Assessing the Influence of Hand-Dug Well Features and Management on Water Quality

Environmental Health Insights
Volume 18: 1–17

DOI: 10.1177/11786302241249844

Christian Julien Isac Gnimadi[1], Kokoutse Gawou[2], Michael Aboah[3], Emmanuel Odame Owiredu[4] and Junias Adusei-Gyamfi[1]

[1]Department of Environmental Science, College of Science, Kwame Nkrumah University of Science and Technology, Kumasi, Ghana. [2]Industrial Chemistry Section, Department of Chemistry, College of Agricultural and Natural Science, University of Cape Coast, Cape Coast, Ghana. [3]Department of Environmental Science, School of Biological Science, University of Cape Coast, Cape Coast, Ghana. [4]Department of Statistics and Actuarial Science, College of Science, Kwame Nkrumah University of Science and Technology, Kumasi, Ghana.

ABSTRACT: Underground water quality can be affected by natural or human-made influences. This study investigates how the management and characteristics of hand-dug wells impact water quality in 3 suburbs of Kumasi, Ghana, using a combination of qualitative and quantitative research methods. Descriptive analysis, including frequency and percentages, depicted the demographic profiles of respondents. Box plot diagrams illustrated the distribution of physicochemical parameters (Total Dissolved Solid [TDS], Electrical Conductivity [EC], Turbidity, Dissolved Oxygen [DO], and Temperature). Factor analysis evaluated dominant factors among these parameters. Cluster analysis (hierarchical clustering) utilized sampling points as variables to establish spatial variations in water physicochemical parameters. Cramer's V correlation test explored relationships between demographic variables and individual perceptions of water management. One-way ANOVA verified significant mean differences among the physicochemical parameters. Logistic regression models assessed the influence of selected well features (e.g., cover and apron) on TDS, pH, Temperature, Turbidity, and DO. The findings revealed that proximity to human settlements affects water quality, and increasing turbidity is associated with unmaintained covers, significantly impacting water quality ($P < .05$). Over 80% of wells were located within 10 to 30 m of pollution sources, with 65.63% situated in lower ground and 87.5% being unmaintained. Other significant contamination sources included plastic bucket/rope usage (87.50%), defective linings (75%), and apron fissures (59.37%). Presence of E. coli, Total coliform, and Faecal coliform rendered the wells unpotable. Factor analysis attributed 90.85% of time-based and spatial differences to organic particle decomposition factors. However, Cramer's V correlation analysis found establishing association between demographic factor associations with individual perceptions of hand-dug well management difficult. It is encouraged to promote hand-dug well construction and maintenance standards to ensure that wells are properly built and protected from contamination sources.

KEYWORDS: Well, water quality, sanitary inspection, water pollution, factor analysis, cluster analysis, logistic regression, microbial analysis

RECEIVED: January 19, 2024. **ACCEPTED:** April 7, 2024.

TYPE: Original Research

FUNDING: The author(s) received no financial support for the research, authorship, and/or publication of this article.

DECLARATION OF CONFLICTING INTERESTS: The author(s) declared the following potential conflicts of interest with respect to the research, authorship, and/or publication of this article: All authors have read, understood, and have complied as applicable with the statement on "Ethical responsibilities of Authors" as found in the instructions for Authors.

CORRESPONDING AUTHOR: Christian Julien Isac Gnimadi, Department of Environmental Science, College of Science, MCMF + 7M4, Commercial Link, Kumasi, Ghana, Kwame Nkrumah University of Science and Technology, Kumasi, Ghana. Email: chris.gnims@gmail.com

Introduction

The access to clean and safe drinking water is a fundamental human right and a key determinant of public health and well-being. More than 800 000 people die from drinking unsafe water annually.[1,2] The Sustainable Development Goal 6 (SDG 6) accentuates on the critical need to ensure universal access to safe and sustainable water sources, alongside adequate sanitation and hygiene practices, by 2030.[3,4] This global initiative acknowledges the fundamental importance of addressing water scarcity and sanitation challenges, particularly in regions where infrastructure for piped water supply systems is deficient or unreliable. In many developing countries, hand-dug wells emerge as pivotal resources, catering to the water needs of millions, especially in rural areas of sub-Saharan Africa and parts of Asia.[5] These wells serve as lifelines, bridging the gap in water access where conventional infrastructure falls short, thus playing a crucial role in advancing the objectives of SDG 6.

Building upon this need for comprehensive research, various methodologies have been employed to assess the water quality of hand-dug wells in these regions. Studies have utilized approaches such as the water quality index, machine learning techniques, Target Hazard Quotient, and multivariate statistics.[6-10] Despite their critical role in providing data to raise awareness, hand-dug wells still often have poor water quality which poses significant health risks to the communities relying on them.[11,12] This situation is exacerbated by the reliance of hand-dug wells on groundwater, rendering them vulnerable to contamination from various sources, including surface runoff, inadequate sanitation practices, and geological conditions.[13,14]

It is evident that the prevalence of waterborne diseases, particularly those caused by faecal contamination, poses a significant threat to public health in communities reliant on such wells. Factors such as the design, location, and environmental conditions of hand-dug well further exacerbate water quality degradation, emphasizing the need for comprehensive interventions to mitigate risks.[11,15] Moreover, the potential consequences of faecal contamination on public health cannot be overstated. Faecal matter in drinking water has been associated with a range of waterborne diseases, including diarrhoea, dysentery, typhoid, cholera, and polio, leading to significant morbidity and mortality worldwide.[2] Studies have highlighted the alarming correlation between home well water and faecal contaminant levels, particularly concerning paediatric diarrhoea.[16-18] The gravity of the situation is stressed by the fact that nearly 68% of individuals in underdeveloped nations using unimproved waterways are at risk of acquiring health issues due to faecal contamination, highlighting the urgent need for targeted interventions to safeguard public health.[19]

Amidst this persistent global concern, it becomes evident that both surface and groundwater interactions with the geological system significantly contribute to water contamination.[20] This intricate interplay between the geosphere and water encompasses 2 distinct facets.[21] On one hand, the geosphere can endure substantial harm from water contamination, leading to the generation of polluted sediments, including those laden with heavy metals.[21] Conversely, the geosphere itself can occasionally serve as a source of water pollution, such as through acidification resulting from exposed metal sulphides or the improper disposal of synthetic compounds in landfills.[20,21]

In delving into the causes of water pollution, it becomes apparent that the geosphere itself can contribute to this environmental challenge. Instances such as acid formation from geosphere-exposed metal sulphides or the improper disposal of artificial compounds in landfills illustrate how geological factors can directly impact water quality. Within this broader context, there are 2 primary groups that comprise the origins of water contamination.[22] Of particular concern are particles transported by water from the ground surface into water bodies' depths, representing a common and detrimental geologic source of water pollution.[23] One of the most recognizable indicators of sedimentary particles in water is turbidity, which not only diminishes the aesthetics of water bodies but also inhibits the growth of algae crucial for ecosystem balance.[24] Moreover, sedimentary debris can disrupt breeding sites, diminish food sources, and ultimately erode animal habitats.[25] This reduction in water clarity due to turbidity significantly hampers photosynthesis, thereby impeding the aquatic habitats' ability to sustain themselves.[26]

Turning attention to Ghana's specific context, the lack of readily accessible data on the percentage of the population at risk of faecal pollution from drinking water sources mirrors the challenges faced by several other emerging nations. Various studies have highlighted the pervasive nature of faecal contamination across all types of water sources, with unimproved water systems bearing a higher risk compared to improved ones.[27-29] Furthermore, factors such as open defecation, inadequate waste management, and poor sanitation facilities contribute significantly to water pollution in Ghana.[30-32] Due to growing human activity, some formerly drinkable groundwater is being contaminated. The water sources and purity of people's water are frequently influenced by their geography and income level.[33,34] In Ghana, a diverse array of water sources is utilized, with hand-dug wells being particularly prominent.[35] Especially in rural areas, groundwater serves as a dependable water supply due to its widespread accessibility, representing over 50% of potable water in these regions where infrastructure for water treatment and supply is lacking.[36] Unlike surface water, which can dwindle during dry seasons, groundwater proves to be more resilient.[37] Even in urban areas like the Kumasi metropolis, hand-dug wells remain a primary source of drinking water for many districts. They are relied upon by 14 and 55% of urban and rural residents, respectively, for their water needs.[35]

The prevalence of hand-dug wells in Ghana's water supply landscape underscores their vital role, especially in areas devoid of reliable piped water systems.[38] As per UNICEF, a significant portion of Ghanaians relies on improved water sources, which include hand-dug wells, boreholes, and protected sources.[19] However, the reliance on such sources highlights the urgent need to address water quality concerns to safeguard the health and well-being of communities throughout Ghana. Despite their ubiquity, hand-dug wells in Ghana encounter various challenges regarding water quality, including contamination risks from microbial pathogens, chemical pollutants, and naturally occurring contaminants such as arsenic and fluoride. The ramifications of poor water quality from contaminated hand-dug wells are substantial, particularly concerning public health. Vulnerable demographics, including children, pregnant women, and those with compromised immune systems, face heightened risks of morbidity, mortality, and long-term health issues due to waterborne illnesses.

Given the critical importance of hand-dug wells in Ghana's water supply, it is essential to recognize the significant variability they exhibit in terms of depth, construction materials, well lining, and wellhead protection. However, comprehensive studies investigating how these specific well features influence water quality are lacking. Despite the Ghana Community Water and Sanitation Agency's emphasis on maintaining a minimum distance of 50 m between wells and sanitation facilities,[39,40] challenges such as overcrowded sanitary facilities and low availability of drinkable water persist, highlighting the need for comprehensive approaches to address water quality and sanitation issues in Ghana.

To enhance understanding of the current state of hand-dug wells and their management practices, this study was conducted to investigate how various factors, including well construction features and management practices, influence water quality. The study focused on selected communities in Kumasi, Ghana, namely Kotei, Ayeduase, and Boadi. Through this research, we aimed to provide empirical evidence that can guide policymakers and stakeholders in implementing measures to enhance the quality and safety of water from hand-dug wells in these communities.

Materials and Method

Study area

Kumasi, the capital city of the Ashanti Region, is situated approximately 500 km north and 200 km south of the equator. It is located within a rainforest region, experiencing a tropical savannah climate characterized by distinct dry and wet seasons, with high temperatures year-round. The average temperature ranges between 21.5 and 30.7°C. Positioned centrally within the region, Kumasi falls between Latitudes 6°37′′N and 6°46′N and Longitudes 1°31′W and 1°40′W.[41] The Ashanti Region is situated within a wet semi-equatorial zone, experiencing dual peaks in rainfall, ranging from 1150 to 1750 mm annually. Rainfall mainly occurs from April to July, with a minor season extending from September to mid-November.[41] Two main rivers, the Barekese and Owabi, have been dammed to provide water to the Kumasi metropolis. Geologically, the area exhibits distinct features, with common lithologies within the Birimian meta-sediments including tuffaceous phyllite, schist, and meta-greywacke, showing strong foliation and jointing, with weathering profiles reaching depths of up to 100 m.[42] Consequently, moderate water quantities are expected in aquifers under favorable conditions. The Dixcove granite, primarily dioritic in composition, dominates the catchment area and may exhibit minor secondary porosity.[42] Three suburbs within the Oforikrom Municipality, namely Kotei, Ayeduase, and Boadi, were selected for this study due to their high usage of hand-dug well water for household activities. These communities are located approximately 10 km from the center of Kumasi.

