UNIVERSITY OF CAPE COAST

ASSESSMENT OF GROUNDWATER QUALITY AND GOVERNANCE IN FOUR COASTAL COMMUNITIES OF GHANA

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2023

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BY

EMUOBONUVIE GRACE AYETA

Thesis submitted to the Department of Fisheries and Aquatic Sciences, School of Biological Sciences, College of Agriculture and Natural Sciences, University of Cape Coast, in partial fulfilment of the requirements for the award of Doctor of Philosophy degree in Integrated Coastal Zone Management

SEPTEMBER, 2023

DECLARATION

Candidate's Declaration

I hereby declare that this thesis is the result of my own original research and that no part of it has been presented in another degree in this university or elsewhere.

Candidate's Signature …………………………… Date 4th Nov, 2024……………

Name: Emuobonuvie Grace Ayeta

Supervisor's Declaration

We hereby declare that the preparation and presentation of the thesis was supervised in accordance with the guidelines on supervision of thesis laid down by the University of Cape Coast.

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ABSTRACT

This study presents the findings of the assessment of groundwater quality, associated health risks, and groundwater governance in four coastal communities (Essiama, Winneba, Accra, and Keta) in Ghana. Membrane filtration method, Canadian Council of Ministers of the Environment Water Quality Index (CCME-WQI), and Nemerow's Pollution Index (NPI) were used to assess groundwater quality while Quantitative Microbial Risk Assessment (QMRA), incremental life cancer risk, and hazard quotient were employed to assess the health risks associated with groundwater use. In addition, policy document review, focused group discussions, and expert-based assessment were employed to assess groundwater governance status. The results showed that mean total coliforms and *Escherichia coli* ranged respectively from 123.40 to 501.30 and 30.98 to 141.90 CFU/100 ml, respectively, in the selected communities. Mean NO_3 concentrations exceeded the World Health Organization's standards in Winneba and Accra for both the rainy and the dry seasons. Arsenic was higher than the acceptable level in Accra and Keta during the dry season, while Fe was higher than the acceptable levels in Accra in both seasons. CCME-WQI indicated that groundwater quality ranged from poor to marginal and NPI revealed that NO_3, As, and Fe contributed to the deterioration of the groundwater sources. QMRA showed that exposure to *E. coli* O157:H7 through drinking groundwater ranged from 5 to 23 cells per day and the annual risk of infection and illness from *E. coli* O157:H7 for all communities was 1 for drinking. Arsenic showed non-cancer risks in Accra and Keta. Assessment of groundwater governance capacity showed that overall groundwater governance capacity in Ghana was incipient. To protect groundwater resources in Ghana, there is a need to regulate activities that degrade groundwater sources, and also build groundwater governance capacity, and promote public participation in the process.

KEYWORDS

Groundwater

Groundwater governance

Groundwater microbiome

Health risk assessment

Quantitative microbial risk assessment

Water quality

LIST OF PUBLICATIONS

1. **Ayeta, E. G**., Yafetto, L., Lutterodt, G., Ogbonna, J. F., & Miyittah, M. K. (2023). Seasonal variations and health risk assessment of microbial contamination of groundwater in selected coastal communities of Ghana. *Heliyon*, *9*(8), e18761. https://doi.org/10.1016/j.heliyon.2023.e18761
2. **Ayeta, E. G**., Yafetto, L., Lutterodt, G., Ogbonna, J. F., & Miyittah, M. (2024). Groundwater governance and a snapshot of associated issues in selected coastal communities in Ghana. *Groundwater for Sustainable Development*, 25, 101164. https://doi.org/10.1016/j.gsd.2024.101164
3. **Ayeta, E. G**., Yafetto, L., Lutterodt, G., Ogbonna, J. F., & Miyittah, M. K. (2024). Groundwater in the coastal areas of Ghana : Quality and associated health risks. *Heliyon*, 10(11), e31652. https://doi.org/10.1016/j.heliyon.2024.e31652

ACKNOWLEDGEMENTS

I would like to express my sincere gratitude to my supervisors: Prof. Michael Miyittah, Prof. Joel Ogbonna, Prof. Levi Yafetto and Dr. George Lutterodt for supervising this thesis. I appreciate the guidance and encouragement you provided me in the course of this research.

I am most grateful to the Africa Centre of Excellence in Coastal Resilience (ACECoR), the Government of Ghana, and the World Bank for funding my doctoral programme. My profound gratitude goes to the Director of ACECoR, Prof. Denis Aheto, his Deputy, Dr. Precious Mattah, and the staff of the Centre.

I am grateful to the Head of Department, and staff of the Department of Fisheries and Aquatic Sciences for their support in making this work a reality. To Mr. Thomas Davis, Mr. Prosper Dordunu, and Mr. Albert Koomson I say thank you for your support in the laboratory. I am grateful to Dr. Mireku, Dr. Akwetey, Dr. Arizi, and Dr. Mensah for their support in the course of my programme.

I sincerely appreciate Mr. Jonathan Nton of the Department of Laboratory Technology and Mr. Theophilus of the Department of Molecular Biology for assisting me in their laboratories. I also appreciate Dr. Samira Woananu-Aggor and Dr. Gertrude Dali for their support.

I lack words to express how grateful I am to my family and friends for their immense support. A big thanks to my husband, Dr. Charles Abimbola Faseyi for his unwavering support and contribution to this work. To my parents, siblings, in-laws, and extended family members I say many thanks for your prayers and encouragement. I especially thank Mr. Emmauel Ayeta for proofreading the first draft of this work. I appreciate Mr. and Mrs. Emmanuel Orji, Mr. Itievwe Oghenekevwe, and Mr. and Mrs. Peter Alake Lastly, I thank my colleagues in ACECoR who made this journey delightful for me. Special thanks to Mrs. Eunice Ofoli-Anum and Mrs. Sheila Ashong.

DEDICATION

To my wonderful family who have always been a pillar of support.

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LIST OF ABBREVIATIONS

AAS	Atomic absorption spectrophotometer
ACECoR	Africa Centre of Excellence in Coastal Resilience
ADI	Average Daily Intake
APHA	American Public Health Association
AT	Average Time
CCME	Canadian Council of Ministers of the Environment
CFU	Colony Forming Unit
CONIWAS	Coalition of Non-Governmental Organizations in Water and Sanitation
CSIR	Council for Scientific and Industrial Research
CWSA	Community Water and Sanitation Agency
DALY	Disability-Adjusted Life Years
DO	Dissolved Oxygen
EC	Electrical Conductivity
ED	Exposure Duration
EF	Exposure Factor
FGD	Focus Group Discussion
FNU	Formazin Nephelometric Units
GAEC	Ghana Atomic Energy Commission
GWCL	Ghana Water Company Limited
GWMATE	Groundwater Management Advisory Team
HQ	Hazard Quotient
ICPMS	Inductively Coupled Plasma Mass Spectrometry
ILCR	Incremental Life Cancer Risk

IR	Ingestion Rate
IRB	Institutional Review Board
NPI	Nemerow's Pollution Index
NTU	Nephelometric Turbidity Units
PCA	Principal Component Analysis
PURC	Public Utilities Regulatory Commission
QA/QC	Quality Assurance and Quality Control
QMRA	Quantitative Microbial Risk Assessment
RfD	Reference Dose
SDGs	Sustainable Development Goals
SF	Slope Factor
TDS	Total Dissolved Solids
USEPA	United States Environmental Protection Agency
WATSAN	Water and Sanitation
WQI	Water Quality Index
WRC	Water Resources Commission
WRI	Water Research Institute
LY	Lifetime

CHAPTER ONE

INTRODUCTION

Groundwater provides over 97% of accessible freshwater; about half of the water needed for drinking and irrigation worldwide; one-third of the water needed by industries; sustains several ecosystems and would play an integral role in achieving the United Nations Sustainable Development Goals (e.g., SDGs 1, 2, 3, 6, and 11) (Giupponi, 2017; Jakeman et al., 2016; United Nations Water, 2022).

Ghana is currently faced with the challenge of providing quality drinking water for its increasing populace due to environmental pollution (Ametepey, 2023; Obuobie & Boubacar, 2015). It has been reported that about 60% of Ghana's surface waterbodies are polluted, leading to increasing dependence on groundwater sources (Ampomah, 2017). However, these groundwater sources are also being contaminated by negative human activities (Li et al., 2021; Yeleliere et al., 2018). In coastal areas, the problem is further worsened by salinization and increased anthropogenic pressure (Plumpton et al., 2020).

Several researchers have reported the pollution of groundwater sources in Ghana (Asare-Donkor & Adimado, 2020; Boateng et al., 2016; Lutterodt et al., 2018, 2021; Yidana et al., 2012). Nevertheless, studies assessing seasonal variations in groundwater quality, and associated health risks in the coastal areas of Ghana are scarce. Similarly, studies assessing the groundwater microbiome and the status of groundwater governance in the country are rare. This study, therefore, sought to assess the groundwater quality and the groundwater governance status along the coast of Ghana. The specific objectives of this study were to (i) assess groundwater pollution along the coast of Ghana using physicochemical parameters, metals, nutrients, and indicator bacteria; (ii) assess seasonal variation in groundwater quality (iii) assess bacterial diversity in the groundwater; (iv) determine the potential health risk associated with groundwater pollution; (v) assess the status of groundwater governance in Ghana.

Background of the Study

Groundwater is a crucial resource on Earth (Vadiati et al., 2018). It provides over 97% of accessible freshwater, and about half of the water needed for drinking, irrigation, and industries worldwide (Jakeman et al., 2016; UN-Water, 2022). In most parts of the world, particularly in sub-Saharan Africa in which the recycling and reuse of water are rare, it is the major source of freshwater (Idowu, 2017). Groundwater is also the most extracted raw material in the world with the rate of global withdrawal being 800 to 1000 km^3/year, which is 20 times higher than that of oil (Jarvis 2012; Margat & Van der Gun, 2013). Aside from being the major source of drinking water, groundwater sustains several ecosystems (Giupponi, 2017) which in turn provides man with numerous benefits. Groundwater is also a vital component of the hydrologic cycle (Giupponi, 2017). Because of the invaluable nature of water, Owusu et al. (2016) described it as life, and it provides several direct and indirect services to man including health, welfare, economic, and social development of many countries.

United Nations Sustainable Development Goals (SDGs) outline global development priorities and ambitions, and strive to mobilize global efforts to end poverty, protect our planet, and improve the lives and prospects of everyone, everywhere (Global Reporting Initaitive, 2018). These global goals were adopted in 2015 and are set to be achieved by 2030 (United Nations Development Programme [UNDP], 2021). Although progress toward achieving these goals has been made in several places, this progress is not occurring at the speed and scale required for their achievement (United Nations, 2019). With less than ten years left to achieve the SDGs, world leaders have called for a 'Decade of Action' to accelerate efforts to achieve the global goals. Howbeit, the achievement of several of these SDGs is closely linked to the provision of groundwater, both in adequate quantity and optimum quality. Improving access to clean water and its sustainable management is an integral part of increasing food production, well-being and health, and sustainable development in cities and communities, thus addressing SDG goal 1 on poverty reduction, goal 2 on zero hunger, goal 3 on well-being and health, goal 6 on clean water and sanitation, and goal 11 on making cities and human settlements safe, inclusive, resilient and sustainable. However, this critical resource is facing challenges such as pollution and increased anthropogenic pressure.

Although water is abundant on earth, not all persons or countries have access to the quantity and quality of water that meets their basic health, sanitation, and recreational needs as well as developmental needs (Owusu et al., 2016). The increased pressure on groundwater sources due to an increase in population, increased agricultural activities to feed the growing population, and industrialization have adversely affected the quantity and quality of water resources worldwide. Aquifers which are a vital component of the Earth's hydrological cycle and a major source of groundwater worldwide are faced with an increasing threat of pollution (Zacchaeus et al., 2020). The pollution is caused by pathogenic microbes (e.g. *E.coli*), heavy metals (e.g. lead and arsenic), nutrients (e.g. nitrates and phosphates), and emerging pollutants (e.g. pharmaceuticals, pesticides, and microplastics). A wide range of pathogenic microbes including bacteria, viruses, and parasites have been reported in groundwater (Keesari et al., 2015). Likewise, bacteria constitute a major group of microorganisms that cause waterborne disease outbreaks globally (Al-Fifi et al., 2019). These diseases range from gastrointestinal, respiratory, systemic disease, etc. (Collier et al., 2021). Heavy metals are also common environmental pollutants that are known for their toxic effects, pernicious nature, and bio-accumulative nature with associated health menaces such as the reduction of growth and development of cancer (Bhutiani et al., 2017; Zacchaeus et al., 2020). An increase in nutrients such as nitrates and phosphate as well as changes in physico-chemical parameters of groundwater also have adverse health effects.

Ghana, a lower middle-income nation is faced with several challenges, including the provision of quality drinking water for its increasing populace (Ametepey, 2023; Cross Catholic Outreach, 2021; Obuobie & Boubacar, 2015). According to Ampomah (2017), about 60% of Ghana's surface waterbodies are contaminated and most are in a severe state. This has made the cost of water treatment very high, forcing some water treatment plants to shut down (Yeleliere et al., 2018). For instance, a water treatment plant in Kyebi was reported to have shut down due to high operational costs (Yeleliere et al., 2018). Similarly, the inability of Ghana Water Company Limited (GWCL) to supply enough water to meet the demands for both household and commercial purposes has led several households to resort to the use of groundwater e.g. shallow wells and boreholes (Sebiawu et al., 2014). The problem (surface water degradation) has also forced the GWCL to provide boreholes for small communities (Yeleliere et al., 2018). Therefore, this increase in the dependence on groundwater resources in Ghana warrants regular monitoring of its quality.

Statement of the Problem

The coastal zone of Ghana is home to about a quarter of the nation's 31 million inhabitants, although it makes up only about 7% of the nation's total landmass (Appeaning, 2021). This places a huge demand on groundwater resources in the area. Furthermore, industrial activities in the coastal zone have some detrimental effects on the region's water resources (Appeaning, 2021). For instance, artisanal and small-scale mining in the Southwestern region of Ghana has led to extensive pollution of surface water in the area (Darko et al., 2021; Faseyi et al., 2022; Yeleliere et al., 2018). These mining activities have been reported to cause heavy metal pollution of groundwater in these areas through seepage, run-off, and interaction of surface water with groundwater (Faseyi, et al., 2022). In addition, coastal degradation and seawater intrusion further worsen the situation (Faseyi et al., 2023).

Moreover, poor sanitation in most coastal communities poses a threat of pollution to groundwater in these communities. The high population in the coastal areas is not commensurate with the availability of sanitation facilities. It has been reported that less than 26% of the population in Ghana's coastal area have access to basic sanitation services; about 16%, 17%, 8%, and 38% of the population in Western, Central, Greater Accra, and Volta regions, respectively, practice open defecation (Ghana Statistical Service, 2019). Consequently, Ghana was ranked as the second-highest country in Africa that practices open defecation (World Health Organization [WHO]/United Nations International Children's Emergency Fund [UNICEF], 2015). Poor sanitation facilities pollute groundwater resources because of the absence of a physical barrier between the stored faeces and the soil (Zume et al., 2021). Improper waste management is also a common problem that results in an increasing risk of microbial contamination.

