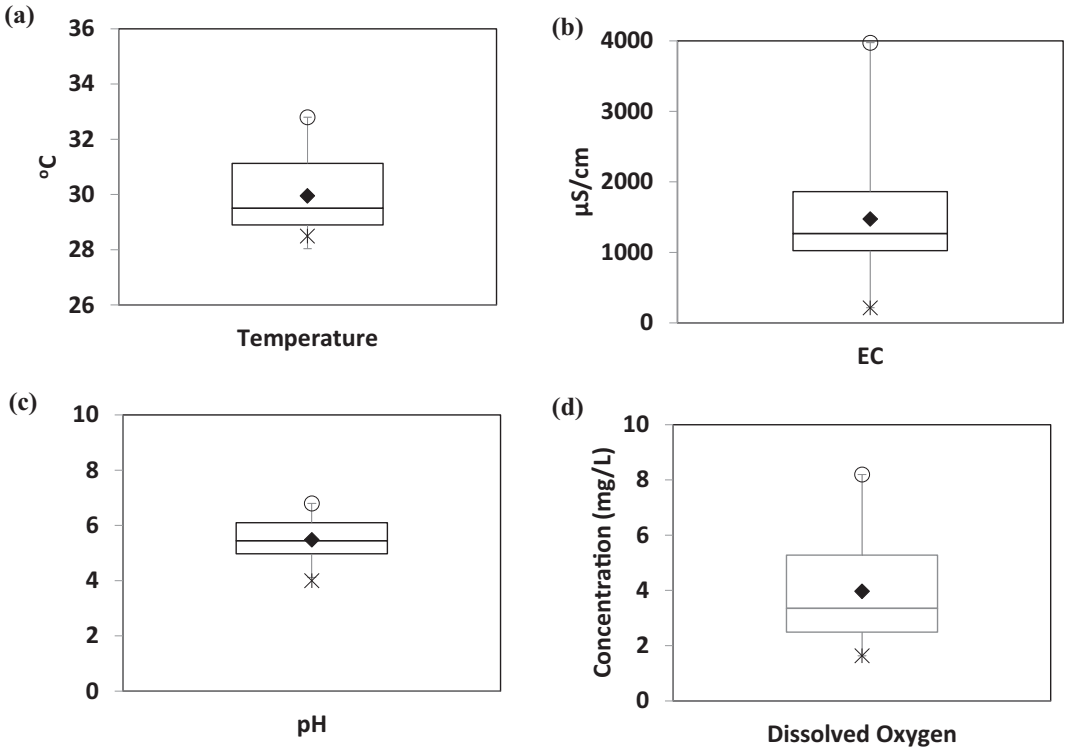

Figure 2. Range of concentrations of measured physical quality parameters displayed by the box-and-whisker method (a) Temperature (b) Electrical Conductivity (c) pH (d) Dissolved Oxygen.