Study design

For this research, a mixed-method research approach that combines quantitative and qualitative modes of inquiry was employed to gain a more comprehensive understanding of the research aim. This approach was used since quantitative data provides statistical insights and trends, while qualitative data offers deeper insights into underlying motivations, perceptions, and experiences, thus deepening understanding and generating insights with greater validity and reliability. The data were collected through observation, interviewing, and measurements. The study employed an observational study design. Observations included assessing the types of wells, the distance of wells to pollution points, the availability of well covers, and the thickness and presence of internal well structures. These observations were necessary to ascertain the well features and assess the water quality of the wells.

Data collection

The selected areas are known to utilize hand-dug wells. Fifty-eight households, with an average of 4 respondents per household, were randomly selected to participate in this study. An average of 3 to 7 individuals per household was confirmed in a previous study.[42] Singh et al.,[43] emphasized that for a population exceeding 100 000 individuals, at least 100 individuals can be selected to achieve a ±10% precision level. Thus, 58 household heads multiplied by 4, which is the minimum number of individuals per household, equals 232. Therefore, the views of a minimum of 232 individuals were collected. Structured questionnaires were employed to collect data from 58 households regarding their perceptions of how the features and management of wells impact water quality within the 3 selected suburbs. The questionnaire was divided into 3 sections, comprising demographic data of respondents, individuals' perceptions, and management of hand-dug wells. Household heads were targeted and interviewed to gather respondents' perceptions on how well features influence water purity.

Sanitary risk inspection. A sanitary risk study was conducted on 32 hand-dug wells selected from 58 households to assess the proportion of risk to microbial pathogens. These 32 hand-dug wells were specifically chosen from the randomly selected 58 households using purposive sampling technique, as they were the only households with hand-dug wells within their houses. Purposive sampling allows researchers to select participants who possess characteristics or experiences that are directly relevant to the research questions. This ensures that the sample aligns closely with the study's focus, increasing the validity and reliability of the findings.[43] The sanitary inspection approach involved evaluating 11 polluting risk factors related to on-site sanitation. This approach was derived from previous studies[44] and has been used in similar research efforts.[45,46] The assessment included a physical examination of the wells, an analysis of their surroundings, and an evaluation of responses to the 11 recognized risk factors. These factors included the presence of a protective cover for the well, proximity to a sewage disposal system, and the structural integrity of the well, among others. Factors such as the position of toilet facilities in relation to the well and the depth of the well were also considered. An affirmative response to a risk factor indicated a higher likelihood of bacterial contamination in the well water. The cumulative score was interpreted on a scale of 1 to 11, with scores falling into categories of extremely high (9-11), high (6-8), and low risk.[44]

Water sampling. Using a random sampling technique, samples were collected from 10 of the 32 hand-dug wells selected for sanitary risk inspection. This number of wells was chosen based on previous research practices. For instance, Akple et al[47] and Lutterodt et al[48] utilized 11 wells in their studies on hand-dug wells in the Kumasi and Dodowa areas. All samples were taken in triplicate, resulting in a total of 30 samples collected between May and September 2022. The samples were collected using well-labeled 500 mL sterilized bottles and transported in an ice chest to the laboratory for storage within minutes. Subsequently, the samples were analyzed at the Environmental Laboratory of the Department of Environmental Science, KNUST.

Laboratory Analysis

Microbial analysis

Faecal, total coliform count and determination. Coliform bacteria are commonly utilized as indicators of pollution, particularly of faecal origin.[49] The Most Probable Number (MPN) test, which detects coliforms within water samples,[50] was employed to evaluate the bacteriological characteristics. Specifically, 1 mL of undiluted water samples was added to 3 tubes containing a 10^{-1} solution of MacConkey broth, and this process was repeated for dilutions up to 10^{-9}. Subsequently, the tubes were incubated at 37°C for 24 hours, and positive results were recorded. This methodology aligns with approaches utilized in previous studies.[51]

Escherichia coli (E. coli) determination. Bacteria such as *E. coli* are also utilized as indicators of pollution. The presence of *E. coli* was assessed by adding a few drops of the sample to a tryptophan solution, followed by the addition of Kovacs reagent. The mixture was then incubated at 44°C, and positive results were recorded. A similar methodology was employed in a previous study.[52]

Heterotrophic plate count (HPC). Rygala[53] emphasized that the HPC test is employed to detect the presence of biofilm in water. A 1 mL sample of the water dilution was added to test tubes containing molten plate count agar at 40°C. The agar was then solidified and incubated in an inverted position at 37°C for 24 hours to promote growth. Subsequently, a colony counter was used to enumerate the colonies on the countable plates. This method has been utilized in previous studies.[54]

Physicochemical parameters. Five parameters of water quality, including electrical conductivity (EC), total dissolved solids (TDS), dissolved oxygen (DO), turbidity, and temperature, were measured. Standard guidelines[55] were followed in the analysis of these parameters to determine water quality. A pH meter (ST3100), Turbidimeter (R109B12150), and DO meter (ST300D) were utilized to measure pH, turbidity, and dissolved oxygen, respectively. A multi-meter (ST3100C) was employed to measure electrical conductivity (EC), total dissolved solids (TDS), and temperature. Prior to use, all instruments were calibrated.

Data analysis

Descriptive statistics, including frequency, percentage, mean, and standard deviation, were utilized to analyze the data. P-P (probability-probability) plots were employed to assess the normal distribution of the data. Cramer's V correlation test was utilized to establish relationships between variables. Multivariate statistics, including factor and cluster analysis, were employed to evaluate the most dominant factor and the spatial variation of the physicochemical parameters of the water. The data were suitable for factor analysis, as a value of 0.615 was found for Kaiser-Meyer-Olkin sampling adequacy, which exceeded the 0.6 threshold.[56] Bartlett's Test of Sphericity was significant at a 95% confidence level with a (P-value $< .05$), indicating a good linear relationship among the parameters. One-way analysis of variance (ANOVA) was adopted to verify whether the mean values across the various physicochemical parameters significantly diverged. Box plots were utilized to describe variations in physicochemical parameters within the samples. The box surrounds the interquartile range (IQR), with its lower and upper bounds representing the first and third quartiles, respectively. In a boxplot, there are 2 limits: the lower limit (LL) and the upper limit (UL). The lower limit is defined as 1.5× IQR lower than Q1, and the upper limit as 1.5× IQR higher than Q3.[57,58] Each plot defines minimum and maximum values at the end of the vertical lines, with the line inside the box indicating the median value; the 25th and 75th percentiles of the dataset are indicated as the lower and upper edges of the box, respectively.[59] The detected physicochemical parameters were used as explanatory variables, with the sampling site as the response variable for ANOVA. Logistic regression models were conducted to assess the effects of selected well features, including the well's cover and apron, on TDS, pH, temperature, turbidity, and DO. The well features were considered response variables, and the physicochemical parameters were explanatory variables. The data were analyzed using statistical package version 28 and Microsoft Excel 2016 (Figure 1).

Results and Discussions

Individual perception of water quality

Table 1 presents the demographic data of survey respondents. Of the 58 household heads surveyed, 62.1% were male, and 37.9% were female. Most of them (29.3%) were within the age range of 48 to 58, while 6.9, 13.8, 25.9, and 24.1% of the respondents were in the age range of 18 to 25, 26 to 36, 37 to 47, and >59, respectively. Additionally, 15.5% of the respondents are not educated, 8.6% have primary education, 37.9% have had education at least to the Junior High School level, 27.6% have Senior High School education, and 10.3% have tertiary education.[26] argue that individuals' education and level of knowledge could influence people's choices in identifying sources of drinking water.[60] Indeed, respondents could sometimes be influenced by choice of their neighbors in selecting the source of drinking water. Furthermore, only 3.4% of the respondents earn > 1000 Ghana Cedis ($ 120) per month, with the same percentage earning below 100 Ghana Cedis ($12) per

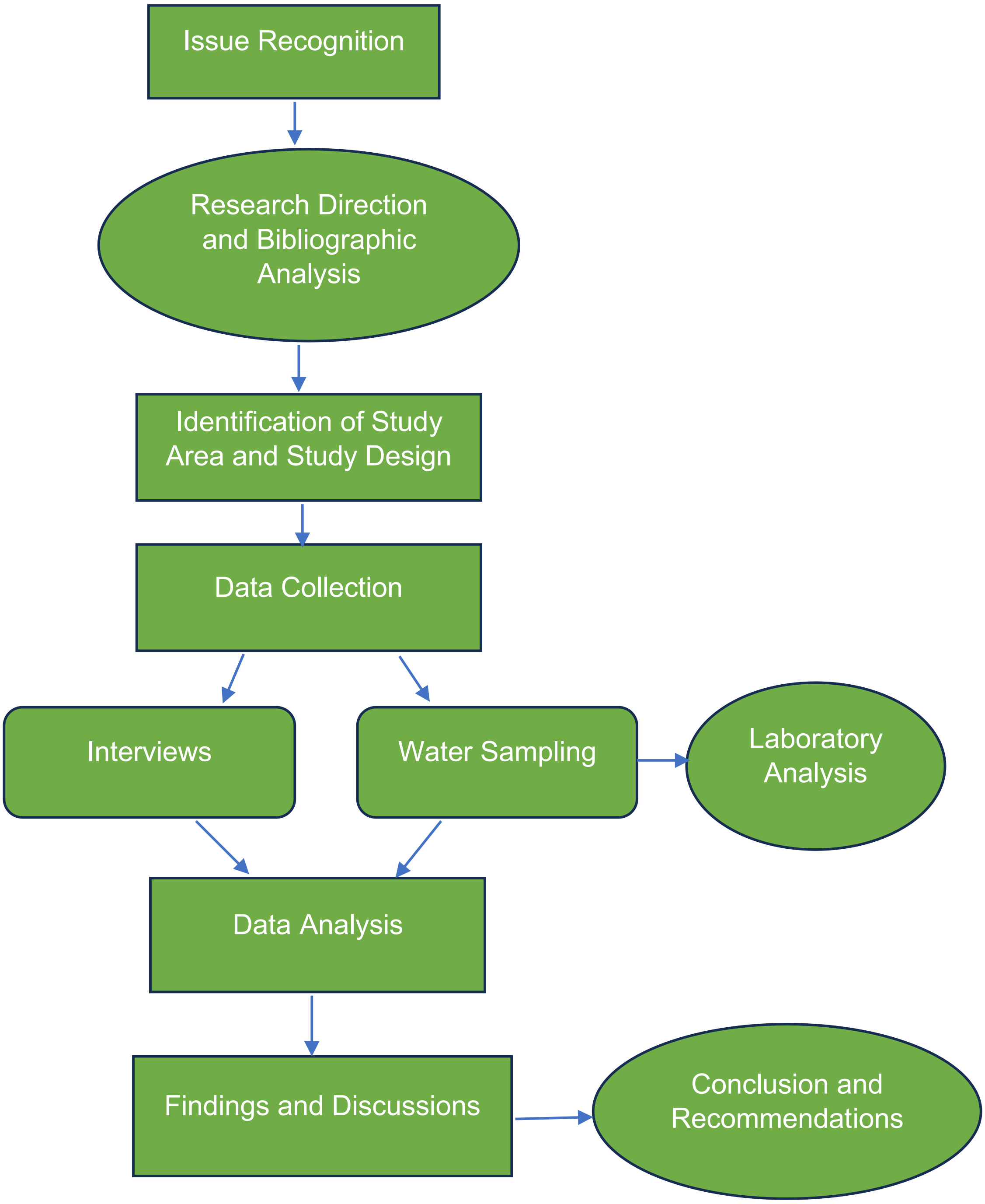

Figure 1. Methodology's flow chart.