A number of studies have reported the pollution of groundwater in Ghana (Amoako et al., 2011; Asare-Donkor & Adimado, 2020; Boateng et al., 2016; Chegbeleh et al., 2020; Kortatsi, 2009; Lutterodt et al., 2018, 2021a; Yidana et al., 2012). Similarly, several studies have reported the pollution of groundwater with faecal bacteria in the country (Lutterodt et al., 2018, 2021; Takal & Quaye-Ballard, 2018; Yeboah et al., 2022). This notwithstanding, long-term assessment of groundwater quality that captures seasonal variations in the coastal communities of Ghana is scarce. Furthermore, studies that assessed the potential health risks associated with bacterial pollution of groundwater in coastal communities of Ghana are rare. In a previous study, Lutterodt et al. (2021a) assessed the suitability of well water for drinking and showed the persistent presence and contamination of bacteria in a coastal aquifer in the Cape Coast Metropolitan Assembly. In the study, only the dry season was considered and no empirical assessment of health risk was carried out. In other studies by Ketadzo et al. (2021) in Accra and Zume et al. (2021) in Cape Coast, one-time sampling was carried out to assess groundwater quality. Also, like Lutterodt et al. (2021a) study, these studies also did not assess the health risks associated with groundwater contamination. Additionally, a literature search on the microbial risk assessment associated with groundwater sources in the coastal communities of Ghana revealed only the work of Machdar et al. (2013) in some slums within Accra City.

In the same vein, although research on bacteria in drinking water has broadened considerably beyond faecal bacteria, a literature search on bacterial diversity in groundwater showed that no study has been done on the subject (to the best of my knowledge). Only the work of Ecklu-Mensah et al. (2019) on the Ghana Water Company Limited Waterworks in Weija surfaced as a related study.

Also, studies assessing the status of groundwater governance in Ghana are rare. The few studies on groundwater governance in Ghana have either been limited to small geographical areas e.g. the work of Grönwall (2016) in Dodowa, or focused on water users and in some cases on water governance in general (Frimpong et al., 2021; Kankam-Yeboah et al., 2011). To proffer practical and holistic solutions to the problems facing groundwater in the country, there is a need to assess the status of the resource in conjunction with the governance structures put in place to manage it.

Given the above gaps in groundwater studies, particularly in the coastal communities of Ghana, it is necessary to assess the groundwater quality, its seasonal variations, associated health risks, and the groundwater governance status in these communities.

Purpose of the Study

United Nations identifies the key roles that water plays in ending poverty, protecting our planet, and improving the lives and prospects of people, hence SDGs 1 and 6. Groundwater would play a critical role if these goals are to be achieved as population growth, socio-economic development, and food demand continue to increase while pollution and climate change increasingly threaten surface water resources. Therefore, the achievement of SDG 1 (no poverty), 2 (zero hunger), 3 (good health and well-being), 6 (clean water and sanitation), 11 (sustainable cities and communities), and 13 (climate action) as well as other regional goals such as the African Union agenda 2063, the African Ministers' Council on Water (AMCOW) goals, and the Pan-Africa Groundwater Program (APAGroP) goals, are greatly connected to the provision of groundwater of adequate quantity and quality.

The scant information and dearth of knowledge in the area of water and sanitation, with a special focus on groundwater quality, suggest a need for a series of investigations to understand the current state and quality of groundwater in the coastal communities, as well as the status of groundwater governance in Ghana.

Aims of the Study

This study aims to assess the groundwater quality and governance in the coastal communities of Ghana.

Objectives of the Study

To attain the above aim, the specific objectives of this study are to:

1. Assess groundwater pollution along the coast of Ghana using physicochemical parameters, metals, nutrients, and indicator bacteria.
2. Assess the seasonal variations in groundwater quality

3. Assess bacterial diversity in groundwater along the coast of Ghana.
4. Determine the potential health risks associated with groundwater pollution.
5. Assess the status of groundwater governance in Ghana.

Hypotheses

1. The increasing environmental pollution along the coast of Ghana increases the concentration of metals, nutrients, and indicator bacteria, and changes the physicochemical parameters in groundwater.
2. Groundwater quality along the coast of Ghana is influenced by seasonal changes.
3. The bacterial community along the coast of Ghana is influenced by human activities.
4. The rise in pollution of groundwater along the coast of Ghana increases the potential health risk posed to the residents of the communities.
5. There is low groundwater governance capacity in Ghana.

Statistical Hypotheses

The following hypotheses are put forth for the study:

Hypothesis 1

$H_{01:}$ The increasing environmental pollution along the coast of Ghana does not increase the metals, nutrients, and indicator bacteria concentrations, and does not affect the physicochemical parameters in groundwater.

$H_{A1:}$ The increasing environmental pollution along the coast of Ghana increases the concentration of metals, nutrients, and indicator bacteria, and affects the physicochemical parameters in groundwater.

Hypothesis 2

$H_{01:}$ Groundwater quality along the coast of Ghana is not influenced by seasonal changes.

$H_{A1:}$ Groundwater quality along the coast of Ghana is influenced by seasonal changes.

Hypothesis 3

$H_{01:}$ The bacterial community along the coast of Ghana is not influenced by human activities.

$H_{A1:}$ The bacterial community along the coast of Ghana is influenced by human activities.

Hypothesis 4

$H_{01:}$ The rise in pollution of groundwater along the coast of Ghana does not increase the potential health risk posed to the residents of the communities.

$H_{A1:}$ The rise in pollution of groundwater along the coast of Ghana increases the potential health risk posed to the residents of the communities.

Hypothesis 5

$H_{01:}$ Groundwater governance capacity in Ghana is not low.

$H_{A1:}$ Groundwater governance capacity in Ghana is low.

Significance of the Study

This study would provide robust data for policymakers such as the Water Resource Commission, Community Water and Sanitation Agency, Ministry of Health, and other stakeholder institutions in Ghana and enable them to make informed decisions and take persuasive actions toward the protection of groundwater resources in the coastal communities of Ghana.

Additionally, the study would bridge the gap between science, policy, and society, as groundwater research in Ghana has been mainly focused on biogeochemical studies. By shifting attention to groundwater governance, this research would help to expand the debate on policy and institutional design which has been long confined to surface water in the country.

Furthermore, the exploration of bacterial diversity in the coastal areas of Ghana will provide a baseline study of groundwater microbiomes in the country. This will form a basis for future research on groundwater microbiomes and their biochemical potentials.

In addition, since groundwater plays a critical role in the survival of ecosystems including coastal ecosystems, this study will contribute to the achievement of the goals of the Africa Centre of Excellence in Coastal Resilience (ACECoR) in addressing ecosystem degradations and protecting coastal resources in West Africa.

The aforementioned would ultimately lead to the reduction of diseases; protection of groundwater-dependent ecosystems such as wetlands, estuaries, and other near-shore ecosystems; protection of groundwater obligate species that might be present in the coastal aquifers; and enhance economic and agricultural activities in the coastal regions of Ghana, thus helping to achieve

SDG 1 (no poverty), 2 (zero hunger), 3 (good health and well-being), 6 (clean water and sanitation), 11 (sustainable cities and communities) and 13 (climate action).

Delimitations

i. The study assessed groundwater quality in selected coastal communities of Ghana
ii. Sampling was done once per season to cover the rainy and dry seasons.
iii. Parameters assessed in the study include physicochemical parameters (temperature, pH, total dissolved solids, turbidity, and salinity), metals (arsenic, lead, and iron), nutrients (nitrate and phosphate), indicator bacteria (*E. coli,* and total coliforms), and bacterial diversity. The microbiome study (microbial diversity) did not include the quantification of the identified bacteria.
iv. The governance status assessment explored groundwater governance based on policy document review, expert opinion, and focus group discussions with community leaders.

Limitations

i. Sampling was done only once in a season (wet and dry season) due to the associated cost.
ii. More frequent sampling regimes e.g., bimonthly sampling will provide a clearer picture of the influence of seasonal changes on groundwater quality.

iii. Composite samples were collected for metal analyses due to the cost implications.

Definition of Terms

Groundwater: Groundwater is the water stored underground in the spaces (pores and fractures) between rocks and sediments.

Aquifer: An aquifer is a body of permeable rock or sediment that stores and transmits significant quantities of groundwater.

Microbiome: A microbiome is a community of microorganisms (e.g. bacteria, fungi, and viruses) that exist in a particular environment.

Focus Group Discussion (FGD): A qualitative research method where data is collected by interviewing participants in a group.

Organization of the Study

This thesis consists of six (6) chapters. The first chapter contains the introduction, background of the study, statement of the problem, purpose of the study, aim and objectives, hypotheses, significance, delimitations and limitations of the study, and definition of terms.

Chapter two (2) contains a review of the literature on groundwater, its importance and role in the achievement of the Sustainable Development Goals, the problems it faces, its occurrence in Ghana, groundwater quality assessment, and the parameters considered. The use of water quality indices and Nemerow's pollution index in communicating groundwater quality information was also reviewed. In addition, health risk assessments (i.e. hazard quotient, incremental life cancer risk, and quantitative microbial risk assessment) were considered. Lastly, a review of groundwater governance was also done in the chapter.

Chapter three (3) contains the first manuscript drafted from the study. The manuscript titled 'Seasonal variations and health risk assessment of microbial contamination of groundwater in selected coastal communities of Ghana' was published in Heliyon. The study evaluated seasonal variations in *E. coli* and total coliforms, sanitary risk assessment to trace the possible sources of groundwater contamination, and health risk assessment using quantitative microbial risk assessment (QMRA). The manuscript containing the findings on groundwater microbiome is yet to be completed and was not included in this report.

Chapter four (4) presents the findings on the physicochemical, metals, and nutrient concentrations in groundwater and associated health risks in a manuscript titled 'Groundwater in the coastal areas of Ghana : Quality and associated health risks. The manuscript was published in Heliyon.

Chapter five (5) presents the findings on groundwater governance in a manuscript titled 'Groundwater governance and a snapshot of associated issues in selected coastal communities in Ghana'. The study employed policy document review, expert-based assessment, field observations, and focus group discussion with community leaders to assess groundwater governance and a snapshot of associated issues in selected coastal communities in Ghana. The was published in the journal "Groundwater for Sustainable Development".

Chapter six (6) consists of the summary, conclusions, and recommendations from the study. A list of references cited and appendices is presented after chapter six. The appendix contains the instruments used for data collection for the governance study.

CHAPTER TWO

LITERATURE REVIEW

This chapter presents the conceptual framework of the study and a review of the literature on groundwater, its importance, the role of groundwater in drinking water supply, the connections between groundwater and SDGs, as well as indicators used in groundwater quality assessments. The chapter also includes a review of the literature on health risk assessment and groundwater governance. The review considered groundwater studies in Ghana and other parts of the world.

Conceptual Framework of the Study

This study is guided by the socio-ecological systems framework; an integrative framework that holds the view that humans and nature are interdependent (Rica et al., 2019). Social ecological systems are complex interdependent systems of society (people) and the environment where the society is viewed as a part of the environment, and not apart from the environment (Berkes et al., 2003). The socio-ecological systems framework provides a background that relates humans and ecological factors while acknowledging the biophysical variables that each system contains and the roles and scales of governance, as well as the factors that influence governance outcomes (Rica et al., 2019). One key advantage of the framework is that it increases methodological pluralism which enhances the understanding of complex systems (Fischer et al., 2015). This core advantage, and the ability of the framework to promote the recognition of the interdependence of humans and nature, and enhance collaboration across disciplines, and between science and society (Fischer et al., 2015), made its adoption in this study imperative.

To gain an in-depth understanding of the groundwater ecosystem, the study encompassed the biological, physical, and chemical quality of groundwater; health implications of the above components to humans who depend on groundwater; and the governance arrangements and institutions put in place to govern the resource. The governance aspect was included in this study because governance is a key human factor that influences common pool resources like groundwater. Also, work on governance in relation to groundwater in Ghana is scarce. Knowledge generation in groundwater studies is largely asymmetric; while there is a remarkable increase in knowledge in the field of hydrology and hydrogeology, little is known about the socio-economic impacts and institutions that govern groundwater (Mukherji & Shah, 2005). As Mukherji and Shah (2005) argued almost two decades ago, the situation remains the same in Ghana.

The conceptual framework of the study (Figure 1) is therefore based on the premise that groundwater governance and scientific groundwater assessment are interdependent (de Chaisemartin et al., 2017b). While groundwater assessment provides a sound knowledge of the resource, which is important in ensuring effective management, groundwater governance provides the framework for groundwater monitoring and assessment (de Chaisemartin et al., 2017b). Adequate groundwater governance and assessment help to unveil the pollution status of groundwater, curtail activities that lead to groundwater pollution including land-use pollution sources, and thus help to improve groundwater quality. The improvement would ultimately lead to the achievement of SDG 3 and SDG 6 by ensuring the availability of safe and affordable drinking water for all, protecting water-related ecosystems including aquifers, and reducing deaths from unsafe water.

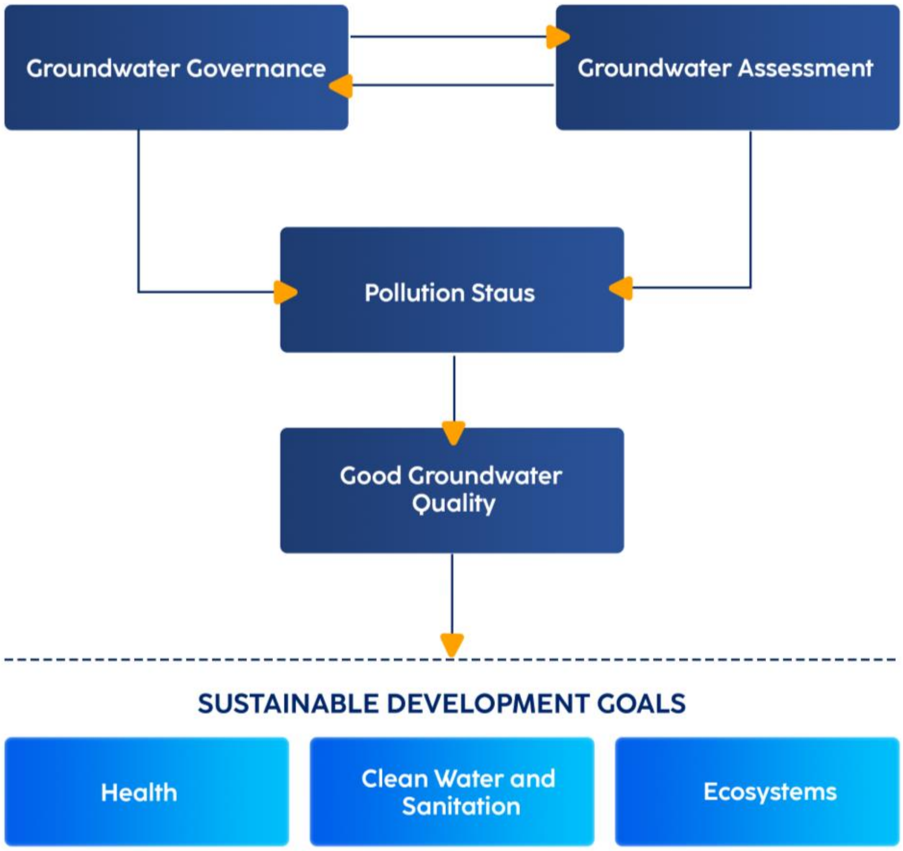

Figure 1: Conceptual framework of groundwater governance

Groundwater

Groundwater is the water that is found below the earth's surface in zones of permeable rock, and sediment materials where all the spaces between rock materials are filled (saturated) with water (Woessner & Poeter, 2020). According to the United States Geological Survey (2018), it is the water found in saturated zones beneath the earth's surface. Groundwater is stored underground in the spaces (pores and fractures) between rocks and sediments.

Permeable rock or sediment materials that store and transmit significant quantities of groundwater are referred to as aquifers. These aquifers have two general characteristics: they can store water in economically usable amounts and are able to transmit the stored water such that it can flow out of the rock either naturally or when pumped (Arthur et al., n.d.; Woessner & Poeter, 2020).

While water covers 70% of the earth's surface, only about 2.5% is freshwater (Figure 2) (Owusu et al., 2016). Approximately 68.7% of the freshwater is locked up in the frozen state in glaciers and polar ice caps, leaving only about 31.3% as unfrozen water (Figure 2) (USGS, 2009 in Cassardo & Jones, 2011). Groundwater makes up about 30.1% of this unfrozen freshwater; about 97% of the unfrozen freshwater on earth is present as groundwater (Gibert & Deharveng, 2002).