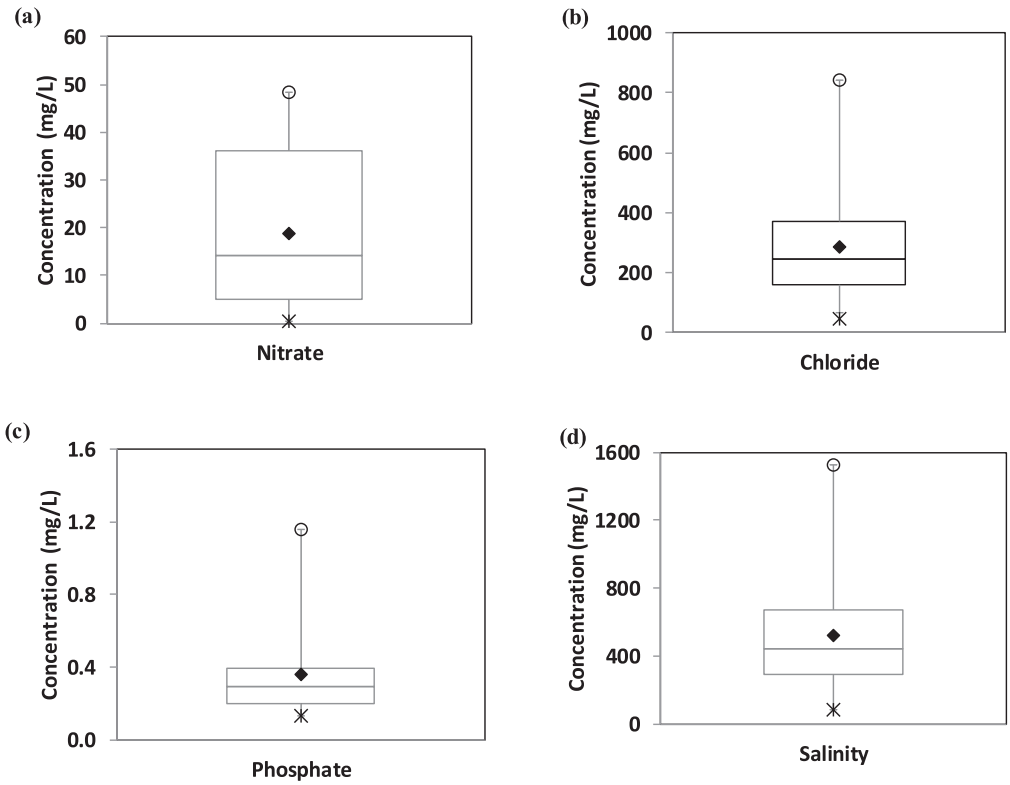

Figure 3. Range of concentrations of chemical parameters measured in water samples displayed by the box-and-whisker method (a) Nitrate (b) Chloride (c) Phosphate (d) Salinity.

Table 3. Correlation matrix between the parameters under study.

	Cl	PO4	NO3	Salinity	Temp	pH	EC	DO	Risk score	*E. coli*	TTC	Well Depth
PO4	0.27											
NO3	0.09	0.20										
Salinity	**1.00**	0.27	0.09									
Temp	0.37	0.34	-0.13	0.37								
pH	0.03	0.17	-0.24	0.03	0.59							
EC	**0.97**	0.27	0.08	**0.97**	0.44	0.12						
DO	-0.45	-0.17	-0.29	-0.45	0.20	0.27	-0.34					
Risk score	0.23	-0.34	0.13	0.23	-0.05	-0.10	0.19	0.07				
E. coli	0.33	-0.19	0.06	0.33	0.06	0.17	0.33	-0.24	-0.09			
TTC	0.07	-0.27	-0.21	0.07	0.12	0.22	-0.03	-0.08h	-0.04	0.46		
Well Depth	-0.04	0.04	-0.05	-0.04	0.04	0.25	0.01	-0.08	-0.32	0.08	0.08	
Depth to Water Table	0.07	0.05	-0.03	0.07	0.10	0.41	0.11	-0.10	-0.33	0.21	0.22	**0.92**

Bold indicate strong correlation between two parameters.

Table 1. The table also presents the depth of wells and depths to water level in the wells.

Results of sanitary risk assessments indicate that 25 (69.4%) of the wells have been sited at distances of at most 10 m from a pit latrine with another 69.4 % of these wells sited on the downstream side of the latrines making them more vulnerable to pollution by faecal matter. Also, 25 of the wells (69.4%) were found to be located within 10 m of other sources of pollution including animal excreta and waste dump. In addition, stagnant water due to poor drainage and broken channels were observed within the surroundings of four (11.1%) of the wells and at radial distances of less than 2 m. Other risk factors identified and their corresponding number of wells around which they were identified as follow: faulty drainage permitting ponding around the wells (4 wells-11.1%), inadequate/short apron walls allowing surface water to enter wells (4 wells-11.1%), concrete floor of diameter <1 m (27 wells, 75%), inadequate sealing at depths of 3 m below the ground (11 wells-30.6 %), cracks found in the concrete floor around wells and could permit water to enter (17 wells - 47.2 %), ropes attached to buckets used for fetching water from the wells left on the ground and likely to be contaminated (27 wells, 75%). None of the wells sampled had protective fencing around them indicating that all wells were at risk of microbial contamination.