month. Most (74.1%) of the respondents earn between 101 and 500 Ghana Cedis ($ 12-60) per month, while 19% earn between 501-1000 Ghana Cedis ($60-120) per month. Most (81%) of the households surveyed were compound houses having at least 7 inhabitants, while very few (3.4%) of the households have between 1 and 3 inhabitants.

The results presented in Table 2 regarding individual perceptions of water quality reveal that 13.8 and 77.6% of the respondents strongly agree and agree, respectively, that drinking untreated well water is unsafe, whereas 3.4 and 5.2% of the respondents strongly disagree and disagree, respectively, with this statement. Moreover, only 5.2% of the respondents solely depend on hand-dug well water for drinking purposes, while 87.9% depend on sachet/bottled water. Additionally, 43.1 and 46.5% rely on machine-dug well water supply and water from the Ghana Water Company, respectively, despite the fact that most respondents earn between 101 and 500 Ghana Cedis ($12-60) a month. The Cramer's V test shows a weak correlation between income and the choice of drinking water source but is not statistically significant ("Cramer's V" = 0.258; P = .239). Similar findings were reported by a previous study,[61] which also found no significant relationship between income

Table 1. Demographic data of survey respondents.

N = 58	DEMOGRAPHIC	FREQUENCY	PERCENTAGE (%)
Gender	Male	22	62.1
	Female	36	37.9
	Total	58	58
Age	18-25	4	6.9
	26-36	8	13.8
	37-47	15	25.9
	48-58	17	29.3
	>59	14	24.1
	Total	58	100
Education	Primary	22	8.6
	Junior High School	16	37.9
	Senior High School	6	27.6
	Tertiary	9	10.3
	None	6	15.5
	Total	58	100
Income in Ghana Cedis/Month	<100	2	3.4
	101-500	43	74.1
	501-1000	11	19
	>1000	2	3.4
	Total	58	100
Inhabitants/household	1-3	2	3.4
	4-6	9	15.5
	>7	47	81
	Total	58	100

level and choice of drinking water sources. Thus, the high dependence of respondents on sachet/bottled water is likely due to the general perception that such waters receive treatment before packaging, coupled with the erratic supply of water by the Ghana Water Company Limited. However, the products of these packaged water bottles and sachets contribute enormously to plastic waste generation in the country. Another study found that people do not prefer drinking piped water due to its taste.[62] Nevertheless, all the respondents use hand-dug well water for other household chores such as cooking, washing bowls, and other related tasks.

Moreover, the findings also reveal that the diverse types of toilets used by dwellers are pit latrines (34.5%); ventilated Improved pit latrines (29.3%); pit latrines with slab (3.4%); composting toilets (3.4%); and hanging toilets (29.4%). This is corroborated by the Ghana Statistical Service, which emphasizes that within the rural areas of Ghana, about 24.4% of the toilet facilities used are pit latrines.[63] Additionally, about 22% of the pit latrines are found within the Ashanti region where this study was conducted. Regarding how children's stools are disposed of, 96.5% of individuals responded that they rinse the stool and dispose of it in the toilet. However, a significant portion of the respondents still lack knowledge about microbial contamination of drinking water sources. While about 85% of respondents agree that the distance of toilet facilities, wastewater drains, or nearby refuse dumps to the hand-dug well can affect water quality, 15% disagree.

Concerning their perception of the influence of some selected hand-dug well features on water quality, 86.2 and 5.1% of the respondents strongly agree and agree, respectively, that the depth

Table 2. Perception of water quality.

VARIABLES N = 58		FREQUENCY/HOUSEHOLD	PERCENTAGE/HOUSEHOLD
Uses of hand-dug well water	Drinking	3	5.2
	Cooking	58	100
	Washing bowl	58	100
	Other washing	58	100
	Watering lawn Garden/ Livestock/Pets	39	67.2
		41	70.7
Other sources of drinking water	Sachet/Bottled water	51	87.9
	Machine dug well	25	43.1
	Ghana water company	27	46.5
Ways of children's stools disposal	Child uses toilet	2	3.4
	Put/rinsed into the toilet	56	96.5
	Put/flushed into drain or ditch	—	—
	Thrown into garbage	—	—
	Buried/left in the open	—	—
Knowledge that drinking untreated well water is unsafe	Strongly agree	8	13.8
	Agree	45	77.6
	Strongly disagree	2	3.4
	Disagree	3	5.2
The depth of the well can affect the quality of water	Strongly agree	3	5.1
	Agree	50	86.2
	Strongly disagree	1	1.7
	Disagree	4	6.9
The diameter of the well can affect the quality of water	Strongly agree	4	6.9
	Agree	40	68.9
	Strongly disagree	2	3.5
	Disagree	12	20.7
The cover of the well can affect the quality of water	Strongly agree	6	10.3
	Agree	50	84.5
	Strongly disagree	—	—
	Disagree	2	3.5
The distance of the well to toilet facilities may affect the quality of water	Strongly agree	5	8.6
	Agree	44	75.9
	Strongly disagree	6	10.3
	Disagree	3	5.1

(Continued)

Table 2. (Continued)

VARIABLES N=58		FREQUENCY/HOUSEHOLD	PERCENTAGE/HOUSEHOLD
The rope or bucket placed on the ground may affect water quality	Strongly agree	5	8.6
	Agree	47	81
	Strongly disagree	2	3.5
	Disagree	4	6.9
Wastewater drains or nearby refuse dump may affect the quality of water	Strongly agree	7	12.1
	Agree	41	70.7
	Strongly disagree	4	6.9
	Disagree	6	10.3
Type of toilet facility used in the household	Pit latrine (without slabs)	20	34.5
	Ventilated improved pit latrine	172	29.3
	Pit latrine with slab	18	3.4
	Composting toilet	—	31.03
	Hanging toilet	—	—

of the well may affect water quality, while 1.7 and 6.9% strongly disagree and disagree. This is quite similar to the cumulative percentages of respondents who agree or disagree at varied extents that the rope or bucket placed on the ground may affect the quality of the hand-dug well water. Also, 6.9 and 68.9% of the respondents strongly agree and agree, respectively, that the diameter of the well can affect water quality, whereas 3.5 and 20.7% strongly disagree and disagree. Interestingly, about 95% of the respondents largely agree that the cover of the well may affect water quality. Those who have access to reliable sources of information, such as educational programs, government health advisories, or community outreach initiatives, are more likely to be knowledgeable about microbial contamination.[64] People who have experienced waterborne illnesses or have seen others affected by such diseases may have a heightened awareness of the risks associated with microbial contamination.[65,66] Cultural beliefs and practices can influence perceptions of water quality and microbial contamination. In some communities, there may be misconceptions or traditional practices that affect people's understanding of waterborne diseases.[67]

Impact of demographics on individual perception

In addition, a weak correlation but not statistically significant was observed between age and awareness concerning the well depth "(Cramer's V = 0.273; P = .369), diameter (Cramer's V = 0.211; P = .740), cover (Cramer's V = 0.273; P = .369), distance to a latrine (Cramer's V = 0.271; P = .384), plastic bucket/rope (Cramer's V = 0.222; P = .677), nearby waste damps (Cramer's V = 0.177; P = .888)." Other researchers found similar results in their studies wherein it was difficult to establish a relationship between age and perceptions regarding water quality.[34]

Furthermore, the Cramer's V correlation analysis of the influence of demographics on individual perceptions shows that there is no significant difference between demographic factors and people's choices regarding well features management. Indeed, Cramer's V correlation analysis demonstrates that formal education level shows a moderately weak correlation, but not significant, with the perception of the well depth (Cramer's V = 0.33; P = .13), diameter (Cramer's V = 0.313; P = .181), cover (Cramer's V = 0.227; P = .706), distance (V = 0.215; P = .716), plastic bucket/rope (Cramer's V = 0.310; P = .195), nearby wastewater drains and refuse dumps (Cramer's V = 0.287; P = .295). These results were similar to the findings of Brouwer et al.[68] In their work, no statistically significant relationship was found between education level and perception of water quality. Past experiences regarding water-related issues play a key role in framing respondents' perceptions or choice of water management attitudes.[69] The knowledge may have been acquired from neighbors, past diseases, newspapers, television, and other communication media. This could have increased individual knowledge about hand-dug well features' impact on water quality.

Similarly, a weak correlation, but not significant, was observed between gender and the choice of the well depth (Cramer's V = 0.24; P = .188), cover (Cramer's V = 0.186; P = .570), distance to a latrine (Cramer's V = 0.064; P = .887),

Table 3. Factors of hand-dug wells contamination.