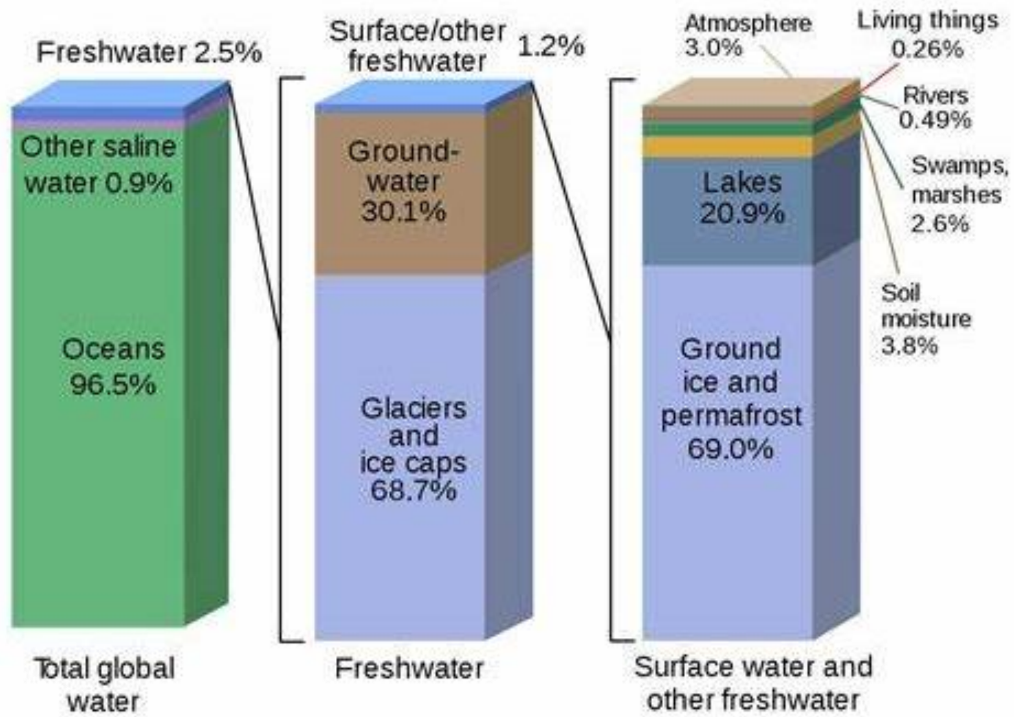

Figure 2: The distribution of earth's water (US Geological Survey Water Science School, 2019)

Importance of Groundwater

Groundwater is a crucial resource on earth (Vadiati et al., 2018). It provides over 97% of accessible freshwater; about half of the water needed for drinking, irrigation, and industries worldwide (Jakeman et al., 2016, UN-Water, 2021). In most parts of the world, particularly in sub-Saharan Africa in which the recycling and reuse of water are rare, it is the major source of fresh water (Idowu, 2017).

Groundwater is also the most extracted raw material in the world with the rate of global withdrawal being 800 to 1000 km^3/year, which is 20 times higher than that of oil (Jarvis 2012; Margat & Van der Gun, 2013). About 70% of groundwater withdrawn globally is used in agriculture (National Ground Water Association, 2021).

Aside from being the major source of drinking water, groundwater sustains several ecosystems (Giupponi, 2017) which in turn provides man with numerous services. These ecosystems are referred to as groundwater-dependent ecosystems (Kløve et al., 2011). Groundwater-dependent ecosystems are ecosystems whose composition, structure, and function rely on a supply of groundwater (Kløve et al., 2011). They range from terrestrial ecosystems such as lakes and rivers to coastal ecosystems such as estuaries. Some of these ecosystems, for example, springs are completely fed by groundwater and would not exist without groundwater (Kløve et al., 2011). Thus, Giupponi (2017) described groundwater as a vital component of the hydrologic cycle. Because of the invaluable nature of water, Owusu et al. (2016) described it as life and that it provides several direct and indirect services to man including health, welfare, economic, and social development of communities and countries.

Global Water Crisis

Water supply is essential to life and the development of resilient cities and communities, but global water supplies are dwindling. Universally, about two billion people lack access to safe drinking water (United Nations, 2023). Currently, almost 50% of the global population lives in places where water scarcity is experienced for at least one month annually (United Nations World Water Assessment Programme, 2018). The number of persons experiencing water scarcity is expected to increase to 57% by 2050 according to United Nations World water Assessment Programme (2018).

Water scarcity is driven by an increase in water use due to population growth which leads to increasing water demands; the increase in the pollution of water resources; and the decrease in water resources (Boretti & Rosa, 2019). It is projected that by 2050, the world's population will be about 9.7 billion people and the current water demand will increase by 20-30% (Burek et al., 2016; United Nations Department of Economic and Social Affairs [UNDESA], 2022). More than half of the projected population growth will occur in sub-Saharan Africa (UNDESA, 2022). This will lead to an increasing demand for water in the region. Of the six continents, Africa has the lowest surface water availabiltiy and water supply sustainability, and this is expected to remain so even beyond 2050 as reported by (Burek et al., 2016). Water scarcity is already a major problem in developing countries and future stress on water resources is expected to be higher in these countries due to population growth (Boretti & Rosa, 2019).

The pollution of water resources is a serious threat to water security. For instance, about 44% of domestic waste worldwide is released into the environment without proper treatment (United Nations, 2023). Similarly, industrial waste discharged into water amounts to about 300-400 megatons per year. The water crisis is further worsened by non-point pollution sources such as seepages from agricultural lands and urban areas (Boretti & Rosa, 2019). A report by the United Nations Environment Programme in 2016 showed that in Latin America, Africa, and Asia, about 30%,14%, and 10% of all rivers are polluted with pathogens, organic matter, and salinity, respectively.

Climate change further worsens the water crisis around the world. For instance, climate change has resulted in to increase in both water scarcity and water-related hazards, due to the disruption of precipitation patterns and hydrological cycles (UNICEF, 2021). Water-related hazards such as floods lead to an increase in surface and groundwater pollution particularly in shallow aquifers (Bates et al., 2008).

Burden of Unsafe Drinking Water

The burden of unsafe water resources and water-borne diseases is enormous. Lack of safe drinking water is a major risk factor for contagious diseases such as diarrhea, cholera, dysentery, typhoid, hepatitis A, and polio (WHO, 2019). Globally, about 1.2 million people died (about 2.2% of global deaths) due to a lack of safe drinking water in 2017 (Stanaway et al., 2018), and about 297,000 children under the age of five die each year from diarrhea (WHO, 2019). In low-income countries, the numbers are much higher, unsafe water sources accounted for about 6% of deaths in 2017 (WHO, 2019), and sub-Sahara Africa is still the region with the highest disease burden from inadequate water, sanitation, and hygiene (International Institute for Sustainable Development, 2020). In 2016, diarrheal diseases caused more than half a billion deaths in sub-Sahara Africa and polluted drinking water was a major risk factor as reported by Troeger et al. (2018).

Between January and August 2021, Nigeria reported 31,425 suspected cases of cholera, 311 confirmed cases, and 816 deaths from 22 states and its Federal Capital Territory (Nigeria Centre for Disease Control, 2021). Likewise, since the 1970s, Ghana has reported intermittent cholera outbreaks, especially in the communities along the coast (Mireku-Gyimah et al., 2018; Noora et al., 2017; Opare et al., 2012). In 2014, 60% of its district reported cholera infections (Mireku-Gyimah et al., 2018).

Water-related diseases are however not peculiar to low-income countries alone. Even in the United States which has one of the safest drinking water supplies, annually, approximately 7.2 million Americans get sick from water-borne diseases costing their healthcare system over 3 billion US dollars (CDC, 2020). The relevance of this problem underpins the fact that SDG6 is geared towards ensuring the availability and sustainable management of water and sanitation for all.

Role of Groundwater in Domestic Water Supply

Groundwater provides drinking water entirely or in part for as much as half of the world's population (The Groundwater Project, 2020). It is the only source of water for about 2.5 billion people worldwide (The Groundwater Project, 2020). This high dependence on groundwater occurs both in urban and rural areas. An estimated 50% of urban dwellers globally are believed to be dependent on groundwater (International Association of Hydrogeologists, 2015).

In developing countries, groundwater use mainly takes the form of self-supply. Self-supply comprises water sources (mainly groundwater and rainwater) within the premises of individual households, that are owned and managed by the households (Grönwall & Danert, 2020). More than 1.5 billion urban residents depend on groundwater supplies, and groundwater is the fastest-growing means of meeting water demands in sub-Saharan African cities (Foster et al., 2010). Therefore, self-supply plays a vital role in the water supply ecosystem of developing countries and has the potential to pivot the pace toward the achievement of SDG target 6.1 (Foster et al., 2021).

The growing dependence on groundwater is mainly due to urbanization, reduced riverine water intake due to pollution and climate change, as well as the low cost of investment in groundwater (Foster et al., 2010). For instance, in Vietnam, Erban et al. (2014) and Nguyen et al. (2022) reported that surface water pollution was responsible for the increasing reliance on groundwater. Nyakundi et al. (2022) also reported similar findings in Kenya. In Ghana, the pollution of surface waterbodies is widespread and has been reported in a number of regions including Western, Eastern, Greater Accra, Central, and Ashanti, leading to the increasing reliance on groundwater resources (Faseyi, et al., 2022a; Faseyi, et al., 2022b; Fianko et al., 2007; Hadzi et al., 2015; Mantey & Owusu-Nimo, 2017; Miyittah et al., 2020; Monney, 2013). For example, 77% of the residents of Wa Municipality in the Upper West region depend on privately owned boreholes (Sebiawu et al., 2014). Other factors that increase the dependence on groundwater in Ghana are the inability of its inhabitants to pay for water utility bills, the closeness of groundwater facilities to the communities, and the resilience of the resource to climate change impacts (Lapworth et al., 2013; MacDonald et al., 2011).

Problems Facing Groundwater Worldwide

Two major threats facing groundwater are over-abstraction and pollution. Over 30% of the world's largest aquifers are stressed (Richey et al., 2015). An increase in the abstraction of groundwater has led to groundwater depletion particularly in major agricultural and urban areas (Lall et al., 2020). Groundwater depletion occurs when groundwater extraction rates exceed recharge rates. Depletion of aquifers can lead to their extinction or seasonal exhaustion (Lall et al., 2020). Likewise, the over-abstraction of groundwater has resulted in land subsidence in some cities (Castellazzi et al., 2016; Kaneko & Toyota, 2011; Sowter et al., 2016).

Pollution has also seriously impacted groundwater resources. The pollution of groundwater may occur due to geogenic or anthropogenic impacts. Arsenic and fluoride are two of the most important geogenic groundwater contaminants; they affect millions of people on every continent in the world (UN Water, 2022). Anthropogenic pollution of groundwater results from agricultural activities, urbanization, increase in population, industrialization, and climate change. For instance, in America and Europe, nitrate and pesticide contamination of water is a major problem. Similarly, chemical pollution of groundwater is a common problem faced by aquifers, particularly in countries located in the eastern hemisphere (Li et al., 2021).

Generally, over-abstraction of groundwater is not a problem in Africa, as groundwater is largely under-utilized in the region (Cobbing & Hiller, 2019). However, pollution is a major concern in the continent. Contamination by nitrate and microbes is common due to poor sanitation and agricultural activities are a key challenge (UN Water, 2022). The main groundwater contaminants in

Africa based on their order of importance are nitrates, microbes, organic loads, salinity, and acid mine drains (Xu & Usher, 2006). Ouedraogo and Vanclooster (2016) reported the contamination of groundwater with nitrates across Africa except for a large part of the Sahara. Heavy metals, phosphate, and salt water intrusion have also been reported in the continent (Bempah & Ewusi, 2016; Darko et al., 2022; Edokpayi et al., 2018; Pessu et al., 2022).

Groundwater Occurrence in Ghana

Groundwater in Ghana occurs in three major geological formations: (i) the basement complex, which covers about 54% of the country; (ii) the consolidated sedimentary formations, which cover about 45% of the country; and (iii) the Mesozoic and Cenozoic sedimentary rocks, which cover about 1% of the country and are found in the extreme southwestern and southeastern parts, along the coast of Ghana (Water Resources Commission, 2023). About 41% of Ghanaian households depend on groundwater; more than 95% of the total groundwater use is for domestic purposes (Plumpton et al., 2020).

United Nations Sustainable Development Goals and Groundwater

The United Nations Sustainable Development Goals (SDGs), also known as the global goals were adopted in 2015 and set to be achieved by 2030 (UNDP, 2021). The goals define global development priorities and ambitions and strive to mobilize efforts to end poverty, protect our planet, and improve the lives and prospects of everyone, everywhere (Global Reporting Initaitive, 2018). Although progress toward achieving these goals has been made in several places, this progress is not occurring at the speed and scale required for their achievement (United Nations, 2019). With less than ten years left to achieve the SDGs, world leaders have called for a Decade of Action.

The achievement of several SDGs is closely related to the provision of groundwater, both in adequate quantity and optimum quality. About 53 SDG targets of the total 169 targets are linked to groundwater (Guppy et al., 2018). Ensuring the availability and sustainable management of water and sanitation for all is the aim of SDG 6. Improving access to clean water and its sustainable management is an integral part of increasing food production, well-being and health, and sustainable development in cities and communities.

Additionally, groundwater plays an important role in industries such as manufacturing, mining, food and beverages, and construction, particularly in places where surface water availability is limited or where quality is important (UN-Water, 2022). It provides about 33.3% of water for industries (United Nations Educational, Scientific and Cultural Organization [UNESCO], 2022), and also plays a vital role in supporting the livelihoods of a number of poor people (Shah, 2005). A large number of subsistence farmers including livestock farmers depend on groundwater (Shah, 2005). In West Africa, several businesses and service providers (e.g. saloon owners, brick makers, restaurants, etc.) are highly dependent on groundwater, making it a strategic resource in bringing an end to poverty in the region (SDG 1).

Similarly, groundwater is an important resource in agriculture and has the potential to boost food production and reduce hunger, particularly in the hunger-prone regions of the world. Globally, about 40% of irrigated-lands depend on groundwater (Siebert et al., 2010). Regions such as North America and South Asia are highly equipped for groundwater utilization. However, only

5% of sub-Saharan Africa is equipped for its use in irrigation despite the presence of vast shallow aquifers (UN-Water, 2022). Africa has the highest prevalence of undernourishment and sub-Saharan Africa is the region mostly affected by food insecurity (Food and Agriculture Organization, 2020; Van Ittersum et al., 2016). Therefore, sustainable groundwater development will present an opportunity to meet SDG 2.

Also, protecting and improving groundwater quality is vital in achieving SDG 3, particularly in meeting target 3.3 (end the epidemics of AIDS, tuberculosis, malaria, and neglected tropical diseases and combat hepatitis, water-borne diseases, and other communicable diseases) and target 3.9 (substantially reduce the number of deaths and illnesses from hazardous chemicals and air, water, and soil pollution and contamination). Hence, the availability of groundwater of good quality will help prevent water-borne diseases and reduce the number of deaths from water contamination.

Likewise, the existence of sustainable cities and communities (SDG 11) is highly dependent on water availability. For instance, evidence has shown that growing water demands in cities and communities have led to high reliance on groundwater (International Association of Hydrogeologists, 2015). According to Foster et al. (2010), groundwater is the fastest-growing means of meeting water demands in sub-Saharan African cities. As a form of self-supply, it plays a vital role in the water supply ecosystem of developing countries and has the potential to pivot the pace towards the achievement of SDG target 6.1 (Foster et al., 2021). Thus, it is key to achieving SDG target 11.1 on ensuring access for all to adequate, safe, and affordable housing and basic services and upgrade slums.