Final risk interpretation shows that one (2.8%) well (AM07) and another (AM01) were at very high and low risk to contamination, respectively. Furthermore, 6 (16.6%) of the wells were identified to be at high risk of contamination (Table 1). Results also indicated that 28 (77.8%) of the wells have intermediate risk to pollution. Well depth ranged from 1.31 m to 8.68 m, whilst the depth to the water level was between 0.31 to 7.4 m (Table 1).

Concerning microbial quality, all wells were contaminated with total coliforms with number of cells per 100mL of water ranging from a single cell in well KW05 to 760. Determination of *E. coli* suspension in water samples as an indicator of faecal pollution showed no *E. coli* cells in 12 of 36 sampled wells, and with two of the wells (KW02 and KW09) having a maximum of 300 cells/100mL.

Based on the results, we can conclude that majority of the wells are polluted with infiltration of wastewater from the surrounding environment. The possibility of leaking effluents from pit latrines in addition to risk factors identified at well locations may be the likely culprits.

3.2. Physical and chemical quality of groundwater

Results of physical and chemical quality of water samples taken from the wells are shown in Table 2. Figures 2 and 3, display box-and-whisker plots of chemical quality and physical parameters, respectively. The chloride content from the wells ranged from 46 mg/L in KW10 to 844 mg/L in KW04. Water samples from 13 of the wells showed high chloride content with concentrations higher than 250 mg/L-the WHO [34] recommended limit for drinking water. An overall average of 360 mg/L chloride concentration in the wells was computed.

Th phosphate content in groundwater ranged from 0.1 mg/L (AM04 and AM08) to 1.2 mg/L (KW05), an average phosphate content in the wells was computed as 0.4 mg/L. The concentration of NO_3–N in the well water samples varied from 0.4 mg/L (AM01) to 48.4 mg/L (KW02), and with an average of 18.7 mg/L. The nitrate content in all the wells were below the 50 mg/L WHO recommended standard for drinking water [34]. The minimum salinity value measured was 81.3 mg/L (KW10) and a maximum of 1523 mg/L (KW04), an average salinity of 518.5 mg/L was computed. Groundwater temperature varied between 28.5 °C (AP07) and 32.8 °C (KW03) with a mean temperature of 30 °C. Measured pH values were all below 7 (ranged between 4.0 and 6.8) indicating acidic conditions in groundwater environments in the area. Average EC value of 1.5 mS/cm is computed for measurements ranging from 213 μS/cm (KW10) to 2.7 mS/cm (KW05). Concentration of dissolved oxygen (DO) in groundwater samples ranged between 1.6 mg/L (AP08) to 8.2 mg/L (AM06) with an average of 4.0 mg/L 25% of the wells had DO concentration within recommended of >5 mg/L for drinking water [34].

From the high average chloride concentration and high EC values in addition to the acidic conditions in the aquifer, we can conclude that, the water is highly mineralised, not hygienic and good enough for drinking unless treated.

3.3. Correlation between studied parameters

Correlation matrix of parameters under study is shown in Table 3. The results indicate non-correlation between all parameters except for pairs of parameters with theoretical link (e.g. salinity-chloride, EC-chloride, EC-salinity) resulting in obvious strong correlation ($R^2 > 0.9$). Significant results are the non-correlations between bacterial suspension (*E. coli*, TTC) on one hand and risk scores, hydrogeological parameters (well depth and depth to water levels), pollution indicator parameters (chloride and nitrates) on the other hand. Also, there was no direct correlation in-between pollution parameters (nitrate, chloride and phosphate). From the results, it can be concluded that multiple sources of pollution may be responsible for the contamination of wells within the study area. The relation between inactivation rates and chemico-physical parameter revealed non-correlation for all parameters with the exception of DO that showed weak correlation weak inverse correlation of 0.72 (data not shown).

3.4. Bacteria re-growth experiments

Possible re-growth of bacteria in groundwater environments revealed inter-strain variability in their die-off rates. Reduction in cell suspension varied widely amongst the strains after 32 days with cell suspension

Table 4. Distribution in cell suspension against time, inactivation rates and extrapolation of days for complete inactivation based on the Chick-Watson Model.