	RISK DETERMINANTS/FACTORS OF HAND-DUG WELLS CONTAMINATION	NUMBER OF HAND-DUG WELLS	PERCENTAGE %
Hand-dug wells	Wells on the lower ground level	21	65.63
N = 32	Minimum distance of latrine to wells (10-30 m)	26	81.25
	The minimum distance of the latrine to another pollution point (10-30 m)	29	90.62
	Unmaintained well cover	28	87.50
	Stagnant water	23	71.87
	Lacking concrete apron	19	59.37
	Plastic bucket/Rope at contaminated point	28	87.50
	Fissure in apron	25	78.12
	Depth and efficacy of the lining internally	24	75.00
	Closest latrine seeping into the ground	2	6.25
	Nearby refuse dump/wastewater	11	34.37

plastic bucket/rope (Cramer's V = 0.172; P = .426), nearby wastewater drains and refuse dumps (Cramer's V = 0.258; P = .146). However, a weak but significant correlation was observed between gender and perception of hand-dug well diameter (Cramer's V = 0.356; P = .026). Similar findings were also obtained in other studies, in which no statistically significant correlation was obtained between gender and perception of water quality.[70,71]

In addition, a weak correlation, but not statistically significant, was observed between age and awareness concerning the well depth (Cramer's V = 0.273; P = .369), diameter (Cramer's V = 0.211; P = .740), cover (Cramer's V = 0.273; P = .369), distance to a latrine (Cramer's V = 0.271; P = .384), plastic bucket/rope (Cramer's V = 0.222; P = .677), nearby waste dumps (Cramer's V = 0.177; P = .888). Similar results were found in other studies, in which it was difficult to establish a relationship between age and perceptions regarding water quality.[72]

Factors influencing hand-dug wells contamination

Table 3 presents an assessment of the factors contributing to contamination of hand-dug wells within the studied area. The results evaluated eleven significant risk determinants for the hand-dug wells. The findings suggest that water quality within the well is primarily influenced by the well's structure, the surrounding facilities, and the practices involved in well management. Generally, it has been observed that areas surrounding the well, such as wastewater, animal faces, drainage systems, and refuse dumps, pose a risk for contamination if not adequately maintained. The distance from the latrine and other sources of pollution, fissures in the apron, and lack of well-cover maintenance are other potential causes of water contamination.[73] Field inspections revealed that 81.30% of hand-dug wells are within 10 to 30 m of the nearest toilet facilities, which is considered a major risk factor for contamination. The Ghana Community Water and Sanitation Agency mandates a minimum distance of 50 m between wells and sanitation facilities; however, these guidelines are often ignored, potentially leading to pollution.[39,40] Additionally, 90.62% of wells are located within 10 to 30 m of another source of pollution. Cracks were observed in 78.12% of the surveyed wells, while 59.37% lacked an apron, possibly due to inexperienced construction of private wells. Field inspections also found that 87.50% of well covers were poorly maintained, often covered with biofilms and dirt, which can pose health risks. Moreover, materials used to collect water, such as buckets and ropes, were found at potentially contaminated points, with biofilms occasionally growing on them. Plastic materials, in particular, were identified as providing a surface for microbial growth when in contact with water. Other studies added that if the bucket used for collecting water from hand-dug wells is not properly cleaned and sanitized between uses, it can harbor harmful bacteria and pathogens.[74,75]

Additionally, stagnant water surrounded 71.87% of the inspected wells. The pollutants present in this stagnant grey water can easily leach or permeate through the cracks into the groundwater. The internal lining of 75% of the wells was observed to be deteriorating. Moreover, 65.63% of the wells were situated at a lower elevation (slope of the land) compared to the latrines. The least prevalent risk factor for contamination was the proximity of the wells to toilets seeping into the ground, accounting for only 6.25%. However, this could still contribute to aquifer pollution, as pollutants can be transported from 1 location to nearby wells. It is recommended that latrines be constructed on higher ground to prevent the penetration of rainwater and the intrusion of animals, including insects and rodents.[2] This measure aims to prevent the transmission of

Table 4. Microbial analysis and risk level.

SAMPLING POINTS	GPS LOCATIONS	DEPTH (M)	TOTAL COLIFORMS (CFU/100 ML)	FAECAL COLIFORMS (CFU/100 ML)	HETEROTROPHIC PLATE COUNTS (CFU/F)	*ESCHERICHIA COLI* (CFU/100 ML)	LEVEL OF RISK
HW 1	N 6°40'12.65196" W1°32'55.60152"	0.4	4.30×10^9	4.30×10^7	3.67×10^4	—	High
HW 2	N6°40'14.49984" W1°33'0.99936"	2.0	2.45×10^9	4.00×10^7	1.7×10^4	4.00×10^3	Very high
HW 3	N6°40'16.1274" W1°33'5.86476"	1.2	7.50×10^9	1.50×10^8	3.60×10^4	—	High
HW 4	N6°40'15.04992" W1°33'5.34744"	2.2	1.45×10^9	3.90×10^7	2.69×10^3	—	High
HW 5	N6°40'10.58412" W1°33'8.21448"	2.1	9.00×10^8	1.40×10^7	1.85×10^3	—	High
HW 6	N6°40'9.29892" W1°33'6.38784"	2.4	3.90×10^9	7.00×10^7	5.75×10^3	7.00×10^3	High
HW 7	N6°40'9.687" W1°33'5.78916"	28	4.35×10^9	7.50×10^7	1.78×10^4	11.00×10^3	Very high
HW 8	N6°40'9.30072" W1°33'2.4444"	24	4.00×10^9	2.70×10^8	18.62×10^4	7.00×10^3	Very high
HW 9	N6°40'3.34848" W1°33'0.19548"	25	2.90×10^8	2.80×10^8	2.30×10^4	6.00×10^3	Very high
HW 10	N6°40'2.83368" W1°33'2.48508"	1.5	9.30×10^{10}	$9.00\ 10^7$	3.35×10^4	3.00×10^3	Very high
WHO standards	–	–	0/100 mL	0/100 mL	–	0/100 mL	–

vectors and mitigate the spread of diseases. Despite providing valuable insights into the risk of underground water pollution, sanitary inspection alone cannot conclusively determine the quality of the well. Studies confirm that sanitary inspection may sometimes be ineffective in establishing the relationship between water quality and features such as the distance of the latrine to the well.[76,77]

Risk of microbial contamination

The microbial assessment and risk level of the 10 sampled wells indicate possible contamination by faecal matter (Table 4), as total and fecal coliforms were detected in all collected samples. This finding was not surprising, considering the features and management practices adopted for these wells (Table 3). Additionally, *E. coli* was detected in 60% of the well samples. However, the World Health Organization recommends that water should not contain any fecal coliforms, total coliforms, or *E. coli*. Furthermore, there was a high heterotrophic count in all the well water samples collected. Although heterotrophic count alone cannot accurately determine water quality, a direct relationship between biofilm and heterotrophic plate count has been established in the literature.[44] Previous studies have also found a positive correlation between coliforms and heterotrophic bacteria; hence, the high heterotrophic count could be attributed to the presence of coliforms.[78-81] Consequently, we can deduce that the wells are contaminated. Other studies have similarly concluded that hand-dug wells are associated with microbial pollution.[82,83] They found that the presence of *E. coli* in water samples could be attributed to the widespread nature of pollution in the environment. These pollutants may have penetrated underground water systems, particularly since 25 of the identified wells lacked aprons and had other defective structures. Likewise, the frequent use of inadequate sanitary systems, such as pit latrines, the defective nature of existing sanitary systems, and the inadequate sanitary habits of dwellers, contribute to the concentration of microbial pollution. Pathogens can then proliferate and spread through the advective conveyance of underground flowing water.[14,84] The extraction of water for various uses can cause forceful convection, easily percolating inflow from neighboring contamination points.

Additionally, sampling points HW 1, HW 3, HW 4, HW 5, and HW 6 have risk scores of 7, 8, 6, 8, and 7, respectively, indicating that these hand-dug wells are at a high risk of contamination. Similarly, HW 2, HW 7, HW 8, HW 9, and HW 10 have extreme risk scores of 9, 10, 9, 11, and 9, respectively, emphasizing that these wells are at a very high risk of contamination.[44]

Figure 2 illustrates the frequency of risk levels associated with hand-dug wells, revealing that most wells exhibit some degree of

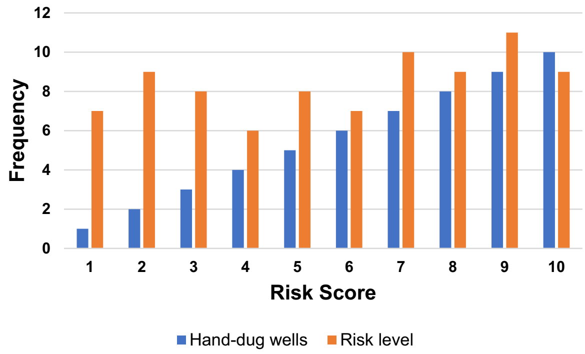

Figure 2. Frequency of sanitary risk score of the hand-dug wells.

Table 5. Factor loading of physicochemical parameters.

PARAMETERS	VARIFACTOR 1 (VF1)	VARIFACTOR 2 (VF 2)
EC (μS/cm)	**0.970**	−0.142
TDS (mg/L)	**0.970**	0.155
Turbidity (NTU)	−0.139	**0.931**
pH	**0.798**	0.445
DO (mg/L)	–	**−0.945**
Eigen values	2.541	2.002
Percentage of variance	50.814	40.039
Cumulative percentage	50.814	**90.853**

The values in bold are the highest value recorded.

risk. The sanitary inspections identified between 1 to 9 risk factors in each well. All inspected wells received a risk score between 6 and 11, indicating a high to extremely high risk of contamination. The analysis of Table 3 shows that out of the 11 investigated factors, only 2 (proximity of latrine seepage and nearby refuse damp/wastewater) were found in 11 wells, constituting less than 50% of those examined. The remaining 9 factors were present in over 58% of the 32 wells inspected, significantly elevating the contamination risk. This explains the high and extremely high contamination risks observed in Table 4. Furthermore, most wells examined were situated within 30 m of potential pollution sources, suggesting a direct flow of contaminants into the wells. As shown in Table 4, 5 of the sampled wells were at high risk of contamination, while the remaining 5 were at very high risk. Interestingly, no correlation was found between well depth and water quality. Seven of the sampled wells had depths of less than 3 m, with the remaining 3 being deeper, despite still presenting a very high contamination risk. Previous studies also noted a high bacterial content in hand-dug wells at a depth of 30 m.[85] Additionally, it has been reported that liquid waste and rainfall can easily infiltrate hand-dug wells, particularly when their apron surfaces are deficient, as observed in this study.[86]

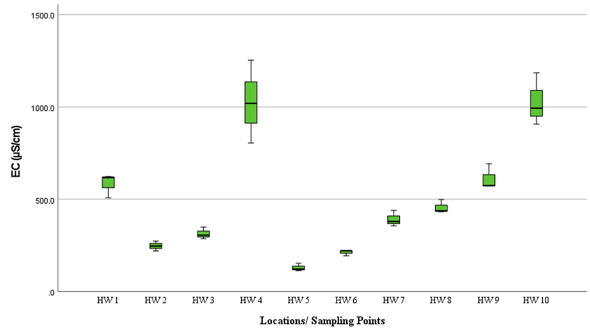

Figure 3. Box plot of the EC level among the sampling points.