Groundwater is also important in achieving SDG 13 (Climate Action), SDG 14 (life below water), and SDG 15 (life on land). It is generally more resilient to climate impacts such as drought and, therefore serves as an important resource in drought-prone areas, thereby increasing their resilience. Similarly, groundwater plays a critical role in the survival of coastal, freshwater, and terrestrial ecosystems. Hence, good groundwater management is needed in the achievement of SDG target 15.1 on the protection of freshwater ecosystems (UN-Water, 2022).

Groundwater Quality Assessment

Groundwater quality is influenced by geogenic minerals and human activities that affect the physical, chemical, and microbiological characteristics of the water (Akter et al., 2016). For water to be potable, the quality indicators must be within specific ranges. Therefore, in assessing water quality, the physicochemical and microbiological components must be considered. Some important indicators of groundwater quality are discussed below.

Physicochemical parameters

Water physicochemical parameters play a vital role in the assessment of its quality (Rahman et al., 2021; Whitehead et al., 2009). The parameters considered in this study were temperature, pH, total dissolved solids, turbidity, salinity, electrical conductivity, nitrate, phosphates, and heavy metals.

pH

pH is a measure of acidity or alkalinity of a solution; it is an important indicator for water quality and could be affected by environmental pollution. World Health Organization has set a range of 6.5-8.5 for the pH of drinking water (WHO, 2017a). Any water source with a pH less down 6.5 is described as acidic while those with a pH higher than 8.5 are said to be alkaline. The prolonged consumption of acidic water can have a negative impact on the gastrointestinal tract and mucous membranes of both humans and animals (Ojekunle et al., 2020). Also, acidity favours the leaching of heavy metals into groundwater (Król et al., 2020). pH can affect water aesthetics, as water with a pH below 6.5 tends to have a bitter taste while water with a pH above 8.5 tends to have a slippery feel, and very high pH values can make water disinfection and treatment ineffective (Foundation Safe Drinking Water, 2023).

Total dissolved solids

Total dissolved solids (TDS) consist of all dissolved substances in water. They consist of inorganic salts and some amount of organic matter. Sources of total dissolved solids in groundwater include natural sources, sewage, urban runoff, industrial wastewater discharges, and road de-icing (WHO, 2022b). Dissolved solids can pass through filters with a pore size of 2 microns (EPA Water Consultants, 2023). Some common dissolved solids in water are chlorides, calcium, nitrates, phosphates, iron, lead, and bacteria (EPA Water Consultants, 2023). According to the World Health Organization (2022b), water containing less than 600 mg/L of TDS is generally considered to be good. Although water with high TDS does not directly pose a health hazard, it has a higher chance of containing contaminants (EPA Water Consultants, 2023; Foundation Safe Drinking Water, 2023). Furthermore, dissolved solids affect water aesthetics such as taste and colour. High amounts of dissolved solids can also result in water hardness leading to the staining of boilers, corrosion of pipes, and reduction in lathering of soap.

Turbidity

Turbidity is a measure of the suspended particles in a liquid. It is an optical characteristic of water that is measured by determining the amount of light scattered by the materials present in water. Turbidity of water is often caused by the present of suspended particles such as silt, clay, inorganic and organic matter, colloidal particles, and microscopic organisms (U.S. Geological Survey, 2018c). It affects water acceptability and can pose a health concern, as suspended particles in turbid water can serve as food, shelter, and surfaces for the attachment of microbes, thus aiding their survival (U.S. Geological Survey, 2018c). Furthermore, suspended particles can provide attachment for heavy metals in water. World Health Organization recommends less than 1 NTU turbidity in drinking water, nonetheless in cases where this is difficult to achieve such as in small water supplies, the goal should be to achieve turbidity of less than 5 NTU (WHO, 2017b). An increase in the turbidity of groundwater after rainfall is an indication of surface contamination (U.S. Geological Survey, 2018a).

Salinity

Salinity is a measure of dissolved salts in a body of water. Salinity strongly affects conductivity and water chemistry. Sources of dissolved salts in waterbodies include natural sources such as salt deposits in soils, weathering of rocks, and sea, and anthropogenic sources such as irrigation, poor land management, and industrial activities. Salinity can be classified as primary: originating from natural sources, and secondary: originating from human activities (Water Quality Australia, 2012).

Water with salinity less than 1000 ppm is regarded as fresh water; between 1000 and 3000 ppm is regarded as slightly saline; above 3000 to 10,000 ppm is regarded as moderately saline; and above 10,000 to 35,000 ppm is highly saline water (U.S. Geological Survey, 2018b). Increased salinity affects water aesthetic and negatively impacts human health as it can result in high blood pressure and kidney problems (Gurmessa et al., 2022; Rosinger et al., 2021). High salinity in drinking water can also lead to an increase in the cost of water treatment and corrosion of water treatment facilities as well as industrial facilities. Furthermore, saline water negatively affects the growth of plants when used for irrigation (Ahmed et al., 2012).

Gurmessa et al. (2022) in their study in Africa reported that 80% of groundwater samples were of acceptable quality in terms of salinity, but noted that salinity greatly threatens water security in certain aquifers, especially in alluvial and coastal aquifers as it leads to the abandonment of groundwater sources especially boreholes. For instance, about 70% of boreholes in sedimentary aquifers of countries located in the Horn of Africa were reported to be abandoned due to increased salinity (Kebede & Taye, 2021). Also, Ganyaglo et al. (2017) observed that about 41% of groundwater in the Ochi-Narkwa Basin of Ghana was either brackish or saline.

Electrical conductivity

Electrical conductivity (EC) is a measure of the ability of water to conduct electricity. This measurement is an important water quality parameter as it estimates the amount of charged particles in water (California State Water Resources Control Board, 2017). Pure water has a very low electrical conductivity, but its electrical conductivity increases as the amount of dissolved salts in it increases. Measurements of electrical conductivity are therefore strongly correlated with total dissolved solids and salinity.

Fresh groundwater typically has an electrical conductivity of 150 µS/cm while seawater typically has an electrical conductivity of 50,000 µS/cm (Land Air Water Aotearoa, 2020). This difference in electrical conductivity for instance can be used to determine the occurrence of seawater intrusion in coastal areas (Land Air Water Aotearoa, 2020). The dissolution of salts in rocks and evaporative enrichment of salts are natural processes that can increase the concentration of salts and thus, electrical conductivity in groundwater (California State Water Resources Control Board, 2017). Human activities such as irrigation, fertilizer application, municipal waste discharge, and industrial processes can also increase salt concentrations and electrical conductivity in groundwater (California State Water Resources Control Board, 2017).

World Health Organization has no set limit for EC in drinking water, however, the European Union has set 2,500 µS/cm as the limit for EC in drinking water (The European Parliament and the Council of the European Union, 2020; WHO, 2022b).

Nitrate

Nitrate is a common chemical pollutant found in groundwater. Inorganic nitrogen occurs in nature as ammonia nitrogen, nitrites, and nitrates (Yu et al., 2020). While ammonia, nitrogen, and nitrite are unstable, readily converted to nitrate, and with low concentrations in water, nitrates are stable and their concentrations do not change over time (Yu et al., 2020).

Sources of nitrates in groundwater include the use of nitrogenous fertilizers, waste from animals, seepages from septic tanks, and improper waste disposal. These sources are either point or non-point sources. An example of non-point sources of nitrate pollution in groundwater is fertilizer application. Septic tanks are the main point source of nitrate pollution and they are common in settlements that lack a central sewer system (Górski et al., 2019). Likewise, agricultural activities are a major source of nitrate pollution worldwide (Zhang et al., 2014). For instance, Yidana et al. (2010) reported that agricultural activities and the discharge of household waste were major factors responsible for high nitrate concentrations in the Keta Basin of Ghana.

An isotopic study by Zhang et al. (2014) showed seasonal variations in nitrate concentrations in sources of groundwater in China. The concentrations recorded in the rainy season were high and exceeded the WHO-recommended limits. Mineralization of soil organic nitrogen and sewage discharges were reported to be the main sources of nitrate during the dry season whereas fertilizers and surface nitrate transport through soil layers by precipitation were the main sources in the rainy season (Zhang et al., 2014).

High nitrate concentration in drinking water poses a concern for public health. In infants, it can impair the ability of blood to transport oxygen around the body, a condition known as methemoglobinemia or blue baby syndrome (Yu et al., 2020; Zhou et al., 2015).

Phosphates

Phosphorus is an important nutrient for plants and animals and is commonly found in fertilizers, manure, organic waste, and industrial waste. Phosphorus is retained by soil particles through adsorption, but when the adsorptive capacity of soils is exceeded, free phosphorus tends to move into aquifers and other waterbodies (Domagalski & Henry, 2012).

World Health Organization has no set limit for phosphorus in drinking water (WHO, 2022b). However, the Recommended Dietary Allowance (RDA) for adults is 700 mg/day (Harvard T.H. Chan School of Public Health, 2023). Adverse health effects associated with high phosphorus intake are rare, nevertheless, some studies have found a link between high consumption of phosphorus and kidney, cardiovascular, and bone diseases (Gutiérrez et al., 2015; Ito et al., 2011; Office of Dietary Supplements, 2021). Additionally, excessive phosphorus in the body can negatively affect calcium metabolism (Harvard T.H. Chan School of Public Health, 2023). Excess phosphorus in surface water is a serious environmental concern as it results in eutrophication. According to Warrack et al. (2022), phosphorus in groundwater can serve as a significant source of phosphorus in surface water.

A study of the global trend of phosphorus in groundwater showed that phosphorus concentrations were highly correlated with agriculture and that China and Brazil had the highest levels of phosphorus in their groundwater (Warrack et al., 2022). Kent et al. (2020) reported moderate and high levels of phosphorus respectively in 43% and 15% of wells used for public water supply in California.

Metals

Metals are inorganic substances that are found in mineral ores in the earth's crust. The terms heavy metals and trace metals are common in the description of metals. Trace metals are metals that are present in small amounts in the earth's crust (Marcovecchio & Freije, 2007; US Geological Survey, 2019). These metals may be essential and needed by living organisms in some amount (often low amount) e.g. iron and zinc, or non-essential i.e. not needed by living organisms e.g. lead and mercury. There is currently no fixed definition for the term heavy metals. Generally, they are considered to be metals that have a high density and they include lead, mercury, arsenic, and cadmium (U.S. Geological Survey, 2019). Going by this description, heavy metals may be essential while others are non-essential (U.S. Geological Survey, 2019). Some authors have also associated the term heavy metals with metals that are toxic at certain concentrations or metals of environmental concern and this is a common usage of the term in literature (Batley, 2012; Marcovecchio & Freije, 2007; Wang et al., 2021). It is important to note that essential trace metals can be toxic at high concentrations (Government of Northwest Territories Canada, n.d.).

The detection of heavy metals in groundwater has gained wide attention because they are toxic, persistent, can bioaccumulate, and cause potential health risks (Burges et al., 2015; Wu et al., 2018). An increase in the amount of trace metals found in the environment can be caused by natural processes such as weathering, volcanic eruption, and the spread of mid-ocean ridges (Government of Northwest Territories Canada, n.d.; Smiljanić et al., 2019). Natural levels of trace metal concentrations can also be increased by human activities such as mining, smelting, industrial effluent discharge, waste disposal, and agricultural activities (He et al., 2015). In this study, arsenic, lead, and iron were considered.

Lead is one of the 10 major chemicals of concern in public health (WHO, 2022c). Common anthropogenic sources of lead in the environment include mining, fertilizer application, manufacturing, combustion of fossil fuel, and industrial activities (Agency for Toxic Substances and Disease Registry [ATSDR], 2007). Recycling of scrap batteries and pipes is also an important source of lead in the environment (The Royal Society of Chemistry, 2023). Lead has been reported to cause abnormal brain development, intellectual disability, anaemia, kidney diseases, hypertension, immunotoxicity, and reproductive problem (WHO, 2022c). Also, there are no safe levels of exposure to lead; all levels of exposure are known to have a harmful effect (WHO, 2022c). The World Health Organization's limit for lead in drinking water is 10 µg/L.

In their study on groundwater in the Kohistan Region in Northern Pakistan, Muhammad et al. (2011) reported that average lead levels ranged from 2.54-24.05 µg/L. Likewise, Lou et al. (2017) recorded lead concentrations of 2.51 µg/L in groundwater in coastal areas of China. Akers et al. (2015) also reported median lead concentrations of 13 µg/L and 9 µg/L for first draw and after flush groundwater samples, respectively, in a coastal city in Madagascar. In the Lower Pra Basin (Ghana), Dorleku et al. (2018) reported mean lead concentrations of 26.5 µg/L and 34.5 µg/L in dry and wet seasons, respectively in the area. On the other hand, Ketadzo et al. (2021) reported mean lead concentrations ranging from 0-1.5 mg/L in groundwater in five slums in Accra. Similar to the high lead concentrations reported by Ketadzo et al. (2021), Appiah-Opong et al. (2021) reported lead concentrations of 70.73 µg/L and 47.67 µg/L in dry and wet seasons, respectively in the Western Region of Ghana.

Iron is an essential nutrient for humans, but excess iron in drinking water can affect its aesthetic quality and lead to health disorders such as cardiovascular diseases, Parkinson's disease, diabetes, Huntington's disease, hyperkeratosis, body pigmentation, Alzheimer's disease, respiratory and neurological disorders (Ghosh et al., 2020). The recommended limit for iron concentration in drinking water by WHO is 0.3 mg/L.

The presence of iron in groundwater has been reported in many studies. For instance, Aladejana et al. (2020) reported iron concentrations of 0.3 mg/L and 1.5 mg/L in wet and dry seasons, respectively, in a coastal aquifer in Southwestern Nigeria. Also, Rusydi et al. (2021) recorded high iron levels (10.3 mg/L) in groundwater in a coastal city in Indonesia. Ahmed et al. (2020), however, reported a mean iron concentration (0.073 mg/L) which was below WHO limit in Rupsha Upazila, a coastal area in Bangladesh. In Ghana, Obeng (2015) reported mean iron concentrations ranging from 0.016 mg/L to 1.285 mg/L in Bogoso. Likewise, Ganyaglo et al. (2012) recorded mean iron concentrations of 0.37 mg/L in groundwater in the Central Region of Ghana. In their study, Ketadzo et al. (2021) reported mean iron concentrations ranging from 0.02-0.13 mg/L in five slums in Accra. According to Plumpton et al. (2020), iron levels are naturally high in aquifers in Ghana.

Arsenic is an important geogenic groundwater contaminant; it affects millions of people on every continent in the world (UN Water, 2022). Arsenic has been classified as a Group I carcinogen and prolonged exposure to the metal can be carcinogenic in human organs such as the bladder, skin, lungs, liver, digestive tract, and lymphatic system (National Cancer Institute, 2022). Arsenic can also have non-cancer-related effects such as adverse pregnancy outcomes, developmental impairment, lung diseases, diabetes, and arsenic-induced myocardial infarction in humans (WHO, 2022a). The recommended limit by WHO for arsenic concentrations in drinking water is 10 µg/L.

Several studies have reported the presence of arsenic in groundwater globally. For example, Maskooni et al. (2020) reported arsenic concentrations of 7.9 µg/L in Gachsaran City of Iran. Similar to their findings, Buragohain et al. (2010) recorded mean arsenic concentrations of 8 µg/L and 6 µg/L in dry and wet seasons, respectively, in Dhemaji, India. In Ha Nam Province of Vietnam, Nguyen et al. (2009) reported high arsenic concentrations (51-348 µg/L) in groundwater in the area. Shah et al. (2020) also reported high arsenic concentrations of 46.9 µg/L in groundwater samples from Vehari, Pakistan. Likewise, in the coastal area of Ghana, Appiah-Opong et al. (2021) reported mean arsenic concentrations of 3.21 µg/L and 3.66 µg/L in dry and wet seasons, respectively, in four districts near the Jubille Oil field in Ghana. Similarly, Dorleku et al. (2018) reported mean arsenic concentrations of 1.47 µg/L and 1.12 µg/L in dry and wet seasons, respectively, in Lower Pra Basin (Ghana). Contrary to the findings discussed earlier, Ketadzo et al. (2021) recorded 0 µg/L of arsenic concentration in their study in five slums in Accra.