Strain	Exponential	Polynomial	Linear	Inactivation rates	Days for complete inactivation
AS9	0.89	0.96	0.92	0.01	32.6
AS8	0.90	0.98	0.75	0.49	1450.9
FS3	0.88	0.97	0.95	0.04	414.5
FS4	0.97	0.98	0.82	0.12	124.0
KS01	0.91	0.98	0.99	0.05	322.4
KS02	0.56	0.97	0.94	0.10	79.8

ranging from 1.4×10^6 cells/ml (AS9) to 0 (AS8) indicating a difference of 6 log-units. Intra-strain variation showed 6 log reduction in cell suspension for AS8 and KS02 with the least being 0.15 log units recorded for AS9.

Distribution in cell suspension over time indicated that second-order polynomial fitted best for all six strains with $R^2 \geq 0.97$ in all cases even though exponential and linear distributions also fitted well with R^2 values of at least 0.8 with the exception of exponential fit for KS02 and linear for AS8 which were respectively, 0.56 and 0.75. The estimation of inactivation rates using the Chick-Watson model [33] revealed values from 0.01/day (AS9) to 0.049/day (AS8) (see Table 4). The duration of time extrapolated for complete inactivation in the absence of predators ranged from 32.6 days (AS9) to 1450.9 days for AS8. From the results, we can conclude that, bacteria can persist in groundwater environments for periods ranging from one month to four years in the absence of predators as a worst-case scenario.

4. Discussion

4.1. Contamination of wells by faecal matter

Results of sanitary risk inspection and microbial quality assessment, revealed that all the wells are at risk of pollution and contaminated with faecal matter. Lutterodt et al. [1] made similar observations and attributed the presence of *E. coli* and total coliforms to effluents from pit latrines and other pollution sources similar to the various risk sources we identified in our work. A number of research reports in the literature has also implicated the presence of various improper sanitation management practises to the high loads of bacteria in groundwater samples [8,16].

In our case, the absence of protective fencing around all wells studied, siting of wells at short distances on the downstream side of pit latrines and waste dumps in addition to the shallow nature of the depth to the water surface in the wells (<8 m, Table 1) together ensures that effluents and coliforms from these risk sources may have short time to reach the water table from advective transport. The risk factors identified may therefore be responsible for the poor microbial groundwater quality in the area. Even though we attribute the poor microbial water quality in our wells to identified risks, statistical analysis revealed non-correlation between risk scores and microbial counts (Table 3). Risk factors to pollution are both dependent on the presence of the risk in addition to the distance of the identified risk to the source in some cases e.g. pit latrines and septic tanks. The observed non-correlation between microbial contamination and risk scores is common in the literature [35,36]and can be ascribed to factors not captured by the sanitary risk assessment methodology; an example is the geological characteristics of an aquifer in the immediate surrounding of the well as reported by Ferrera et al [18]. More specific examples are [1]: physical heterogeneity due to pores, fractures and root channels which creates preferential flow paths for rapid transport of microbes/colloids and other contaminants [37,38,39] and [2] grain surface charge heterogeneity which promotes bacteria retention during transport in saturated porous media or aquifers [40,41]. Also, microbial population heterogeneity [42] may have profound impact on the number of cells reaching groundwater sources regardless of the distance between potential pollutant sources and hand dug wells. The aquifer under study comprises of weathered sedimentary and igneous rocks. Weathering is known to create preferential flow zones within the sub-surface in addition to the modification of mineral surface grain charges. These might have contributed to the lack of association between cell suspension in water samples and risk scores in addition to other unidentified factors.

4.2. Physical and chemical quality of well water

The observed high values of EC and chloride contents in water samples can mainly be linked to the short distance (<2 km) between the sea/coast to the aquifer, even though identified wastewater freely flowing in the area may be an additional factor. Our results are similar to observations made by Ganyaglo and co-workers [43] who measured high EC values ranging from 0.5 to 6 mS/cm in a coastal aquifer with similar hydrogeological characteristics and located on the East of our study area. A number of research reports in the literature also recorded the EC and chloride ranges we observed in our work [44]. Sea water intrusion and or sea aerosol spray have variously been implicated for high EC and chloride concentrations in coastal aquifers [43,45]. In our work, we ruled out the possibility of the influence of sea water intrusion due to:

1) The shallow nature of the sampled wells (depths <9 m) ensuring that they do not intersect seawater which intrudes at deeper levels due to their high density in nature.
2) The seemingly inverse relation between parameter values of contour plots (data not shown) which showed high values of EC, chloride, salinity and DO at distances further away from the sea.