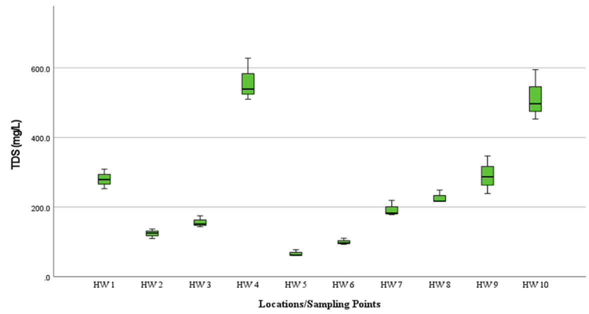

Figure 4. Box plot of the TDS level among the sampling points.

Assessment of water physicochemical parameters

Electronic conductivity (EC) and total dissolved solid (TDS). Electrical Conductivity (EC) assesses the water's ability to conduct an electrical current, directly related to the presence of dissolved ions and salts. Total Dissolved Solids (TDS) represents the total concentration of dissolved substances in the water, encompassing minerals, salts, metals, and organic compounds. Figures 3 and 4 depict box plot representations of EC and TDS at each sampling point. The mean EC and TDS values exhibit significant variation across the samples, suggesting differences in water composition and mineral content. Notably, samples HW 4 and HW 10 display elevated EC and TDS values compared to others, indicating potentially higher concentrations of dissolved solids and ions. Specifically, the EC value recorded at sampling point HW 4 was 1029 μS/cm, surpassing the WHO standard EC value of 400 μS/cm for drinking water.[44] This could be attributed to geological factors. Moreover, the rainy season replenishes groundwater reserves by infiltrating rainwater into the soil, dissolving minerals and salts, thereby increasing the TDS concentration in groundwater. The higher TDS levels may lead to increased EC values due to the presence of more dissolved ions, impacting water conductivity overall. Previous studies have linked higher EC values to elevated concentrations of dissolved solids, minerals, or salts in water.[87] Elevated TDS levels can also affect water taste, clarity, and suitability for various uses.[88] Furthermore, chemical reactions during the weathering process and the duration of water in the aquifer can influence ion concentrations. In a similar study, it was reported a TDS value of 1,112 μS/cm for

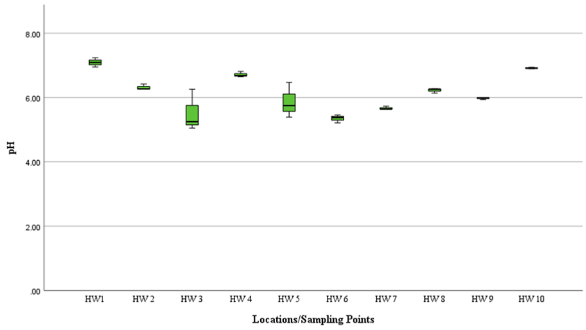

Figure 5. Box plot of the pH level among the sampling points.

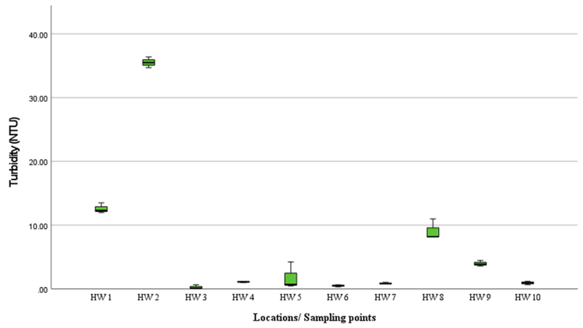

Figure 6. Box plot of the turbidity level among the sampling points.

underground water within the region.[89] However, the lowest EC value recorded was 29.67 µS/cm at HW 5. Additionally, the ANOVA test revealed statistically significant variation among the sampling points ($P < .05$).

pH. pH is a measure of the acidity or alkalinity of water.[90] Figure 4 presents the boxplot of the pH values across the various samples. While 60% of the study's wells were within the WHO guidelines for drinking water (pH 6.5-8.5), 40% of the wells exhibited pH levels below the threshold, indicating acidity that may pose adverse effects on human health. The lowest recorded value from the samples is 5.35 (HW 6), which falls outside the WHO-recommended range, while the highest recorded value is 7.07 (HW 1). The occurrence of low pH in underground water may result from interactions of metals within the soils or from the interaction of ions or rocks that generate acid.[91,92] During periods of heavy rainfall, such as the rainy season, there may be more frequent inputs of acidic precipitation, leading to fluctuations in pH levels.[93,94]

Turbidity. Turbidity denotes the haziness of a fluid caused by suspended particles.[95] Figures 5 and 6 presents the boxplots of the recorded turbidity across the various sampling sites. Turbidity levels vary among the samples, suggesting differences in sedimentation, erosion, or pollution sources. The findings indicate that the maximum turbidity measured at the 10th sampling point was 35.53 NTU at HW 2, which exceeds the maximum value established by WHO of less than 5 NTU, while the minimum turbidity value measured was 0.26 NTU at HW 3.[44] The high rate of turbidity observed in the water could be due to poorly constructed wells. The construction and maintenance of hand-dug wells play a crucial role in preventing surface water contamination and turbidity. Proper well design, such as constructing the wellhead above ground level and sealing the area around the well casing, helps minimize the risk of surface runoff entering the well. When well covers, casings, or aprons are improperly built or destroyed, debris, soil, and runoff from the surface can enter the well, causing the water to become more turbid. Additionally, urban growth may erode soil and alter it, increasing the amount of silt that runs into the water source.[96,97] Colloidal matter, clay

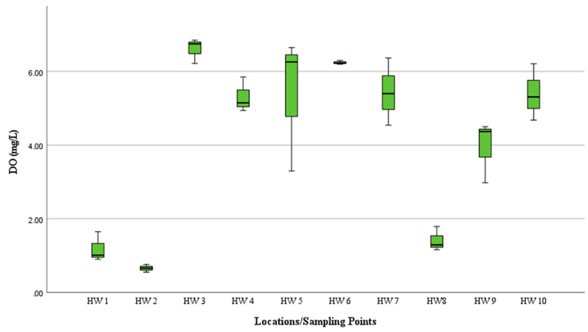

Figure 7. Box plot of the DO level among the sampling points.

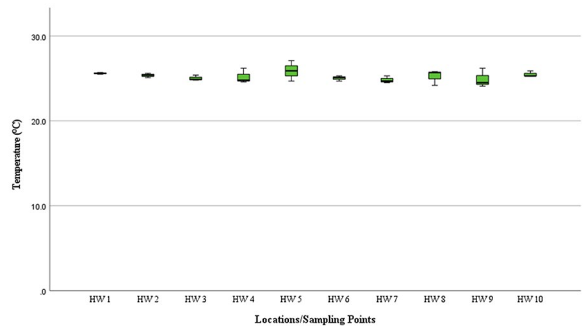

Figure 8. Box plot of the temperature among the sampling points.

materials, and organic and inorganic materials may increase the water's turbidity.[98] The high level of turbidity in hand-dug well water can indicate potential contamination and the presence of pathogens, which pose health risks to users.[99] Regular monitoring of turbidity levels, especially after rainfall events, is essential for assessing water quality and implementing appropriate treatment measures.

Dissolved oxygen (DO) and temperature. Dissolved oxygen (DO) refers to the amount of oxygen gas dissolved in water. Figures 7 and 8 present the boxplots of the recorded DO and temperature across the various sampling sites respectively. The dissolved oxygen values observed at the study wells demonstrate that 1.19 mg/L was the minimum value recorded at HW 1. However, the maximum value of DO (6.61 mg/L) was obtained at HW 3. The lower recommended value by the Water Resource Commission of Ghana, for water intended for

Table 6. Physicochemical parameters and logistic regression.

MAINTAINED AND UNMAINTAINED COVER					
PARAMETERS	B	WALD	*P*-VALUE	ODD RATIOS	95% CI
EC (uS/cm)	0.127	3.386	.066	1.14	[0.99, 1.30]
TDS (mg/L)	−0.231	3.146	.076	0.79	[0.61, 1.02]
pH	−5.645	2.278	.131	0.004	[0.00, 5.39]
Turbidity (NTU)	0.552	4.623	.032	1.737	[1.05, 2.87]
DO (mg/L)	1.244	1.392	.238	3.468	[0.44, 27]
PRESENCE AND ABSENCE OF APRON					
PARAMETERS	B	WALD	*P*-VALUE	ODD RATIOS	95% CI
EC (uS/cm)	−0.013	0.093	.761	0.987	[0.91, 1.07]
TDS (mg/L)	0.039	0.214	.644	1.040	[0.88, 1.23]
pH	−3.329	0.867	.352	0.036	[0.00, 39.60]
Turbidity (NTU)	−2.907	3.770	.052	0.055	[0.003, 1.028]
DO (mg/L)	−3.245	3.331	.068	0.039	[0.001, 1.27]

domestic use, is 5 mg/L.[100] The low value recorded within our samples could be attributed to the high microbial activities observed in Table 4. A similar study, emphasized that the presence of organic matter may increase the microbial content of the water.[101] The design and condition of the hand-dug well could also influence its susceptibility to contamination and its ability to maintain dissolved oxygen levels.[102,103] Proper well construction, including adequate casing, wellhead protection, and sealing, can help minimize the entry of surface runoff and contaminants. Furthermore, there was a statistical difference among the variations observed at the various sampling points. Moreover, the generally warm temperature (24.83-25.90°C) of the wells suggests that they are likely to contain more microbes than cooler water.[44]

Factor analysis. Table 5 presents the factor loadings of the physicochemical parameters. After conducting factor analysis on the dataset, the most influential factors were identified. All factor loadings >0.3 are considered adequate values.[104] However, temperature did not meet that requirement and was thus omitted from the factor analysis. The analysis reveals the presence of 2 factors with eigenvalues greater than 1. Retaining factors with eigenvalues exceeding 1 is based on the hypothesis that a component is of negligible importance if it explains less variation than a single variable.[105] The first component, or varifactor, represents 50.81% of all the studied variables. This supports the assertions, which state that the chosen collection of variables or components should collectively describe a minimum of 40% of the variation.[106]

Factor analysis of the data indicates a strong positive correlation between EC, TDS, and turbidity, but a positive moderate correlation towards pH (Table 5). This could be attributed to the high amount of TDS or particles in water affects its turbidity. Higher electrical conductivity in water implies more dissolved ions and other materials present. Additionally, higher pH levels in water may signify more dissolved ions, thereby elevating EC and TDS measurements. This correlation aligns with previous studies, which have similarly identified a strong positive relationship between TDS and EC.[87,107]

Furthermore, the variation observed among the sampling points was statistically significant ($P < .05$). The second component or varifactor represents 90.85% of all the studied variables and exhibits a strong positive correlation with turbidity and a negative strong correlation with dissolved oxygen. This could be due to the fact that high turbidity can increase microbial activity and oxygen demand, consequently reducing dissolved oxygen concentrations. This suggests that the contamination could be of anthropogenic origin. However, other studies argued that while DO and turbidity are inversely related to factors such as low light penetration and organic matter, certain environmental conditions and processes can lead to a positive correlation.[108-110]

Logistic regression. Table 6 presents the contribution of physicochemical parameters in the model and their significance level. The findings demonstrate that the logistic regression models examining the effects of cover state (maintained and unmaintained) and apron presence (or absence, with cracked apron considered absent) on the studied physicochemical parameters were statistically significant. Indeed, the Omnibus Test of Model Coefficient, indicating the overall goodness of fit of the models, shows that $P < .05$. The regression models on cover and apron elucidated 75.1 and 66.1% (Nagelkerke R^2) of the variance, respectively, in the physicochemical parameters under study. Additionally, the models on cover and apron appropriately classified 93.% and 90% of cases, respectively.