Microbiological parameters

Microorganisms play key roles in drinking water quality; hence, regulatory agencies have set rules and regulations for the microbiological quality of drinking water to protect public health. According to Keesari et al. (2015), a wide range of pathogenic microbes is found in groundwater. Bacteria, however, constitute a major group of microorganisms that cause waterborne disease outbreaks (Al-Fifi et al., 2019). Also, bacterial infections are among the top 10 causes of death worldwide (WHO, 2020). Hence, bacteria as a microbiological indicator or parameter was considered in this study.

Bacteria

A large array of bacteria is present in water. Some diseases caused by these bacteria are cholera, typhoid, campylobacteriosis, Legionnaires' disease, non-tuberculous mycobacteria (NTM) infection, acute otitis externa, *Pseudomonas* pneumonia and septicemia, Shiga toxin-producing *Escherichia coli* (STEC) infection serotype O157, non-O157 serotype STEC infection, salmonellosis, shigellosis, and vibriosis. These diseases include gastrointestinal, respiratory, and systemic diseases, amongst others. (Collier et al., 2021). However, health concerns associated with the bacteriological quality of drinking water are mainly attributed to enteric diseases, hence, microbial safety is often assessed using indicators of faecal pollution (Verhille, 2013). Indicators of faecal pollution are organisms that occur in large numbers in human or animal faeces; their presence often depicts that there is a likelihood of faecal contamination and the presence of enteric pathogens in drinking water (Verhille, 2013).

The four main indicator bacteria used in monitoring water quality are heterotrophic plate counts (HPC), total coliform (TC), feacal coliform (FC), and *Escherichia coli* (*E. coli*) (Verhille, 2013). The heterotrophic plate count represents a broad range of bacteria that utilize organic carbon as their carbon source and comprise aerobic and facultative anaerobic bacteria in a sample (Verhille, 2013). Total coliforms are a group of bacteria that are mainly found in the environment. Coliform bacteria are defined as facultative anaerobic, gram-negative, non-spore-forming rods that ferment lactose to acid and gas at 35± 2 ^{o}C within 24 to 48 hours (Halkman & Halkman, 2014). They generally belong to four genera of Enterobacteriaceae*: Citrobacter freundii*, *Enterobacter cloacae, Enterobacter aerogenes, E. coli*, and *Klebsiella pneumonia*. Some of these coliform bacteria are found in the colons of warm-blooded animals (faecal coliforms), while others are associated with plant materials (Halkman & Halkman, 2014). Faecal coliforms are a subset of the total coliforms and are mainly found in faeces. Examples are *E. coli, salmonella, and Klebsiella pneumonia*. However, *E. coli* is the only member of the faecal coliform that is specific to the intestinal tract of warm-blooded animals and is the most reliable indicator of recent faecal contamination and enteric diseases (Verhille, 2013).

The use of indicator bacteria in assessing drinking or groundwater quality has however shown several limitations such as their short survival when compared with most pathogens, their inactivation during treatment processes or exposure to sunlight while other pathogens are not inactivated, poor correlation of indicator bacteria with pathogenic organisms, laborious culture process, inability to detect them at low concentrations even though they can cause diseases at those concentrations (Levy et al., 2012; McFeters et al., 1974;

National Research Council (US) Committee on Indicators for Waterborne Pathogens, 2004; Saxena et al., 2015). Consequently, the application of molecular techniques in the study of microbial quality of drinking water has risen considerably (Abada et al., 2019; Bautista-De los Santos et al., 2016; Ecklu-Mensah et al., 2019; Lautenschlager et al., 2014; Tassadaq et al., 2013; Zeng et al., 2013). Molecular techniques have the advantage of being able to identify microbial communities in groundwater, including those that are not culturable.

Groundwater Microbiome

Microbial assemblages in groundwater are referred to as groundwater microbiomes. A microbiome is a collection of microbial communities that live in a given habitat. The composition of the groundwater microbiome is important in determining the health risks of groundwater consumption. For instance, in the United States where drinking water is generally free of indicator bacteria, bacteria such as *Campylobacter*, non-tuberculous mycobacteria, and *Legionella* cause a great deal of water-borne diseases in the country (CDC, 2020). Groundwater microbiomes also play important roles in nutrient cycling within groundwater ecosystems, thus influencing water quality (Retter et al., 2021).

Knobloch et al. (2021) reported that the bacteria composition of groundwater in the Heiðmork water catchment area of Iceland was mainly of Proteobacteria, Omnitrophica, Firmicutes, Acidobacteria, Bacteroidetes, and Actinobacteria phyla, and accounted for about 64.8% of the bacteria community in the area. Likewise, Ji et al. (2022) observed that the groundwater microbiome in the Honghu Basin of China was mainly of Pseudomonas (25.72%), Acinetobacter (11.22%, Limnohabitans (6.32%), and Methylotenera (5.05%) genera. In the Rayong groundwater basin (Thailand), Sonthiphand et al. (2019) reported the dominance of phyla Proteobacteria and the presence of Firmicutes, Bacteroidetes, Planctomycetes, Actinobacteria, and Nitrospirae in all the groundwater sampled. The study also reported Gammaproteobacteria, Betaproteobacteria, Alphaproteobacteria, and Deltaproteobacteria as the major classes of the Proteobacteria phylum observed in the basin. The observed Alphaproteobacteria consisted majorly of the Methylocystaceae, Rhodospirillaceae, and Sphingomonadaceae family; the Betaproteobacteria consisted majorly of the Rhodocyclaceae, Oxalobacteraceae, and Methylophilaceae family; while the Gammaproteobacteria consisted majorly of the Pseudomonadaceae, Moraxellaceae, and Methylococcaceae family (Sonthiphand et al., 2019). In their study, Tassadaq et al. (2013) reported that bacteria found in drinking water sources in Kohat (Pakistan) were mainly the alpha-proteobacteria (e.g. Sphingomonas, Hyphmicrobium, and Pedomicrobium) and beta-proteobacteria (e.g. Dechlormonas, Aquaspirillium). While the Sphingomonadaceae, Caulobacteraceae, and Methylobacteriaceae families dominated in the Alpha-proteobacteria class, the Burkholderiaceae, Methylophilaceae, Comamonadaceae, and Rhodocyclaceae dominated in the Beta-proteobacteria (Vaz-Moreira et al., 2013; Zeng et al., 2013). Gamma-proteobacteria e.g. Mycobacteria and Legionella; Bacteroidetes, Chloroflexi, Nitrospirae, Planctomycetes, and Acidobacteria are also present in drinking water systems (Bautista-De los Santos et al., 2016; Lautenschlager et al., 2014; Tassadaq et al., 2013).

Temporal changes are central to understanding the mechanism of assemblage and succession of the drinking water microbiome and would play a key role in the development of models for predicting changes in water quality and potential microbial contamination events (Zhang & Liu, 2019). Also, temporal changes occur in the drinking water microbiome within a water distribution system from season to season (Zhang & Liu, 2019). Some studies found seasonal variation as the main cause of change in drinking water microbiome, especially during the summer when temperatures are elevated (Ling et al., 2015; Prest et al., 2016). For every 10 °C increase in the temperature of water, microbial activity doubles (Zeng et al., 2021).

Geographical locations may also play a role in determining the microbial community present in a place. Attempts have been made by some studies to ascertain if geographic locations affect the drinking water microbiome (Bautista-De los Santos et al., 2016; Roeselers et al., 2015). These studies showed that water originating from different sources showed differences in the microbial community in them.

In Ghana, a study on microbial diversity in drinking water was conducted by Ecklu-Mensah et al. (2019). Although this study was not conducted on groundwater, it highlights an investigation of bacterial diversity in drinking water in Ghana. The study showed that water from water treatment plants, taps, and storage tanks contained complex microbial assemblage, some of which could be of human health concern. Specifically, the Burkholderiales taxa which has several pathogenic strains that are antibiotic-resistant were identified in many amplicon sequence variants. Several taxa of the order Rickettsiales which are obligate intracellular pathogens of free-living amoeba were also identified in some samples. Some free-living amoeba has been implicated in primary amebic meningoencephalitis (an acute and lethal disease of the central nervous system), keratitis, cutaneous lesions, and amebic encephalitis (CDC, 2017).

Groundwater pollution assessments in Ghana

Numerous groundwater studies have been carried out in Ghana (Table 1). The scope of these studies includes studies on saltwater intrusion, hydrochemical characterization, assessment of bacteriological quality, assessment of physicochemical quality, and heavy metal pollution in groundwater sources. For instance, Jørgensen and Banoeng-Yakubo (2001) assessed the source of groundwater salinization in the Keta Basin using environmental isotopes. They reported high chloride concentrations in shallow groundwater due to evaporation and salinity interference. Also, Yidana (2010) classified groundwater types in Southeastern Ghana and traced the sources of salinity variations in the region to seawater intrusion. The study reported the main groundwater type in the study area was Ca-Mg-HCO_3 water type, which deteriorates into Na-Cl-SO_4 water type towards the coast. Salinity variation was stated to be majorly caused by weathering of silicate rock, saltwater intrusion, and human activities. The impact of large-scale shallow water withdrawals on saline water intrusion in relation to agriculture in the Keta Strip has also been explored. Kortatsi et al. (2005) reported that large-scale water withdrawals will result in saltwater intrusion which will negatively affect the medium salt-tolerant crops grown in the region.

Furthermore, Ganyaglo et al. (2017) carried out an assessment of the source of salinization in the Ochi-Narkwa Basin. His study reported that shallow groundwaters were mainly of the Na-Cl water types and deep groundwaters were of the Ca-Mg-HCO_3, Na-Cl, and Ca-Mg-Cl-SO_4 water type. Groundwater salinization majorly results from the dissolution of halite and to a minor degree from silicate weathering and seawater intrusion. Asare et al. (2021) also undertook an assessment of saltwater intrusion in some coastal communities in the Central Region of Ghana.

Studies incorporating microbial contamination of groundwater include the works of Affum et al. (2015), Zume et al. (2021), Ketadzo et al. (2021), Lutterodt et al. (2018; 2021a), Armah, (2014), Yeboah et al. (2022), Boamah et al. (2011), Safo-Adu, (2022) and Cobbina et al. (2010). Some of these studies were carried out in the coastal areas. Affum et al. (2015) assessed the contribution of non-point sources of pollution to the degradation of groundwater quality in fourteen peri-urban communities in the Sekondi-Takoradi Metropolis. The study which was carried out in the wet season reported that *E coli* was not detected in groundwater samples but total coliforms were detected. Affum et al. (2015) also indicated that groundwater quality in the area is influenced by both natural and anthropogenic factors. Ketadzo et al. (2021) performed a one-time sampling to assess groundwater quality in five slums in Accra. Ketadzo et al. (2021) reported that mean *E coli* and total coliforms ranged between 12.5 to 249 CFU/100 ml and 90.75 to 490.25 CFU/100 ml.

In another study, Lutterodt et al. (2021a) investigated the groundwater in Cape Coast. The study considered sanitary risk inspection, microbial quality, and bacterial regrowth. Findings from the study showed that all the groundwater samples were contaminated with faecal bacterial, and that *E coli* could persist in the aquifers for a long time. The study identified on-site sanitation facilities as a major risk factor leading to the contamination of groundwater. In their study, Zume et al. (2021) assessed the contribution of on-site sanitation facilities and saltwater intrusion to the pollution of groundwater in some peri-urban settlements in Cape Coast. Results from the study indicated that on-site sanitation facilities strongly influenced groundwater quality, with wells within 25 m of septic tanks and pit latrines having higher contaminant concentrations than wells that were not within 25 m. Findings from Zume et al. (2021) also revealed that wells within 2 km of the coastline were influenced by sea water intrusion.

The works of Affum et al. (2015), Appiah-Opong et al. (2021), Armah (2014), Asare-Donkor and Adimado (2020), Avi et al. (2014), Bempah and Ewusi (2016), Dorleku et al. (2018a), Ketadzo et al. (2021), Kortatsi (2009a, 2009b), Obeng (2015), Obiri et al. (2010), Osiakwan et al. (2021), Yidana et al. (2012), Zume et al. (2021) highlight some studies that have investigated metal concentrations in aquifers in Ghana. Some of these studies recorded metal concentrations that were above set limits and these include some studies in the coastal area. In their study on groundwater quality in the Central Region, Osiakwan et al. (2021) recorded mean iron and manganese concentrations of 0.59 mg/L and 0.12 mg/L which were higher than WHO standards. Affum et al. (2015) also recorded high arsenic and cadmium concentrations in the Sekondi-Takoradi Metropolis, Western Region. Similarly, the work of Ketadzo et al. (2021) in slums in Accra showed that Nima, Chorkor, Jamestown, and Abokobi-Pantang had lead concentrations that exceeded WHO limits. A similar trend was also observed by Akoto et al. (2019) who observed that cadmium and lead concentrations in some groundwater samples in Anloga (Volta Region) were above the WHO standard limit; with maximum average cadmium and lead concentrations of 0.04 mg/L and 0.012 mg/L, respectively.

Table 1: Groundwater pollution studies in Ghana

Region	Aim	Parameters assessed	Sampling time: duration, season, or year	Analysis performed	References
Studies in the coastal area					
Western Region (Ankobra Basin)	Assess the level of trace metals (Dry season)	Physicochemical parameters, major irons, and trace metals	15th-20th November 1999	Descriptive statistics	Kortatsi (2009a)
Western Region (Wassa West District)	Physicochemical quality (Sampling time not stated)	Physicochemical parameters including major ions, trace metals, fluoride, and nitrates.	Not stated	Descriptive statistics	Kortatsi (2009b)
Western Region (Fourteen peri-urban communities in the Sekondi-Takoradi Metropolis)	To assess the contribution of non-point pollution sources to groundwater quality (Wet season)	*E. coli*, total coliform, physical parameters, As, Cd, and Hg, and major ions including phosphate and nitrates.	Rainy season, 2013	Health risk assessment for heavy metals, multivariate analysis	Affum et al. (2015)
Western Region (Ellembelle District)	Hydrogeochemistry and isotope hydrology	Physicochemical parameters including major ions and nitrates.	February 2012	Descriptive statistics and hydrochemical plots	Edjah et al. (2015)
Western Region (Bogoso)	Assess groundwater quality (Seasonal variations)	Physicochemical parameters including heavy metals	March, May and June	Descriptive statistics	Obeng (2015)
Western Region (Ellembelle District)	Assess the simpact of tailings storage facility on groundwater quality	Physicochemical parameters including heavy metals	June to December 2014	Descriptive and correlation	Acheampong and Nukpezah (2016)
Western Region (Lower Pra Basin)	Heavy metal concentration	Physical parameters and heavy metals	Twice per season; wet and dry season, 2012)	Descriptive statistics and cluster analysis	Dorleku et al. (2018)