This assertion is supported by Ganyaglo et al, [43] who used Na/Cl ratios to infer sea aerosol deposition as the main source of high chloride and EC in the shallow wells they studied. We therefore conclude that high values of the parameters may be due to dry atmospheric aerosol deposition even though infiltrated wastewater and mineral dissolution might have contributed to the Chloride and EC values.

Even though most pH values reported in the literature for coastal aquifers are within the alkaline range; e.g. [44], due to the alkaline nature of sea water. Our results indicated acidic conditions in groundwater of the area. Working in the same area, Ganyaglo et al. [43] and Yao [27], observed acidic conditions, with Yao [27] recording an average of 6.46 with a minimum of 2.25. The acidic conditions observed in our work can be ascribed to wastewater recharge and interaction between the sekondian formation (sandstones, schist) and groundwater.

The nitrate content is observed to be within the drinking water standards for all wells, this is even though they are supposed to have been released from the same sources (wastewater and effluents from pit latrines) as the high numbers of *E. coli* and TTC. This observation can be attributed to possible presence of a nitrate sink in the aquifer, conservative transport of nitrates to deeper groundwater levels, and dilution of infiltrated wastewater through mixing with unpolluted groundwater. Although the results indicate non-correlation ($R^2 = 0.05$) (Table 3) between well depth and nitrate, the possibility of conservative transport of the nitrates to deeper levels in the aquifer cannot be ruled out as well depth range of <7 m is not

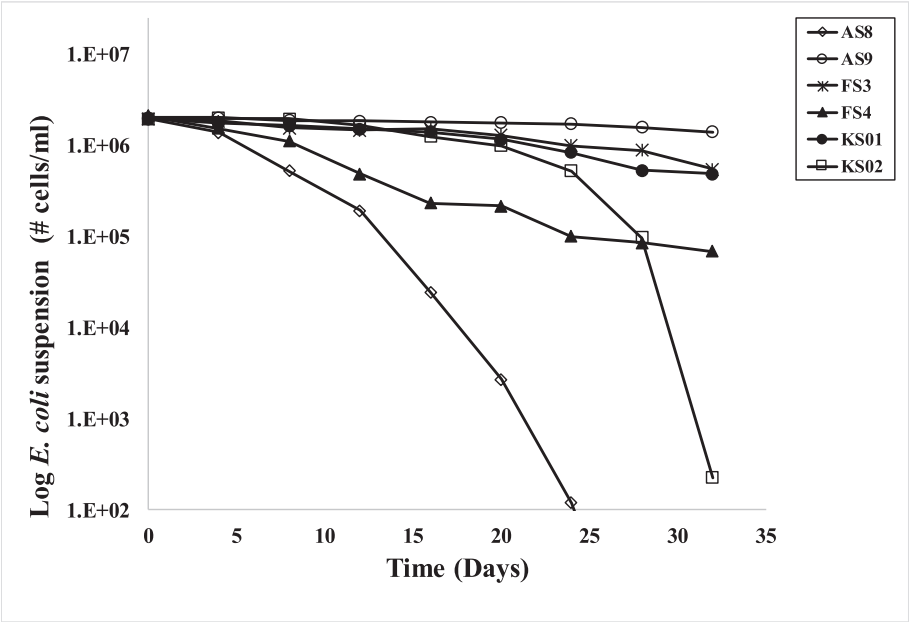

Figure 4. Distribution in cell suspension against time, inactivation rates and extrapolation of days for complete in inactivation based on the Chick-Watson Model.

wide enough to influence an association between the two parameters, in addition dilution of nitrate content might have occurred. The assertion of dilution and conservative transport as nitrate reduction mechanisms is supported by the deductions that the high DO values possibly occurred at the interface between the open wells and the atmosphere where oxygen concentrations are expected to be high due to diffusion of the gas from the atmosphere. In addition, the two implicated nitrate reduction mechanisms would be dominant within the aquifer.