Table 6 illustrates that the likelihood of EC decrease is associated with an increase in the likelihood of an apron affecting water quality. Additionally, an increase in TDS is found to be associated with the rise in the likelihood of an apron affecting water quality. A well-maintained apron can help protect the integrity of a hand-dug well by preventing surface water runoff, animal waste, and other contaminants from entering the well, thereby contributing to improved water quality. High TDS levels can alter the flavor, color, and odor of water, making it less appealing to drink.[111,112] However, Table 6 also indicates that the increase in TDS is associated with a decrease in the likelihood of displaying an effect on water quality, and the maintenance of a cover is associated with an increase in the likelihood of displaying an effect on EC. However, these associations are not statistically significant ($P > .05$). Similarly, the decrease in the likelihood of pH is associated with an increase in the likelihood of an apron affecting water quality. However, these associations are not statistically significant ($P > .05$). In comparison, the state of the apron can directly influence the pH of water in hand-dug wells.[113,114] A well-maintained apron acts as a barrier, preventing the ingress of contaminants that could alter the pH of the water.

Furthermore, Table 6 shows that increasing turbidity is associated with the likelihood of an unmaintained cover exhibiting an effect on water quality, and this association was statistically significant ($P < .05$). The likelihood of an unmaintained cover affecting turbidity is approximately 2 times. This could be due to the well cover acting as a physical barrier to reduce the number of particles and sediments that enter the well water. Other researches found similar results in their study, where they stipulated that a well becomes prone to different impurities, such as soil, leaves, debris, and pollutants, if it is left uncovered or has a cover that is broken or not properly fitted.[115] Additionally, animals and insects may enter the well, introducing organic matter that contributes to a rise in turbidity. The turbidity of the water around the well can be reduced with a properly built well apron. The odds ratio for the presence or absence of an apron affecting water quality is <1. Also, the decrease in the likelihood of turbidity is associated with the increase in the likelihood of an apron affecting water quality.

In addition, Table 6 reveals that increasing dissolved oxygen (DO) is associated with a decrease in the likelihood of the absence of an apron of hand-dug wells affecting water quality, and this association was not statistically significant ($P > .05$). Also, the maintenance of a cover is associated with the increase in the likelihood of displaying an effect on DO, but that association was not statistically significant ($P > .05$). In a similar work, it was added that the prevention of soil erosion and reduction of sediment introduction help maintain clearer and less turbid water, preserving higher DO levels.[116]

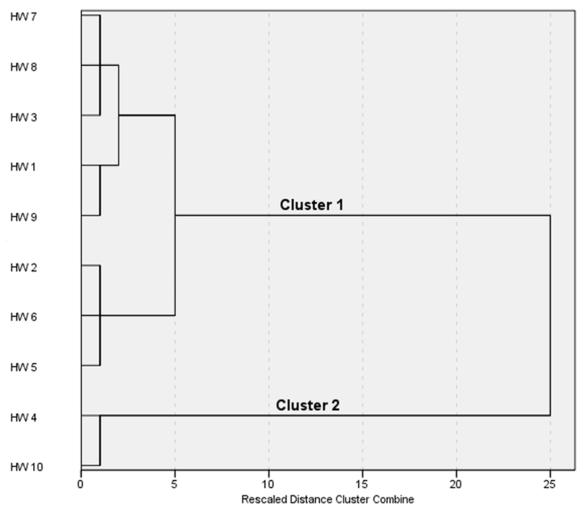

Figure 9. Dendrogram.

Cluster analysis. The dendrogram from cluster analysis (Figure 9) also illustrates the representation of 2 clusters. These clusters are positioned at a combined rescaled distance value of less than 10. HW 4 and HW 10 were part of cluster 2, likely due to their locations being distant from human settlements. These 2 hand-dug wells were the only ones exhibiting high electrical conductivity, which could explain why they are grouped into the same cluster. Additionally, the dendrogram (Figure 9) reveals that cluster 1 comprises HW 1, HW 2, HW 3, HW 5, HW 6, HW 7, HW 8, and HW 9. This cluster was characterized by its proximity to human settlements. These sampling points were generally influenced by low total dissolved solids (TDS), low turbidity, and high dissolved oxygen (DO).

Generally, the influence of hand-dug wells on the water quality can be diverse. The study found that Poor sanitation practices, including improper waste disposal, open defecation, and lack of hygiene, can contribute to microbial contamination of hand-dug well water, increasing the risk of waterborne diseases. Inadequate well construction, including insufficient casing, lack of sealing materials, or improper wellhead protection, can compromise the integrity of hand-dug wells, allowing surface contaminants to enter the groundwater. Poor maintenance practices, such as neglecting to repair or clean wells, can also degrade water quality over time. Also hand-dug wells located near sources of pollution are susceptible to contamination by chemicals and wastewater runoff. In areas with shallow water tables or inadequate well construction, surface water may infiltrate hand-dug wells during periods of heavy rainfall or flooding, introducing contaminants such as bacteria and sediment into the groundwater.

Limitations

The study did not include the identification of specific microorganisms or viruses. Furthermore, it focused solely on 5 physicochemical parameters and did not analyze heavy metals in the water. Seasonal variations in the physicochemical parameters were not investigated, as the study was conducted during the rainy season, which could have influenced the distribution of these parameters.

Conclusions

The findings indicate difficulty in establishing a relationship between demographic factors and individual perceptions regarding the management of hand-dug well features. Pollution of the identified hand-dug wells was determined through field studies and laboratory tests, contrasting the groundwater's susceptibility to microbial pathogens. Microbial water quality was examined using total coliform, fecal coliform, heterotrophic plate count, and E. coli bacteria. The findings shows that groundwater in the region is highly contaminated by fecal matter, posing a significant risk of contamination observed in the sampled water. Most of the investigated risk factors were present in all wells. ANOVA findings reveal variations in physicochemical parameters among sampling points, except for temperature. Cluster analysis shows that proximity to human settlements affects water quality, with the ten sampling points grouped into 2 clusters. Binary logistic regression reveals a statistically significant association ($P < .05$) between increasing turbidity and the likelihood of an unmaintained cover affecting water quality. Similarly, increasing dissolved oxygen (DO) is associated with a decrease in the likelihood of absence of an apron affecting water quality, also statistically significant. Sanitation infrastructure on-site, such as pit latrines and unprotected toilet facilities, as well as the well's structure and management practices, are identified as the main sources of contamination risk. Groundwater pollution from fecal matter stems largely from widespread contamination by multiple sources.

Based on the findings it is recommended a regular maintenance and cleaning of hand-dug wells should be encouraged to prevent contamination and deterioration of water quality, to establish a system for routine water quality testing to monitor well water for contamination which can be done in collaboration with local health or environmental agencies, to develop and promote well construction and maintenance standards to ensure that wells are properly built and protected from contamination sources, to provide educational programs for the community on the importance of well water quality, safe water handling practices, and the risks associated with contamination, to explore the feasibility of alternative water sources, such as boreholes or piped water systems, if hand-dug wells consistently show poor water quality and work with local authorities to establish regulations or guidelines for well construction, maintenance, and water quality standards.

Moreover, the study opened several avenues for further research and investigation. These areas of further study can help to deepen our understanding of the topic and contribute to more effective water resource management. A long-term, multi-year study to track changes in water quality and the sustainability of well features and management practices over time could be conducted. This can provide insights into trends and patterns.

Acknowledgements

The researchers are grateful to the Environmental Laboratory of the Department of Environmental Science, Kwame Nkrumah University of Science and Technology, for their assistance in conducting the laboratory analysis.

Author Contributions

Christian J. I. Gnimadi conceptualized, administrated, supervised, collected data and drafted the manuscript. Kokoutse Gawou designed the methodology, assisted in data collection, analysed the data and reviwed the manuscript. Micheal Aboah disigned the methodology, assisted in data collection and reviewed the manuscript. Emmanuel Odame Owiredu designed the questionnaire, validated the data and reviwed the manuscript. Junias Adusei Gyamfi supervised the study, edited, administrated and reviewed the manuscript.

Compliance With Ethical Standards

This research did not involve human or animal experiments.

Data Availability

Data available upon request.

REFERENCES

1. World Health Organization. *Progress on Household Drinking Water, Sanitation and Hygiene 2000-2020: Five Years Into the SDGs*. World Health Organisation; 2021.
2. World Health Organization. *Progress on Household Drinking Water, Sanitation and Hygiene 2000-2017: Special Focus on Inequalities*. World Health Organisation; 2019.
3. Biswas RR, Sharma R, Gyasi-Agyei Y. Adaptation to climate change: a study on regional urban water management and planning practice. *J Clean Prod*. 2022;355:131643.
4. Arora NK, Mishra I. Sustainable development goal 6: global water security. *Environ Sustain*. 2022;5:271-275.
5. Zhang Q, Xu P, Qian H. Groundwater quality assessment using improved water quality index (WQI) and human health risk (HHR) evaluation in a semi-arid region of Northwest China. *Expo Health*. 2020;12:487-500.
6. Uddin MG, Nash S, Olbert AI. A review of water quality index models and their use for assessing surface water quality. *Ecol Indic*. 2021;122:107218.
7. Liu Y, Wang P, Gojenko B, et al. A review of water pollution arising from agriculture and mining activities in Central Asia: facts, causes and effects. *Environ Pollut*. 2021,291:118209.
8. Uddin MG, Moniruzzaman M, Quader MA, Hasan MA. Spatial variability in the distribution of trace metals in groundwater around the Rooppur nuclear power plant in Ishwardi, Bangladesh. *Groundw Sustain Dev*. 2018;7:220-231.
9. de Andrade Costa D, Soares de Azevedo JP, dos Santos MA, et al. Water quality assessment based on multivariate statistics and water quality index of a strategic river in the Brazilian Atlantic *Forest Sci Rep*. 2020;10:22038.
10. Uddin MG, Imran MH, Sajib AM, et al. Assessment of human health risk from potentially toxic elements and predicting groundwater contamination using machine learning approaches. *J Contam Hydrol*. 2024;261:104307.
11. Viban TB, Herman ONN, Layu T C, et al. Risk factors contributing to microbiological contamination of boreholes and hand dug wells water in the Vina Division, Adamawa, Cameroon. *Adv Microbiol*. 2021;11:90-108.
12. Egbueri JC, Ameh PD, Ezugwu CK, Onwuka OS. Evaluating the environmental risk and suitability of hand-dug wells for drinking purposes: a rural case study from Nigeria. *Int J Environ Anal Chem*. 2022;102:5528-5548.
13. Maju-Oyovwikowhe EG, Emofurieta WO. Groundwater quality determination from hand-dug wells in Ososo Town, Akoko-Edo North local government area Edo state. *Niger J Technol*. 2021;40:540-549.
14. Ocheli A, Otuya OB, Umayah SO. Appraising the risk level of physicochemical and bacteriological twin contaminants of water resources in part of the western Niger Delta region. *Environ Monit Assess*. 2020;192:1-16.
15. Mathew D, Ndububa OI. Analysis of impact of communal activities on ground water quality from hand dug wells in Shere village, Abuja Nigeria. *Open J Eng Sci*. 2023;4:35-49.