Table 1: Cont'd

Region	Aim	Parameters assessed	Sampling time: duration, season, or year	Analysis performed	References
Western Region (Four districts near the Jubilee Oil field: Ellembelle, Jomoro, Nzema East municipality, and Ahanta West)	Assess seasonal variations in groundwater quality (wet and dry season)	Parameters, physicochemical parameters including heavy metals	October 2014 to March 2015	Descriptive statistics, heavy metals pollution index, and Pearson correlation	Appiah-Opong et al. (2021)
Western Region (Lower Tano basin)	Assess groundwater pollution	Physicochemical parameters including major ions and heavy metals.	2013 and 2015	Statistical methods (descriptive statistics, ANOVA, PCA, multiple linear regression, etc.)	Edjah et al., (2021)
Western Region (Shama Municipality- in a waste treatment plant)	Assess water quality in a waste treatment facility	*E. coli*, total coliform, physicochemical parameters including ions, heavy metals, fluoride, and phosphate	16^{th} November 2020 to 2^{nd} May 2021	Descriptive statistics, correlation matrix, PCA, and weighted arithmetic WQI	Safo-Adu (2022)
Central Region	Assess groundwater quality	Physicochemical parameters including major ions, trace metals, heavy metals, nitrates, and phosphate	2^{nd} to 5^{th} May, 2019	Geostatistical methods, hydrochemical plot, and multivariate analysis	Ganyaglo et al. (2012)
Central Region (Ayensu River Basin)	Assess the physical and chemical quality and establish the hydrochemical facies (Dry season)	Physicochemical parameters including trace metals, major ions, phosphate, and nitrates.	January and May 2010	Phase diagram, Gibb's diagram, and sodium chloride relationship.	Avi et al. (2014)

Table 1: Cont'd

Region	Aim	Parameters assessed	Sampling time: duration, season, or year	Analysis performed	References
Central Region (10 districts)	Assess groundwater quality and its suitability for domestic and agricultural use	Physicochemical parameters including major ions, trace metals, heavy metals, nitrates, phosphate, and fluoride	Not clearly stated	Hydrochemical plots and multivariate analysis	Asare et al. (2016)
Central Region (Ochi-Narkwa basin	Assess the origin of salinity in the Ochi-Narkwa Basin	Stable isotope composition, physicochemical parameters including major ions and nitrates	2010 to 2011	Descriptive statistics, geostatistical methods, and hydrochemical plots	Ganyaglo et al. (2017)
Central Region (Coastline of the region)	Assess saltwater intrusion	Physicochemical parameters including major ions and nitrates	2013-2016 (Seasonal variation not considered)	Geostatistical methods and ionic ratios	Asare et al. (2021a)
Central Region (Coastline of the region)	Assess water quality (Seasonal variation not considered)	Physicochemical parameters including major ions and nitrates.	2013-2016	Geostatistical analysis, and weighted average WQI	Asare et al. (2021b)
Central Region (Cape Coast)	Dry season	*E. coli*, total coliform, bacterial regrowth, and physicochemical parameters including phosphate and nitrates.	Dry season (year not stated)	Sanitary risk inspection, bacterial regrowth analysis	Lutterodt et al. (2021)
Central Region	Determine water quality and evolution	Physicochemical parameters including major ions, trace metals, and nitrates.	2018	Geostatistical analysis, hydrochemical plots, multivariate analysis, and WQI	Osiakwan et al. (2021)

Table 1: Cont'd

Region	Aim	Parameters assessed	Sampling time: duration, season, or year	Analysis performed	References
Central Region (Cape Coast)	Assess the impacts of on-site sanitation facilities and saltwater intrusion on the shallow groundwater quality (August 2019)	*E. coli*, fecal coliform, total coliform, physicochemical parameters including major ions, trace metals, fluoride, and nitrates.	7-8th August 2019	Descriptive statistics, multivariate analysis, and ionic ratios.	Zume et al. (2021)
Central Region	Delineation of potential zones	hydrochemical data, remote sensing, and GIS	2014-2016	Fuzzy Analytic Hierarchy Process (FAHP), weighted overlay analysis (generated the entropy-based WQI)	Osiakwan et al. (2022)
Greater Accra Region (rural communities in Tema District)	Assess the physical and chemical quality of groundwater	Physicochemical parameters including major ions, and nitrates	Not stated	Descriptive statistics and hydrochemical plots	Fianko et al. (2010)
Greater Accra (Dodowa)	Assess groundwater quality	Physicochemical parameters including major ions, trace metals, nitrates, and fluoride	November 2012 to February 2013	Descriptive and inferential statistics, and geographical mapping	Arko et al. (2019)
Greater Accra (Ga West)	Suitability of groundwater for household use and irrigation	Physicochemical parameters including major ions, fluoride, phosphate, and nitrates	Not clear	Descriptive statistics, multivariate analysis, and hydrochemical plots	Daanoba et al. (2019)
Greater Accra Region (Five slums in Accra)	Assess groundwater quality in different slums in Accra	*E. coli*, total coliform, physicochemical parameters including major ions, trace metals, heavy metals, fluoride, and nitrates.	May to June 2019 (One-time sampling)	Descriptive statistics	Ketadzo et al. (2021)

Table 1: Cont'd

Region	Aim	Parameters assessed	Sampling time: duration, season, or year	Analysis performed	References
Southeastern Ghana	Classify groundwater in Southeastern Ghana and trace sources of salinity variations	Physicochemical parameters including major ions, fluoride, phosphate, and nitrates.	Not stated	Multivariate statistics and graphical methods	Yidana (2010)
Volta Region (Keta Basin)	Trace source of groundwater salinization using environmental isotopes (wet and dry seasons)	Physicochemical parameters, oxygen and hydrogen isotopes, and Sr	October 1996 and February to March 1998	Relationships between isotopes	Jørgensen and Banoeng-Yakubo (2001)
Volta Region (Keta strip)	Assess the effect of large-scale shallow groundwater withdrawals on agriculture	Geophysical investigation, irrigation water requirement, test drilling, physicochemical parameters	Not stated	Geonics EM34-3 profiling and hydrochemical plots	Kortatsi et al. (2005)
Volta Region (Keta Basin)	Assess groundwater quality for several purposes	Physicochemical parameters including major ions, nitrates, phosphate, and fluoride.	2004 to 2005	Multivariate analysis, geostatistical, and CCME WQI	Yidana et al. (2010)
Volta Region (Keta Basin)	Assess the physicochemical quality of groundwater and sanitation around wells	Physicochemical parameters including major ions, nitrates, and phosphate.	Not stated	Descriptive and correlation	Awo (2017)
Volta Region (Anloga)	Assess chemical quality and health risk assessment of metals	Physicochemical parameters including major ions, heavy metals, fluoride, iron, and nitrates	November 2015 to March 2016 (seasonal variations not considered)	Descriptive statistics, cancer, and non-cancer risk assessment	Akoto et al. (2019)

Table 1: Cont'd

Region	Aim	Parameters assessed	Sampling time: duration, season, or year	Analysis performed	References
Lower Volta River basin South Tongu and Ada East	Assess groundwater quality	Stable isotope composition, physicochemical parameters including major ions, fluoride, iron, and nitrates	Not stated	Geostatistical analysis, multivariate analysis, CCME WQI	Egbi et al. (2019)
Lower Volta River Basin (Lower Volta River Basin)	Assess the migration of trace metals and their health risks	Physicochemical parameters, soil properties, and heavy metals	November 2017	Descriptive statistics, correlation matrix, geostatistical methods, cancer risks, and non-cancer risks	Egbi et al. (2021)
Studies in non-coastal areas					
Northern Region	Assess groundwater quality	*E. coli*, total coliform, physicochemical parameters including major ions, heavy metals, fluoride, nitrates, and phosphate	May and March 2005 (rainy and dry)	Descriptive statistics and correlation	Cobbina et al. (2010)
Ashanti Region (Obuasi)	Assess health risks due to metals in the mining area	Heavy metals	March to June 2006	Cancer and non-cancer risk assessment	Obiri et al. (2010)
Ashanti Region (Three peri-urban communities in Kumasi)	Microbial quality	Physicochemical parameters, faecal coliforms, faecal streptococci, and data on diarrhea cases	2007 to 2008	Descriptive statistics	Boamah et al. (2011)
Northern Ghana	Assess groundwater quality using multivariate statistics	Physicochemical parameters including major ions, trace, and heavy metals.	Secondary data; date of source not stated	Multivariate analysis and GIS	Yidana et al. (2012)

Table 1: Cont'd

Region	Aim	Parameters assessed	Sampling time: duration, season, or year	Analysis performed	References
Western Region (Tarkwa-Prestea area)	Relationship between coliform bacteria and water chemistry	*E. coli*, total coliform, physicochemical parameters including heavy metals and nitrates.	January 2010-December 2011	Descriptive statistics, correlation, bivariate analysis, and multivariate analysis	Armah (2014)
Ashanti Region (Obuasi)	Heavy metals in groundwater, vegetables, and soils	Physicochemical parameters and heavy metals	March to August 2014	Descriptive statistics, cancer, and non-cancer risk	Bempah and Ewusi (2016)
Ashanti Region (Ejisu-Juaben)	Assess the sources of groundwater pollution	Metals	June, 2014	Multivariate statistics, pollution indices, and cancer and non-cancer risks	Boateng et al. (2015)
Ashanti Region (Ejisu-Juaben)	Assess groundwater hydrochemistry, quality, and suitability for household use	Physicochemical parameters including ions, phosphate, and nitrates	June, 2014	Descriptive statistics and weighted arithmetic WQI	Boateng et al. (2016)
Western Region (Tarkwa)	Assess groundwater quality using statistical methods, hydrogeochemical methods, and WQI	Physicochemical parameters including major ions, phosphate, and nitrates	Not stated	Descriptive statistics, hydrochemical plots, and weighted arithmetic WQI	Seidu and Ewusi (2017)
Ashanti Region (Nine peri-urban communities in Kumasi)	Assess water quality in relation to sanitation issues	*E. coli*, fecal coliform, fecal enterococci, physicochemical parameters including heavy metals, and demographics of water users	Wet and dry seasons (year not stated)	Descriptive statistics	Aboagye and Zume (2019)

Table 1: Cont'd

Region	Aim	Parameters assessed	Sampling time: duration, season, or year	Analysis performed	References
North and Upper East Region (57 communities)	Assess water quality and heavy metal health risks	Physicochemical parameters including trace metals, heavy metals, nitrates, phosphate, and fluoride	October 2016 to March 2017	Weighted arithmetic WQI, heavy metals pollution index, cancer and non-cancer health risk	Asare-Donkor and Adimado (2020)
Upper East Region (Talensi District)	Assess groundwater for domestic and irrigation purposes and factors controlling hydrochemistry (Dry season)	Physicochemical parameters including major ions, phosphate, and nitrates.	November 2017	Geostatistical analysis, hydrochemical plots, and weighted arithmetic WQI	Chegbeleh et al. (2020)
North East Region (Kwahu-Bombouaka Group of the Voltaian Supergroup)	Suitability of groundwater for household use and irrigation	Physicochemical parameters including ions, fluoride, and nitrates	January to February 2018	Geostatistical analysis, hydrochemical plots, multivariate analysis	Sunkari et al. (2020)
Ahafo Region (Tano North Municipal)	Assess groundwater quality and associated health risks	*E. coli*, fecal coliform, total coliform, physicochemical parameters including fluoride, nitrates, and phosphate.	March to April 2020	Descriptive statistics and QMRA	Yeboah et al. (2022)

Communicating Groundwater Quality

Water quality parameters are numerous and data obtained from their measurements can be bulky. Also, a given source of water can meet the criteria for some parameters while not meeting others, making the communication of water quality difficult. For these reasons, water quality indices (WQIs) are used in the communication of water quality data.

Water quality index (WQIs)

WQIs serve as tools for summarizing numerous water quality data into a single number that can be easily understood by a wide range of data users including water professionals, and non-professionals for regulations and policy formulations (Canadian Council of Ministers of the Environment, 2017). They are useful in the appraisal of overall water quality (Adimalla & Qian, 2019). WQIs have been employed across the globe to assess water quality (Adimalla & Qian, 2019; Adimalla, 2021; Akter et al., 2016; Faseyi et al., 2022; Gao et al., 2020; Haider et al., 2019; Miyittah et al., 2020; United Nations Environment Programme Global Environment Monitoring System for Freshwater [UNEP GEMS/Water], 2007; Zhang et al., 2021).

Water quality indices that have been applied in groundwater quality appraisal include the Weighted Arithmetic Water Quality Index (WAWQI), Integrated Weighted Water Quality Index (IWQI), Entropy Weighted Water Quality Index (EWQI), Water Quality Index for Groundwater Resources (WQIG) which uses weighting, Canadian Council of Ministers of the Environment water quality index (CCME-WQI), the modified CCME, and industrial water quality index (IndWQI) (Adimalla, 2021; Akter et al., 2016;

Gao et al., 2020; Haider et al., 2019; Li & Wu, 2019; Maskooni et al., 2020; Najafi Saleh et al., 2020; Nsabimana & Li, 2023; Udeshani et al., 2020; Zhang et al., 2021). Of these, the WAWQI and the CCME WQI are the most widely used.

The Canadian Council of Ministers of the Environment (CCME) WQI was employed in this study. The choice of the CCME WQI was due to its flexibility; as the parameters, time, and guidelines (standards to be used) are not defined, thus making it applicable for assessing the water quality in different regions, different times, and water use scenarios. That is parameters, standards and sampling time can be chosen based on prevailing local conditions, the purpose for which the water is used, and the existing water quality issues (Canadian Council of Ministers of the Environment, 2017). In addition, unlike WAWQI which uses weighting of parameters (which is largely subjective), the CCME uses standards that are mainly set based on empirical studies. In the case of drinking water quality, standards such as WHO standards are applied. Water quality indices are sometimes used in combination with pollution indices to assess the contribution of contaminants such as heavy metals and hydrocarbons to the pollution of water sources. In this study, Nemerow's pollution index was used.

Nemerow's pollution index

Nemerow's pollution index (NPI) is a simple pollution index that was introduced by Neme and it is also known as Raw's pollution index (Rathod et al., 2011). It unveils the extent of contamination for a given water quality parameter with reference to its standard/recommended value. The calculation and analysis of NPI values of different water quality parameters for an area helps in the identification of principal contaminants and it is very useful for the enhancement of water quality in the area (Swati & Umesh, 2015).

Nemerow's pollution index is a very effective tool for communicating the overall water quality status to water users and policymakers (Shankar, 2018). It is also very useful in conveying raw environmental information to managers, decision-makers, technicians, and the general public (Caeiro et al., 2005). Each value of NPI represents the relative pollution contributed by a given parameter and should be less than or equal to one (Rathod et al., 2011). If the NPI values exceed one for a given parameter, it is an indication of impurity (Rathod et al., 2011). The Nemerow Pollution Index is employed in assessing groundwater quality, as it emphasizes the factors contributing most to the contamination of groundwater while considering the contribution of other factors (Su et al., 2022).

Health Risk Assessment

Human health risk assessment is a process of estimating the nature and likelihood of adverse health risks that a population may face due to exposure to a chemical or biological contaminant (United States Environmental Protetction Agency [U.S. EPA], 2011). It is the first step of risk analysis which encompasses risk management and risk communication (WHO, 2010).

As the adverse health effects of contaminants differ, health risk assessment is dependent on the contaminant of concern. The contaminants considered in this study include carcinogenic and non-carcinogenic chemicals as well as microbiological contaminants. Thus, the health risk assessment comprising the aforementioned is highlighted below.

Incremental lifetime cancer risk

Cancer risk is used to assess the health risks associated with potential carcinogens. Incremental lifetime cancer risk (ILCR) estimates the likelihood of an individual developing cancer over his or her lifetime due to exposure to a carcinogenic heavy metal such as mercury and arsenic (Famiyeh et al., 2021; U.S. EPA, 2019).

Cancer risk is calculated using the formula described by ATSDR (2022).

$$CR = D \times SF \times (ED/LY) \quad (1)$$

$$D = \frac{C \times IR \times EF}{BW} \quad (2)$$

Where D is the exposure dose (in mg/kg/day), SF is the cancer slope factor for the given heavy metal:1.5 × 10^{-3} for As and 8.5 × 10^{-3} for Pb (U.S. EPA IRIS, 2011), ED is the exposure duration (years), LY is the lifetime in years, C is the heavy metal concentration (mg/L), IR is the ingestion rate, EF is the exposure factor, and BW is body weight. When CR is equal to or less than 10^{-6}, it indicates that there is no concern for increased cancer risk. CR between 10^{-6} and 10^{-4} indicates that there may be a concern or no concern for increased cancer risk (further evaluation is needed; other factors need to be considered to make a decision). CR higher than 10^{-4} indicates a concern for increased cancer risk (ATSDR, 2022b).