Rivett et al. [46] has also shown that an upper limit of DO concentrations of between 1 to 2 mg/L is needed for denitrification to occur in groundwater environments under the influence of septic waste plume. In our work an average of 4 mg/L was measured with 26 out of the 28 wells having DO content of above 2 mg/L, therefore ruling out bacterial mediated denitrification in the aquifer as a major influence of the low nitrate concentrations. It can therefore be concluded that a possible combination of conservative transport and dilution may be responsible for the acceptable nitrate concentrations recorded. The nitrate-chloride ratios were low ranging from 0 to 0.2 (data not shown), indicating a high possibility of different sources of input. A low inverse correlation between chloride and dissolved oxygen may also indicate different sources of input with dissolved oxygen likely through wastewater recharge and atmospheric interaction with the aquifer.

4.3. Implication of bacteria survival rates on vulnerability of hand dug wells

Our results show that second-order polynomial model fitted best for all strains. The inadequacy of the use of first order expressions in the description of bacterial re-growth has been reported in the literature [47]. The dominant quadratic distribution we observed in our case can be ascribed to the observed pseudo lag-stationary phase before the inactivation stage for all strains studied and an initial short (pseudo lag/-growth) growth period observed (Figure 4) prior to the advent of the death phase for two of the strains (KS02 and AS9) studied.

Our next article under preparation would provide more insight into the application of a second-order polynomial in extrapolation of time for inactivation of 99.99% cells in batch cultures. The survival rates of *E. coli* in groundwater environments is very complex and known to be influenced by a number of factors including pH, temperature [48], nutrient concentration in addition to the geochemistry of aquifer [49] and chloride concentration [50]. In our work, we observed non-correlation between k_d and all chemo-physical parameters indicating low influence of the parameters on bacterial survival rates in groundwater of the area. This observation is difficult to explain and may possibly be due to a complex combination of numerous reasons including environmental, biological and geochemical factors.

The observed low inactivation rates may be due to the possible presence of cations in groundwater as a result of mineral dissolution. For example, McFeters and Stuart [51] measured low die-off rates in their experiments when they increased ionic strength of their solutions. Basnet [52], also observed low *E. coli* inactivation rates in groundwater surrogate made up of divalent cations compared to inactivation rates in demineralised water. The high survival rates of bacteria in groundwater environments of the area has an implication on the protection of wells from contamination by faecal matter. The location of pit latrines at distances ranging from 10-30 m from some of the wells is an indication of high vulnerability of the wells to contamination. The long duration (0.1–4 years) of possible survival of bacteria, in addition to the continuous abstraction of groundwater by the communities for various uses increases the likelihood of well contamination. The continuous abstractions of water would lower the water table around the wells and increase the radii of influence around the wells. This can eventually lead to intersection of well-head-protection-areas (WHPA) and potential pollutant sources.

5. Conclusions and recommendations

Field work involving sanitary risk inspection, measurement of physical quality parameters and sampling of water for microbial and chemical analyses were conducted within three communities around the environs of the University of Cape Coast in Ghana. Also, experiments to assess the possible re-growth of bacteria was conducted. From the results obtained the following conclusions are made:

- All the wells were contaminated with faecal matter with infiltration of wastewater from the surrounding environment, leaking effluents from pit latrines and the various identified potential pollution sources as the main possible culprit.

- Groundwater in the study area is mineralised and acidic with average EC values and chloride concentrations above drinking water standards.
- Bacteria (*E. coli*) can persist in groundwater environments within the study area for periods ranging from one month to four years in the absence of predators as a worst-case scenario.

Declarations

Author contribution statement

George Lutterodt, Bright Addy: Conceived and designed the experiments; Wrote the paper.

Michael K. Miyittah: Analyzed and interpreted the data.

Ebenezer D. O. Ansah: Contributed reagents, materials, analysis tools or data.

Mohammed Takase: Performed the experiments; Contributed reagents, materials, analysis tools or data.

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Data availability statement

Data will be made available on request.

Declaration of interests statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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