16. Odagiri M, Schriewer A, Daniels ME, et al. Human fecal and pathogen exposure pathways in rural Indian villages and the effect of increased latrine coverage. *Water Res*. 2016;100:232-244.
17. Bain R, Cronk R, Wright J, Yang H, Slaymaker T, Bartram J. Faecal contamination of drinking-water in low-and middle-income countries: a systematic review and meta-analysis. *PLoS Med*. 2014;11:e1001644.
18. Onda K, LoBuglio J, Bartram J. Global access to safe water: accounting for water quality and the resulting impact on MDG progress. *Int J Environ Res Public Health*. 2012;9:880-894.
19. UNICEF/WHO Wash in Health Care Facilities, Global Basic Report; 2019.
20. Verma K, Manisha M, Santrupt RM, et al. Assessing groundwater recharge rates, water quality changes, and agricultural impacts of large-scale water recycling. *Sci Total Environ*. 2023;877:162869.
21. Huggett R. Soil as part of the Earth system. *Prog Phys Geogr*. 2023,47:454-466.
22. Adimalla N. Spatial distribution, exposure, and potential health risk assessment from nitrate in drinking water from semi-arid region of South India. *Hum Ecolog Risk Assess*. 2019;26(2):310-334.
23. Wu Q, Zhou H, Tam NF, et al. Contamination, toxicity and speciation of heavy metals in an industrialized urban river: implications for the dispersal of heavy metals. *Mar Pollut Bull*. 2016;104:153-161. https://doi.org/10.1016/j.marpolbul.2016.01.043
24. Mintenig SM, Löder MG, Primpke S, Gerdts G. Low numbers of microplastics detected in drinking water from ground water sources. *Sci Total Environ*. 2019;648:631-635.
25. Sajedi-Hosseini F, Malekian A, Choubin B, et al. A novel machine learning-based approach for the risk assessment of nitrate groundwater contamination. *Sci Total Environ*. 2018;644:954-962.
26. Xu X, Fan H, Chen X, et al. Estimating low eroded sediment concentrations by turbidity and spectral characteristics based on a laboratory experiment. *Environ Monit Assess*. 2020;192;130.
27. Berendes DM, Kirby AE, Clennon JA, et al. Urban sanitation coverage and environmental fecal contamination: Links between the household and public environments of Accra, Ghana. *PLoS ONE*. 2018;13:e0199304.
28. Dongzagla A, Jewitt S, O'Hara S. Seasonality in faecal contamination of drinking water sources in the Jirapa and Kassena-Nankana Municipalities of Ghana. *Sci Total Environ*. 2021;752:141846.
29. Antwi-Agyei P, Biran A, Peasey A, et al. A faecal exposure assessment of farm workers in Accra, Ghana: a cross sectional study. *BMC Public Health*. 2016;16:587.
30. Abanyie SK, Sunkari ED, Apea OB, et al. Assessment of the quality of water resources in the Upper East Region, Ghana: a review. *Sustain Water Resour Manage*. 2020;6:52.
31. Amuah EE, Boadu JA, Nandomah S. Emerging issues and approaches to protecting and sustaining surface and groundwater resources: emphasis on Ghana. *Groundw Sustain Dev*. 2022;16:100705.
32. Saana SBBM, Fosu SA, Sebiawu GE, et al. Assessment of the quality of groundwater for drinking purposes in the Upper West and Northern regions of Ghana. *Springerplus*. 2016;5:2001.
33. Price HD, Adams EA, Nkwanda PD, Mkandawire TW, Quilliam RS. Daily changes in household water access and quality in urban slums undermine global safe water monitoring programmes. *Int J Hyg Environ Health*. 2021;231:113632.
34. Abubakar, Ismaila Rimi. Factors influencing household access to drinking water in Nigeria. *Utilit Policy*. 2019;58:40-51.
35. Ghana Statistical Service, General Report Water and Sanitation, Population and Housing Census Vol. 3L; 2021.
36. Gaye CB, Tindimugaya C. Challenges and opportunities for sustainable groundwater management in Africa. *Hydrogeol J*. 2019;27:1099-1110.
37. Bazaanah P, Dakurah M. Comparative analysis of the performance of rope-pumps and standardized handpumps water systems in rural communities of the northern and upper east regions of Ghana. *Groundw Sustain Dev*. 2021;13:100563.
38. Parker A, Carlier I. National regulations on the safe distance between latrines and waterpoints: Final Report December. Blisworth; 2009.
39. Graham JP, Polizzotto ML. Pit latrines and their impacts on groundwater quality: a systematic review. *Environ Health Perspect*. 2013;121:521-530.
40. World Meteorological Organisation. 2022. Site accessed August 22, 2023. https://worldweather.wmo.int/en/city.html?cityId=922
41. Ghana Statistical Service, General Report, Housing Characteristics, Population of Region and Districts; Vol. 3A; 2021.
42. World Health Organization. *Guidelines for Drinking Water Quality*. 4th ed. World Health Organization; 2011.
43. Mushi D, Byamukama D, Kirschner AK, Mach RL, Brunner K, Farnleitner AH. Sanitary inspection of wells using risk-of-contamination scoring indicates a high predictive ability for bacterial faecal pollution in the peri-urban tropical lowlands of Dares Salaam, Tanzania. *J Water Health*. 2012;10:236-243.
44. Lutterodt G, Van de Vossenberg J, Hoiting Y, Kamara AK, Oduro-Kwarteng S, Foppen JWA. Microbial groundwater quality status of hand-dug wells and boreholes in the Dodowa area of Ghana. *IJERPH*. 2018;15:730.
45. Akple M, Keraita B, Konradsen F, Agbenowu E. Microbiological quality of water from hand-dug wells used for domestic purposes in urban communities in Kumasi, Ghana. *Urban Water J*. 2011;8:57-64.
46. Cisneros BJ. Safe sanitation in low economic development areas. *Treatise Water Sci*. 2011;147-200.
47. Delelegn A, Sahile S, Husen A. Water purification and antibacterial efficacy of Moringa oleifera Lam. *Agric Food Secur*.2018;7:1-10.
48. Bellot J, Chirino E. Hydrobal: an eco-hydrological modelling approach for assessing water balances in different vegetation types in semi-arid areas. *Ecol Modell*. 2013;266:30-41.
49. Jha DK, Kirubagaran R, Vinithkumar NV, Dharani G, Madeswaran P. The Andaman and Nicobar Islands. In: *World Seas: An Environmental Evaluation*. Academic Press; 2019:185-209. https://doi.org/10.1016/B978-0-08-100853-9.00013-0
50. Rygala A, Berlowska J, Kregiel D. Heterotrophic plate count for bottled water safety management. *Processes*. 2020;8:739.
51. Rathna R, Varjani S, Nakkeeran E. Sequestration of heavy metals from industrial wastewater using composite ion exchangers. In: Inamuddin, Ahamed MI, Asiri AM, eds. *Applications of Ion Exchange Materials in the Environment*. Springer, Cham; 2019:187-204.
52. APHA. *Standard Methods for the Examination of Water and Wastewater*. American Public Health Association; 1999.
53. Yong AG, Pearce S. A beginner's guide to factor analysis: Focusing on exploratory factor analysis. *Tutor Quant Methods Psychol*. 2013;9:79-94.
54. Chang CJ, Li DC, Huang YH, Chen CC. A novel gray forecasting model based on the box plot for small manufacturing data sets. *Appl Math Comput*. 2015;265:400-408.
55. Nuzzo R. The box plots alternative for visualizing quantitative data. *PM&R*. 2016;8:268-272.
56. Li R, Dong M, Zhao Y, et al. Assessment of water quality and identification of pollution sources of plateau lakes in Yunnan (China). *J Environ Qual*. 2007;36:291-297.
57. Stoler J, Tutu RA, Winslow K. Piped water flows but sachet consumption grows: The paradoxical drinking water landscape of an urban slum in Ashaiman, Ghana. *Habitat Int*. 2015;47:52-60.
58. Straub CL, Leahy JE. Application of a modified health belief model to the pro-environmental behaviour of private well water testing. *J Am Water Resour Assoc*. 2014;50:1515-1526.
59. Kulinkina AV, Kosinski KC, Liss A, et al. Piped water consumption in Ghana: A case study of temporal and spatial patterns of clean water demand relative to alternative water sources in rural small towns. *Sci Total Environ*. 2016;559:291-301.
60. Tarannum F, Kansal A, Sharma P. Understanding public perception, knowledge and behaviour for water quality management of the river Yamuna in India. *Water Policy*. 2018, ;20:266-281.
61. Flanagan SV, Marvinney RG, Johnston RA, Yang Q, Zheng Y. Dissemination of well water arsenic results to homeowners in Central Maine: influences on mitigation behaviour and continued risks for exposure. *Sci Total Environ*. 2015;505:1282-1290.
62. Ghana Statistical Service, General Report Water and Sanitation, Population and Housing Census, Vol 3L; 2021.
63. Khalid S, Murtaza B, Shaheen I, Imran M, Shahid M. Public perception of drinking water quality and health risks in the District Vehari, Pakistan. VertigO-la revue électronique en sciences de l'environnement, 2018. (Hors-série 31). https://doi.org/10.4000/vertigo.21171
64. Gizachew M, Admasie A, Wegi C, Assefa E. Bacteriological contamination of drinking water supply from protected water sources to point of use and water handling practices among beneficiary households of boloso sore woreda, wolaita zone, Ethiopia. *Int J Microbiol*. 2020;2020:5340202.
65. Gevera PK, Dowling K, Gikuma-Njuru P, Mouri H. Public knowledge and perception of drinking water quality and its health implications: an example from the Makueni County, South-Eastern Kenya. *Int J Environ Res Public Health*. 2022,19:4530.
66. Francis MR, Nagarajan G, Sarkar R, et al. Perception of drinking water safety and factors influencing acceptance and sustainability of a water quality intervention in rural southern India. *BMC Public Health*. 2015;15:731.
67. Ahmed A, Shafique I. Perception of household in regards to water pollution: empirical evidence from Pakistan. *Environ. Sci. Pollut. Res*. 2019;26:8543-8551.
68. Brouwer S, Hofman-Caris R, van Aalderen N. Trust in drinking water quality: understanding the role of risk perception and transparency. *Water*. 2020;12:2608.
69. Gevera PK, Dowling K, Gikuma-Njuru P, Mouri H. Public knowledge and perception of drinking water quality and its health implications: an example from the Makueni County, South-Eastern Kenya.*Int J Environ Res Public Health*. 2022; 8:4530.
70. Straub CL, Leahy JE. Application of a modified health belief model to the pro-environmental behaviour of private well water testing. *J Am Water Resour Assoc*. 2014;50:1515-1526.
71. Adedeji OH, Olayinka OO, Oladimeji O. Physicochemical and microbiological examination of hand-dug wells, boreholes and public water sources in selected areas of Ibadan, Nigeria. *J Appl Sci Environ Manage*. 2017;21:576-584.