ILCR has been applied by some researchers in estimating cancer risk associated with heavy metals in groundwater. In their study on groundwater in Iran, Mohammadi et al. (2019) obtained an ILCR of 8.54x10^{-4} due to lead contamination. Similarly, Shah et al. (2020) observed a mean ILCR of $1.8x10^{-3}$ in their study on groundwater in Pakistan. Likewise, Zhang et al. (2022) reported mean ILCR of $4.72x10^{-4}$ and $6.45x10^{-4}$ for children; and $3.35x10^{-4}$ and $3.81x10^{-4}$ for adults due to arsenic in unconfined and confined aquifers respectively in China. In the Obuasi municipality of Ghana, Obiri et al. (2010) reported that the cancer health risk associated with arsenic, cadmium, and copper in groundwater exceeded the U.S. EPA acceptable range. Similar to their findings, Bempah and Ewusi (2016) obtained a cancer health risk of $1.55x10^{-4}$ due to arsenic contamination of groundwater around Obuasi gold mine (Ghana).

Studies assessing cancer health risks associated with heavy metals in groundwater in the coastal areas of Ghana include the research by Egbi et al. (2021) and Akoto et al. (2019). Egbi et al. (2021) reported that nickel poses a significant cancer risk to people who drink groundwater in the Lower Volta River Basin of Ghana (ILCR ranged from $3.52x10^{-4}$ to $3.79 x10^{-2}$). Similarly, Akoto et al. (2019) reported that the consumption of groundwater in the Anloga Community in Anloga District was associated with cancer health risks due to the presence of lead and cadmium contamination.

Hazard quotient

Hazard Quotient (HQ) is used to assess the possibility of a non-carcinogenic health hazard occurring due to exposure to a contaminant. It is obtained by dividing the estimated exposure dose with a non-cancer health guideline such as an oral reference dose (ATSDR, 2022a). When HQ is greater than 1, there is a potential risk. When HQ is less than 1, there is no potential risk.

A study in the Thulamela Municipality of Limpopo, South Africa recorded a hazard quotient that was less than 1 for aluminum, manganese, iron, cobalt, nickel, and zinc; indicating the absence of a non-cancer risk. In the same vain, Mohammadi et al. (2019) recorded hazard quotient values of 7.17x10^{-5} for lead in Iran. In Pakistan, Shah et al. (2020) observed a mean hazard quotient of 3.9 for arsenic in their study on groundwater, indicating a potential non-cancer risk. Likewise, Maigari et al. (2016) reported a non-cancer risk for iron (HQ of 1.27) in groundwater in Dadinkowa dam and Kwadon boreholes, in Gombe State, Nigeria.

In Ghana, Obiri et al. (2010) have reported that the non-carcinogenic health risk associated with arsenic, cadmium, and copper in groundwater in Obusai municipality was higher than 1 in most samples. In contrast, Bempah and Ewusi (2016) reported acceptable non-carcinogenic health risk levels for arsenic, iron, lead, cadmium, copper, manganese, zinc, chromium, and mercury in groundwater around the Obuasi gold mine.

In the coastal area of Ghana, Egbi et al. (2021) reported that in the Lower Volta River Basin, lead and nickel pose significant non-cancer risks to groundwater consumers. Also, Akoto et al. (2019) findings showed non-cancer health risks due to cadmium and lead consumption from groundwater in the Anloga Community.

Quantitative microbial risk assessment

Quantitative Microbial Risk Assessment (QMRA) is a mathematical modeling approach that is used in estimating the risk of infections and illnesses due to exposure to pathogens (Minnesota Department of Health, 2022). It is an important tool for determining the risk posed by microbial contamination as it combines information regarding the nature, presence, movement, and fate of disease-causing microorganisms into a single assessment that allows for data-informed, sufficient, and comprehensive risk management (WHO, 2016). It provides a cost-effective and practical alternative for human health risk estimation when compared with epidemiological studies (U.S. Geological Survey, 2015). QMRA is therefore an important tool that can be applied in health risk assessment in resource and data-scarce regions of the world.

Quantitative Microbial Risk Assessment involves four steps: hazard identification, exposure assessment, dose-response relationship calculations, and risk characterization (Health Canada, 2019; Minnesota Department of Health, 2022). Hazard identification involves identifying the pathogens that are of concern as well as the diseases that these pathogens can cause (Minnesota Department of Health, 2022). Often, reference pathogens are chosen for QMRA assessment. Exposure assessment involves measuring the amount (dose) of the chosen pathogen that individuals are exposed to. This is obtained by multiplying the amount of the pathogen in an environmental medium with the amount of the medium that an individual is exposed to. Dose-response relationships determine the likelihood of health outcomes such as infections and illness given an exposure dose. They are mathematical models formulated by professionals using data from previous outbreaks or dosing studies in laboratories that estimate the number of persons who were infected or ill due to exposure to a given dose of a pathogen (Minnesota Department of Health, 2022; U.S. Geological Survey, 2015). This third step often involves choosing an appropriate dose-response relationship for a given pathogen. Risk characterization involves putting the information obtained from the exposure assessment into the selected dose-response relationship to estimate health risks such as probability of infection, probability of illness, and disability-adjusted life year (DALY). The DALY represents the total burden of a disease in terms of mortality and morbidity. One DALY indicates the loss of one year of full health (WHO, 2023).

QMRA has been widely applied in estimating microbial health risk (Amatobi & Agunwamba, 2022; Byrne et al., 2021; Machdar et al., 2013; Ngubane et al., 2022; Petterson et al., 2015; Scallan et al., 2015; Uprety et al., 2020). Amatobi and Agunwamba (2022) obtained a daily risk of infections of 0.325 due to *E. coli* O157:H7 in groundwater sources in Afikpo, Nigeria. Barragán et al. (2021) reported a mean daily risk of illness of 6.29×10^{-3} and an annual risk of illness of 0.655 for ETEC (a related serotype of *E. coli* O157:H7), in five rural areas of Villapinzon, Columbia. Uprety et al. (2020) reported DALYs higher than acceptable DALY in Nepal, particularly in the low-lying regions.

The application of QMRA in estimating microbial risk associated with groundwater in Ghana has been done by Yeboah et al. (2022) and Machdar et al. (2013). Yeboah et al. (2022) obtained a daily risk of infection of 6.9×10^{-6} and an annual risk of infection of 2.5×10^{-3} due to *E. coli* O157:H7 in Northern Ghana. Machdar et al. (2013) who estimated the DALY due to *E. coli* O157:H7 in drinking water in Accra obtained a DALY of 0.4.

Groundwater Governance

Wijnen et al. (2012) defined governance as "the operation of rules, instruments, and organizations that can align stakeholders' behavior and actual outcomes with policy objectives". It is the process of making decisions and implementing those decisions (United Nations, 2000). Groundwater Governance Project (GGP) defined groundwater governance as "the promotion of responsible collective action to ensure control, protection and socially-sustainable utilisation of groundwater resources and aquifer systems for the benefit of mankind and dependent ecosystems" (FAO, 2016b). According to Foster et al. (2009), groundwater governance is the use of appropriate authority and the promotion of responsible collective action to ensure that groundwater resources are sustainably and efficiently used for the benefit of man and dependent ecosystems.

According to Foster et al. (2009), some of the principal instruments for sound groundwater governance are:

a. Institutional and legal provisions: These include the nation's constitution, organizational arrangements (organizations involved in water management and provision), primary legislation (legislative material e.g. Water Law), and legal regulations (legislative document issued by the executive to describe implementation details, as permitted by the primary legislation) (Foster et al., 2009). Commonly, institutional capacity deals with how institutional settings, rules, and regulations empower actors to cooperate and solve common problems (Dang & Visseren-hamakers, 2016).

b. Stakeholder participation: Participation and local management can be a very effective approach to good water governance and may help increase sustainability (Wijnen et al., 2012). Participation is effective in improving groundwater governance outcomes because it increases stakeholder ownership as well as more access to information and can develop solutions better than or complementary to those delivered from the top-down approach (Wijnen et al., 2012). Participatory approaches range from consultation to fully delegated groundwater management. The more bottom-up the approach, the stronger the participation and empowerment of local stakeholders (Wijnen et al., 2012). A necessary pre-requisite for mobilizing stakeholder participation is that the regulatory agency has emphasized generating a reasonably comprehensive and detailed inventory of groundwater users, uses, and use status – and from this established a 'user profile' for each groundwater body requiring management measures (Foster et al., 2009).
c. Groundwater resource administrations: These administrations are government agencies that play important roles such as financial resource allocation, the establishment of guidelines to address the management of trans-state and internationally-shared aquifers, and the provision of minimum reference standards to identify, characterize, monitor, and evaluate groundwater sources 'at risk', and define procedures to specify and implement management measures suitable to the level of risk involved. To optimize the roles of existing agencies, there is a need for these agencies to transform from being mere knowledge providers and advisers on supply development to combine the function of being the

'guardian' of groundwater (Foster et al., 2009). The major roles of the transformed agencies would be:

i. Information and planning: ensuring that groundwater status and user inventories are up-to-date, monitoring the levels and quality of aquifers, and providing authoritative information at both policy level and user level.

ii. Guiding Supply- and Demand-Side Interventions: ensuring that proposed measures and investments are sound scientifically, rational economically, and coordinated appropriately.

iii. Fostering Community-Based Management: Enabling and encouraging community-based initiatives and being a ′lighthouse' to ensure they are sustained and replicated.

iv. Regulatory Inputs: Providing advice on the technical foundation for resource use administration and the control of pollution where the regulatory approach is needed and enforceable.

Groundwater governance is dependent on local needs and conditions which differ greatly across the globe. For instance, Ananda and Aheeyar (2020) reported that the absence of formal institutions in charge of groundwater management and ill-defined well rights were the major problems hampering sustainable groundwater use in India, while Molle et al. (2017) reported that the fragmentation of agencies and lack of technical capacity were major challenges preventing effective groundwater governance in Lebanon. In the case of the Grootfontein aquifer in South Africa, inadequate governance arrangements were the major impediment to the potential of groundwater as a sustainable source of water supply despite in-depth knowledge of the hydrogeological properties of the aquifer (Cobbing & De Wit, 2018). In Dodowa, Ghana, Grönwall (2016) reported that the presence of agencies with overlapping responsibilities, poorly managed multi-level governance structures, and poor accountability were the major governance problems facing groundwater in the peri-urban town.

Framework for Groundwater Governance

Frameworks are tools used to analyze complex governance regimes, and the links between management and the resultant effects on the benefits derived from a resource (Knüppe & Pahl-Wostl, 2011). Additionally, frameworks provide an understanding of how governance arrangements are designed and they are mostly generated by insights from empirical data and current thinking about governance (Franks & Cleaver, 2007).

Several well-established and holistic analytical frameworks such as the European Union (Water directive) and the Organization for Economic Co-operation and Development frameworks exist for water governance (Wijnen et al., 2012). Although these frameworks make provision for groundwater through principles of Integrated Water Resources Management (IWRM), they do not provide sufficient details for addressing specific groundwater governance needs (Wijnen et al., 2012). This presents a challenge for the implementation of the groundwater components. Consequently, while several countries have adopted the IWRM framework, the groundwater component of these frameworks is often missing (Wijnen et al., 2012). Indeed, the innate characteristics of groundwater (invisibility and ease of individual exploitation) make its management more challenging and complicated when compared to surface water (Lall et al., 2020; Oguama et al., 2019). Despite these challenges, the discourse on groundwater governance has continued to expand as the relevance of groundwater is more glaring in the face of the increasing global water crisis (Gudaga et al., 2018a).

Efforts have been made to develop groundwater-specific analytical frameworks. These efforts include the works by Foster et al. (2009), Knüppe and Pahl-Wostl (2011), and Wijnen et al. (2012). Some common features of these frameworks are that they all consider the role of policies and legal tools, as well as community participation as key to effective groundwater governance.

Groundwater Management Advisory Team GWMATE developed a priority checklist of benchmarking criteria for assessing groundwater governance based on their years of experience in the assessment of the efficiency of prevailing provisions and capacity for adequate groundwater governance (Foster et al., 2009). In this study, a checklist developed by GWMATE was used to assess the groundwater governance status in Ghana (Table 2). This checklist has been employed in Portugal, Kenya, and South Africa (Cruz & Soares, 2018; Matshini, 2016; Mumma et al., 2011; Pietersen et al., 2012).

Table 2: Check-list of top-20 benchmarking criteria for the evaluation of groundwater governance provision and capacity
Ranks (0-non-existent; 1- incipient; 2- acceptable; 3- optimum) (Foster et al., 2009)

Type of provision/ capacity	**CHECKLIST** *In each instance the criteria should be individually ranked in relation to considerations of 'existing provisions' and 'institutional capacity to implement'*	
	Criterion	**Context**
Technical	Existence of basic hydrogeological maps	For identification of groundwater resources
	Groundwater body/aquifer delineation	With classification of typology
	Groundwater piezometric monitoring network	To establish resource status
	Groundwater pollution hazard assessment	For identifying quality degradation risks
	Availability of aquifer numerical 'management models'	At least preliminary for strategic critical aquifers
	Groundwater quality monitoring network	To detect groundwater pollution
Legal and institutional	Water well drilling permits and groundwater use rights	For large users, with interests of small users noted
	Instrument to reduce groundwater abstraction	Water well closure/constraint in critical areas
	Instrument to prevent water well construction	In overexploited or polluted areas
	. Sanction for illegal water well operation	Penalizing excessive pumping above permit
	. Groundwater abstraction and use charging	'Resource charge' on larger users
	. Land-Use control on potentially-polluting activities.	Prohibition or restriction since groundwater hazard
	. Levies on generation/discharge of potential pollutants	Providing incentive for pollution prevention
	. Government agency as 'groundwater resource guardian'	Empowered to act on cross-sectorial basis
	. Community aquifer management Organizations	Mobilizing and formalizing community participation

Table 2: Cont'd

Type of provision/ capacity	**CHECKLIST** ***In each instance the criteria should be individually ranked in relation to considerations of 'existing provisions' and 'institutional capacity to implement'***	
	Criterion	**Context**
Cross-sector policy coordination	. Coordination with agricultural Development	Ensuring 'real water saving' and pollution control
	. Groundwater-based urban/industrial planning	To conserve and protect groundwater resources
	. Compensation for groundwater protection	Related to constraints on land-use activities
Operational	. Public participation in groundwater management	Effective in control of exploitation and pollution
	. Existence of groundwater management action plan	With measures and instruments agreed

CHAPTER THREE

SEASONAL VARIATIONS AND HEALTH RISK ASSESSMENT OF MICROBIAL CONTAMINATION OF GROUNDWATER IN SELECTED COASTAL COMMUNITIES OF GHANA

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Abstract

This study investigated seasonal variations in microbial contaminations of groundwater and associated health risks in four coastal communities (Essiama, Winneba, Accra, and Keta) in Ghana. Membrane filtration methods, sanitary risk inspection, and quantitative microbial risk assessment were employed to (i) quantify bacteriological quality, (ii) identify risks to contamination, and (iii) assess health risks associated with *Escherichia coli* in groundwater, respectively. Results showed 70.00%, 53.33%, 70.37%, and 90.00% of groundwater sources in Essiama, Winneba, Accra, and Keta, respectively, were at intermediate risk, whereas 3.33%, 40.00%, 14.81%, and 3.33%, respectively, were at high risk. Very high-risk levels of contamination were recorded only in Accra. The presence of animal wastes within a 10 m radius of the groundwater collection point, bad drainage systems, collection of spilt water in the apron area, the use of ropes and buckets when fetching groundwater, and absence of aprons and well covers put more than 60.00% of the groundwater points in two or more locations at risk of pollution. Assessment of the bacteriological quality of groundwater indicated that mean total coliforms and *E. coli* ranged, respectively, between 123.40-501.30 and 30.98-141.90 CFU/100 ml for the communities; the highest microbial counts for dry and wet seasons occurred in Winneba and Keta, respectively. Seasonal variations in *E. coli* counts in Winneba and Accra were significantly higher in the dry season than in the wet season; Essiama and Keta showed no significant seasonal variations. Exposure to *E. coli* O157:H7 through drinking groundwater ranged between 5 – 23 cells per day. Although exposure to *E. coli* O157:H7 through bathing was less than 1 cell per day in all communities, residents were exposed to one *E. coli*, at least, every 62, 141, 237, and 282 days in Winneba, Accra, Keta, and Essiama, respectively. The annual risk of infection and illness for all communities was 1 for drinking, whereas that for bathing ranged from 0.65-0.99. The estimated Disability-Adjusted Life Years (DALY) exceeded the WHO-acceptable DALY. These findings show that groundwater resources in the selected coastal communities were prone to microbial contaminations; this may be a setback to Sustainable Development Goals 6. Implications of the findings are discussed.