72. Tekpor M, Akrong MO, Asmah MH, Banu RA, Ansa EDO. Bacteriological quality of drinking water in the Atebubu-Amantin district of the Brong-Ahafo region of Ghana. *Appl Water Sci*. 2016;7:2571-2576.
73. Hammuel C, Udiba UU, Gauje B, Raplong HH, Batari ML. Bacteriological and physicochemical quality of hand-dug well water used for drinking and domestic purposes in Dareta Village, Anka, Nigeria. *Br J Appl Sci Technol*. 2014;4:1119.
74. Wen B, Liu JH, Zhang Y, et al. Community structure and functional diversity of the plastisphere in aquaculture waters: does plastic colour matter? *Sci Tot Environ*. 2020;740:140082.
75. Ercumen A, Pickering AJ, Kwong LH, et al. Animal faeces contribute to domestic fecal contamination: evidence from E. coli measured in water, hands, food, flies, and soil in Bangladesh. *Environ Sci Technol*. 2017;51:8725-8734.
76. Snoad C, Nagel C, Bhattacharya A, Thomas E. The effectiveness of sanitary inspections as a risk assessment tool for thermotolerant coliform bacteria contamination of rural drinking water: a review of data from West Bengal, India. *Am J Trop Med Hyg*. 2017;96:976.
77. Battin TJ, Besemer K, Bengtsson MM, Romani AM, Packmann AI. The ecology and biogeochemistry of stream biofilms. *Nat Rev Microbiol*. 2016;14:251-263.
78. Salehi M. Global water shortage and potable water safety; Today's concern and tomorrow's crisis. *Environ Int*. 2022;158:106936.
79. Tsvetanova Z, Tsvetkova I, Najdenski H. Antimicrobial resistance of heterotrophic bacteria in drinking water-associated biofilms. *Water*. 2022;14:944.
80. Armanidaz N, Zafarzadeh A, Mahvi AH. The interaction between heterotrophic bacteria and coliform, fecal coliform, fecal streptococci bacteria in the water supply networks. *Iran J Public Health*. 2015;44:1685.
81. Onuigbo AC, Onyia CE, Nwosu IG, Oyeagu U. Impacts of bacterial pollution on hand-dug well water quality in Enugu, Enugu State, Nigeria. *Afr J Environ Sci Technol*. 2017;11:331-338.
82. Shiigi K. Underground pathways to pollution: the need for better guidance on groundwater hydrologically connected to surface water ecological. *Law Q*. 2019;46:519.
83. Wanke H, Nakwafila A, Hamutoko JT, et al. Hand dug wells in Namibia: an underestimated water source or a threat to human health? *Phys Chem Earth Parts A/B/*C. 2014; 76:104-113.
84. Murphy HM, McGinnis S, Blunt R, et al. Septic systems and rainfall influence human fecal marker and indicator organism occurrence in private wells in Southeastern Pennsylvania. *Environ Sci Technol*. 2020;54:3159-3168.
85. Tirkey P, Bhattacharya T, Chakraborty S, Baraik S. Assessment of groundwater quality and associated health risks: a case study of Ranchi city, Jharkhand, India. *Groundw Sustain Dev*. 2017;5:85-100.
86. Rusydi AF. Correlation between conductivity and total dissolved solid in various type of water: a review. *IOP conference series: earth and environmental science*, Vol. 118, IOP Publishing; Bandung, Indonesia, 2017.
87. Rout C, Sharma A. Assessment of drinking water quality: a case study of Ambala cantonment area, Haryana, India. *Int J Environ Sci*. 2011;2:933-945.
88. Miraj A, Pal S, Bhattacharya S, et al. Observation on the TDS and EC values of different water bodies at Cooch Behar, West Bengal, India. *Int J Theor Appl Sci*. 2017;9:106-113.
89. Banna MH, Najjaran H, Sadiq R, Imran SA, Rodriguez MJ, Hoorfar M. Miniaturized water quality monitoring pH and conductivity sensors. *Sens Actuators B Chem* 2014; 193: 434-441.
90. US EPA.2023. Accessed August 9, 2023. https://www.epa.gov/newsreleases/search/year/2023
91. Egbueri JC, Ameh PD, Ezugwu CK, Onwuka OS. Evaluating the environmental risk and suitability of hand-dug wells for drinking purposes: a rural case study from Nigeria. *Int J Environ Anal Chem*. 2020;102:5528-5548.
92. Samayamanthula DR, Sabarathinam C, Alayyadhi NA. Trace elements and their variation with pH in rain water in arid environment. *Arch Environ Contam Toxicol*. 2021;80:331-349.
93. Gao Z, Zhang Q, Wang Y, Jv X, Dzakpasu M, Wang XC. Evolution of water quality in rainwater harvesting systems during long-term storage in non-rainy seasons. *Sci Tot Environt*. 2024;912:168784.
94. Singh S, Elumalai SP, Pal AK. Rain pH estimation based on the particulate matter pollutants and wet deposition study. *Sci Total Environ*. 2016;563:293-301.
95. Isah MA, Salau OB, Harir AI, Chiroma MA, Umaru A. Parameters of water quality in hand dug wells (HDW) from Hardo Ward, Bauchi Metropolis, Nigeria. *ARPN J Eng Appl Sci* 2015; 10:6804-6810.
96. Apau J, Acheampong A, Akoto O, Boateng ED. Physicochemical and Microbial Analysis of Water from Selected Hand-Dug Wells in Ayeduase, Kumasi. *Int J f Chem Biomolec Sci*. 2015; 1(4):292-296.
97. Sader M. Turbidity measurement: a simple, effective indicator of water quality change. OTT Hydromet. 2017. https://www.ott.com/download/turbidity-white-paper/
98. Adityas Y, Ahmad M, Khamim M, Sofi K, Riady SR. Water quality monitoring system with parameter of pH, temperature, turbidity, and salinity based on internet of things. *JISA*. 2021;4:138-143.
99. World Health Organization. *Water Quality and Health-Review of Turbidity: Information for Regulators and Water Suppliers*. World Health Organization; 2017.
100. WRC. *Ghana Raw Water Criteria and Guidelines*. Vol. 1. Water Resource Commission, 2003.
101. Abbas T, Zhang Q, Jin H, Li Y, Liang Y, Di H, Zhao Y. Anammox microbial community and activity changes in response to water and dissolved oxygen managements in a paddy-wheat soil of Southern China. *Sci Total Environ*. 2019;672:305-313.
102. Omotoso AJ, Dada OE, Oyedeji O. Physicochemical and microbiological assessment of selected hand-dug wells for water quality in Ilesa Metropolis, southwest Nigeria; *Not Sci Biol*. 2018;10(1):52-59.
103. Laniyan TA, Olatunji AS, Bayewu OO, et al. Physicochemical assessment and bacteriological studies of hand-dug wells of major markets in south western, Nigeria. *Arab J Geosci*. 2016;9:261.
104. Samuels P. *Advice on Exploratory Factor Analysis*. Centre for Academic Success, Birmingham City University Publishing; 2017.
105. Deborah L. Bandalos, Sarah J. Finney. Factor analysis: exploratory and confirmatory. In: *The reviewer's guide to Quantitative Methods in the Social Sciences*. Routledge; 2018: 2nd Edition 98-122.
106. Kline P. *An Easy Guide to Factor Analysis*. Routledge; 2014.
107. Boamah VE, Gbedema SY, Adu F, Ofori-Kwakye K. Microbial quality of household water sources and incidence of diarrhoea in three peri-urban communities in Kumasi, Ghana. *J Pharm Sci Res*. 2011;3:1087.
108. Nkansah MA, Opoku F, Ephraim JH, Wemegah DD, Tetteh LP. Characterization of beauty salon wastewater from Kwame Nkrumah University of Science and Technology, Kumasi, Ghana, and its surrounding communities. *Environ Health Insights*. 2016;10:EHI-S40360.
109. Onabule OA, Mitchell SB, Couceiro F. The effects of freshwater flow and salinity on turbidity and dissolved oxygen in a shallow Macrotidal estuary: a case study of Portsmouth Harbour. *Ocean Coast Manage*. 2020;191:105179.
110. Irvine KN, Richey JE, Holtgrieve GW, Sarkkula J, Sampson M. Spatial and temporal variability of turbidity, dissolved oxygen, conductivity, temperature, and fluorescence in the lower Mekong River–Tonle Sap system identified using continuous monitoring. *Int J River Basin Manage*. 2011;9:151-168.
111. Sarang A, Parsa S, Ahmadi A, Azarnivand AR. Analysis of the relationship between EC and TDS and their changes in the Karaj River. In: 11th international congress on civil engineering at: University of Tehran, Tehran, Iran, Vol. 7, 8th-10th May, University of Tehran Publishing; 2018.
112. Royte E. *Bottlemania: Big Business, Local Springs, and the Battle Over America's Drinking Water*. Bloomsbury Publishing; 2011.
113. Nyamekye E. *An investigation into quality of water from private hand dug wells sited in close proximity to on-site sanitation systems in households of small towns: A case study of Kintampo municipality in Brong-Ahafo Region, Ghana*. Doctoral's dissertation, Knust Publishing; 2013.
114. Ndububa Olufunmilayo I, Idowu Temitope J. Sanitary risk assessment of domestic hand-dug wells in Yelwa-Tudu, Bauchi State of Nigeria. *Int Res Public Environ Health*. 2015;2(8):102-111.
115. Kelly ER, Cronk R, Kumpel E, Howard G, Bartram J. How we assess water safety: a critical review of sanitary inspection and water quality analysis. *Sci Total Environ*. 2020;718:137237.
116. Kabeer HA. *Physicochemical Parameters of Water and Method of Their Analysis*. LAP LAMBERT Academic Publishing; 2013.