Keywords: Groundwater quality, coastal aquifers, *E. coli*, sanitary inspection, quantitative microbial risk assessment, Southern Ghana.

Introduction

Groundwater is a crucial resource on Earth (Vadiati et al., 2018); it provides over 97% of accessible freshwater (UN Water, 2022) particularly in Sub-Saharan Africa (Idowu, 2017) and half of the water needed for drinking worldwide (UN Water, 2022). The achievement of several of the United Nations Sustainable Development Goals (UN-SDGs) is closely linked to the provision of groundwater, both in adequate quantity and optimum quality. For example, improvement in access to clean water and its sustainable management is a mechanistic approach to increasing well-being and health (SDG 3), and sustainable development in cities and communities (SDG 11). However, this critical resource is facing various challenges such as pollution and increased anthropogenic pressure. Aquifers are faced with an increasing global threat of pollution (Zacchaeus et al., 2020).

Water-borne infections and unsafe water sources are major global issues resulting from groundwater pollution. Lack of safe drinking water leads to remarkable increases in contagious illnesses like cholera, typhoid, dysentery, hepatitis A, poliomyelitis, and diarrhoea (WHO, 2019). Globally, about 1.2 million people died in 2017 due to the lack of safe drinking water (Stanaway et al., 2018), and more than a quarter of a million children under the age of 5 years die each year from diarrhoea (WHO, 2019). The number of deaths is high in low-income countries where sub-Saharan Africa records the highest disease burden from inadequate water, sanitation, and hygiene (International Institute for Sustainable Development, 2020). In 2016, diarrheal diseases caused over half a million deaths in sub-Saharan Africa, where polluted drinking water was a major risk factor (Troeger et al., 2018). The relevance of this problem underpins the fact that clean water and sanitation (SDG 6) is geared towards ensuring the availability and sustainable management of water and sanitation for all.

A wide range of pathogenic microbes is found in groundwater (Keesari et al., 2015). Bacteria, however, constitute a major group of microorganisms that cause waterborne disease outbreaks (Al-Fifi et al., 2019). Indicators of faecal pollution are often used in the monitoring of the bacteriological quality of drinking water. *Escherichia coli* (*E. coli*) is an excellent example of an indicator of faecal pollution in drinking water. Quantitative Microbial Risk Assessment (QMRA) is an important tool for determining the risk posed by microbial contamination as it combines information regarding the nature, presence, movement, and fate of disease-causing microorganisms into a single assessment that allows for data-informed, sufficient, and comprehensive risk management (WHO, 2016).

Findings by Ampomah (2017) indicate that 60% of Ghana's surface waterbodies are contaminated, leading to increasing dependence on groundwater. Other studies have reported similar findings from other countries (Nguyen et al., 2022; Nyakundi et al., 2022). The increased cost of water treatment due to pollution in Ghana has caused several water treatment plants to shut down (Ampomah, 2017). Additionally, many households have resorted to the use of wells and boreholes due to the (i) cost of water bills, (ii) the inability of the Ghana Water Company Limited (GWCL) and the Community Water and Sanitation Agency (CWSA) to expand water supplies to new communities, and (iii) assumption that groundwater is free from pollution. According to the 2021 Ghana Population Census, only 31.7% of Ghanaians rely on pipe-borne water as a source of drinking water (Ghana Statistical Service, 2022). Other sources of drinking water include water in plastic sachets, boreholes, tube wells, and protected and unprotected hand-dug wells (Ghana Statistical Service, 2022). Several studies have reported the pollution of groundwater in Ghana with faecal bacteria (Aboagye & Zume, 2019; Akoto et al., 2022; Arko et al., 2019; Lutterodt et al., 2018; Takal & Quaye-Ballard, 2018; Tekpor et al., 2017; Yeboah et al., 2022). This notwithstanding, few studies have focused on aquifers in coastal areas where a quarter of Ghana's population live (Ketadzo et al., 2021; Lutterodt et al., 2021; Zume et al., 2021). The high population in the coastal areas is not commensurate with the availability of sanitation facilities. Less than 26% of the population in each of the coastal regions have access to basic sanitation services; about 16, 17, 8 and 38% of the population in Western, Central, Greater Accra, and Volta regions, respectively, practice open defecation (Ghana Statistical Service, 2019). Also, the inadequate attention given to sanitation is majorly placed on solid waste, with little focus on liquid waste which can lead to the faecal contamination of groundwater (Mansour & Esseku, 2017). The limited provision of sewerage services in Ghana has led to the dominance of onsite sanitation facilities (e.g., septic tanks, cesspools, etc.) that pose a threat to the quality of groundwater if not well constructed and maintained (Mansour & Esseku, 2017).

Ghana was unable to achieve the Millennium Development Goal on Sanitation and progress towards the achievement of the related SDG is slow (World Health Organization/United Nations International Children's Fund Joint Monitoring Program, 2015; Kanyagui & Viswanathan, 2022). Sanitation and the quality of drinking water are so interwoven that they cannot be separated (Adams et al., 2016). Cholera is endemic in Ghana especially in the coastal communities, in the Central, Eastern, and Greater Accra regions (Noora et al., 2017; Opare et al., 2012). There is a dire need to protect the health of the teeming population of coastal dwellers in Ghana, but the long-term assessment of bacteriological groundwater quality that captures seasonal variations in the coastal communities of Ghana is scarce. This may be attributed to (i) lack of funding by governmental and non-governmental agencies for broader, comprehensive studies, (ii) few practicing experts in the field of water and sanitation, and (iii) lack of by-laws to support institutions like Community Water and Sanitation Agency (CWSA) to carry an assessment of self-supply water sources. Furthermore, studies that assessed the potential health risks associated with bacterial pollution of groundwater in coastal communities of Ghana are rare. In a previous study, Lutterodt et al. (2021) assessed the suitability of well water for drinking and showed the persistence presence and contamination of bacteria in a coastal aquifer in Cape Coast, a prominent historic Metropolis in the Central Region of Ghana. In that study, only the dry season was considered and no empirical assessment of health risk was carried out. In other studies, a one-time sampling was carried out to assess the quality of groundwater; these studies also did not assess the health risks associated with groundwater contamination (Ketadzo et al., 2021; Zume et al., 2021). A literature search on quantitative microbial health risk assessment associated with groundwater sources in the coastal communities of Ghana revealed only the work in some slums of Accra (Machdar et al., 2013). Thus, the scant information and dearth of knowledge in the area of water and sanitation, with a special focus on groundwater quality, suggest a need for a series of investigations to understand the current state and quality of underground water in the coastal communities in Ghana. To this end, this study, therefore, sought to assess (i) the bacteriological quality of groundwater sources in the coastal communities of Ghana, (ii) seasonal variations in microbial contamination, and (iii) the potential health risks associated with the use of groundwater. This study is significant because it fills the gap in the long-term assessment of microbial quality as well as quantitative microbial risk assessment of groundwater in the coastal communities of Ghana. The findings of this present study serve as a springboard for future studies concerning groundwater quality in Ghana and also highlight significantly the potential sources of bacterial contaminations and the consequential health risks.

Materials and Methods

Study sites

The study was carried out in four selected coastal towns/settlements of Ghana namely: Essiama, Winneba, Accra (Korle lagoon catchment area), and Keta (Figure 3 and 4). The four coastal towns/settlements were selected from each of the coastal regions of Ghana because of the tendency of exposure of their groundwater to faecal contamination within the coastal aquifers.

Figure 3: Map showing study areas

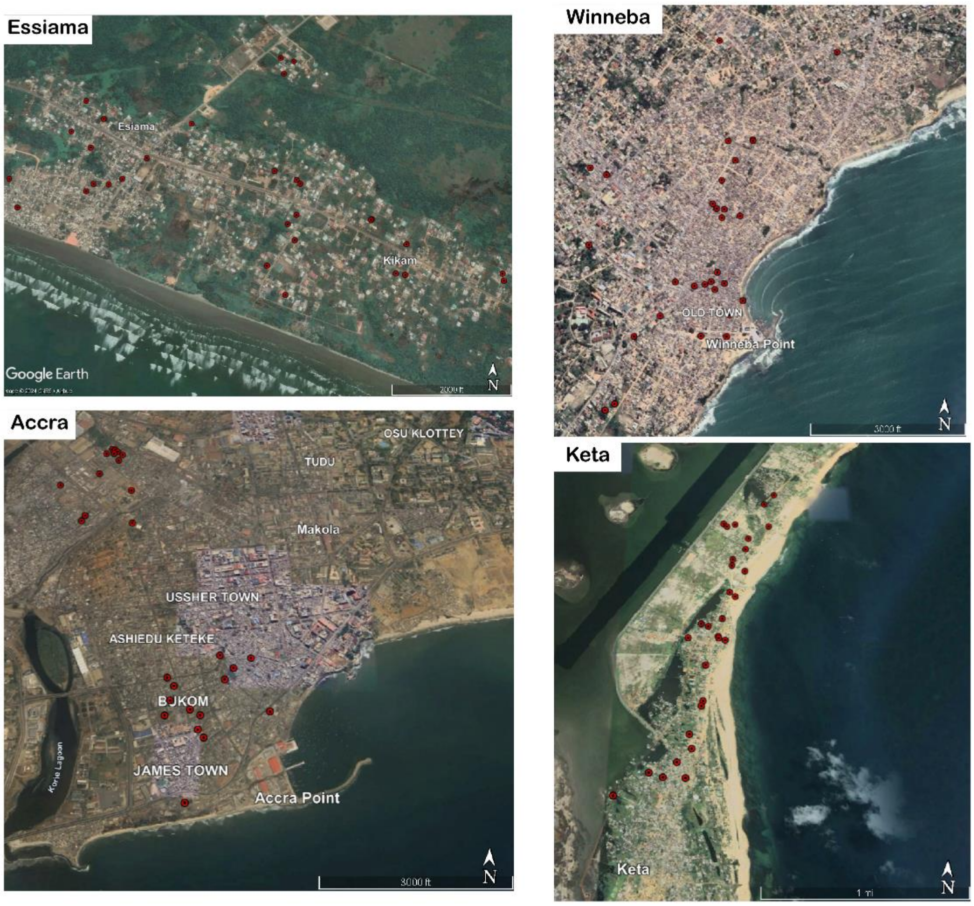

Figure 4: Map showing sampling points

Essiama is located in Ellembele District, in the Western Region of Ghana. The Community Water and Sanitation Agency (CWSA) of Ghana provides water for the town. However, several households in the town have yet to subscribe to the services provided by CWSA; they depend on water from wells and boreholes for domestic use.

The Korle lagoon catchment area is located in Accra, the capital of Ghana. It is home to some of Accra's notable slums including Agblobloshie, Old Fadama, and James Town, from which samples were collected. These settlements, like most typical slums, lack good sanitary facilities. Inhabitants use public bathrooms and toilets. Wastewater, including urine, is mostly drained into open drainage systems within the settlements. Solid waste and sewage disposal are also major sanitary problems in these settlements. Major sources of water for domestic use are piped water from GWCL, water in plastic sachets, wells, and boreholes. When there is a water shortage due to disruption of flow from GWCL, some members of these settlements purchase water from vendors who store and sell the GWCL in large plastic storage tanks and retail it.

Winneba is located in the Central Region of Ghana. The major economic activities in the town are fishing and trading. The town is divided into New Winneba and Old Winneba. The New Winneba obtains its water supplies from the GWCL; there are almost no wells and boreholes in this part of the town. However, in Old Winneba town, groundwater remains an important source of water for drinking and domestic use.

Keta is located in the Volta region of Ghana and it is home to Keta Lagoon, the largest lagoon in Ghana. Fishing is the major economic activity in Keta. Several neighbouring communities around Keta are involved in farming. Generally, hand-dug wells are the major sources of water supply for most communities in the Keta basin.

Data collection

Sanitary risk assessment

A sanitary risk assessment was performed before sampling to assess the exposure of wells and boreholes to possible microbial contamination. Methods detailed by Howard et al. (2001) and Viban et al. (2021) for sanitary risk assessment in hand-dug wells and boreholes were combined and adopted for this study (Table 3). The presence or absence of possible risk factors that could lead to the contamination of groundwater at each water point was documented.

A total of nineteen (19) risk factors were used for the sanitary risk assessment: eleven (11) were used for both wells and boreholes; five (5) for wells only; and three (3) for boreholes only (Table 3). "Yes" was checked when a risk factor was present; "No" was checked when a risk factor was absent. The "Risk score" for each water point was determined by the total number of factors present (Yes), which was then used to calculate the percentage risk score as follows:

$$\%\,Risk\ score\ = (Risk\ score/Total\ number\ of\ risk\ factors)\ \times 100 \quad (3)$$

The risk of contamination was then categorized as Low (0-25%), Intermediate (26-50%), High (51-75%), and Very High (76-100%). The results on risk factors for wells and boreholes were pulled together in each community because few boreholes were sampled in most communities.

Table 3: Risk factors used in sanitary risk assessment

	Risk factors	Risk affects
1	Pit latrine/septic tank soak away within a distance of less than 10 m	Wells and boreholes
2	Nearest pit latrine is uphill (at higher ground than the well/borehole) within 30 m away	Wells and boreholes
3	Surface water uphill	Wells and boreholes
4	Waste dump site within a distance of less than 10 m	Wells and boreholes
5	Wastewater drains within a distance of less than 10 m	Wells and boreholes
6	Absence of apron/apron does not extend more than 1.5 m/apron or cement floor does not slope away from well	Wells and boreholes
7	Collection of spilt water in the apron area	Wells and boreholes
8	Faulty masonry	Wells and boreholes
9	Drainage channel is in bad condition (cracked, broken, blocked, or unlined)	Wells and boreholes
10	Presence of trees around wells that can lead to well contamination	Wells and boreholes

Table 3: Cont'd

	Risk factors	Risk affects
11	Presence of animals or their waste 10 m radius	Wells and boreholes
12	Lack of well cover	Wells only
13	Use of bucket and rope	Wells only
14	Absence of wellhead or wellhead is less than 0.3 m high	Wells only
15	Lack of inner lining	Wells only
16	Abandoned materials/waste inside well	Wells only
17	Uncapped well within 10-15 m of a borehole (for boreholes)	Boreholes only
18	Unsanitary/worn-out seal of borehole pump	Boreholes only
19	Pump is operated by feet	Boreholes only

Sample collection

Sampling of wells and boreholes from the selected communities was carried out between April and June 2022 for the rainy season and in December 2022 for the dry season. Sample bottles were prewashed before fieldwork, and rinsed several times with the sampled water from the water points. Boreholes were purged before collecting water samples while hand-dug wells were sampled after the wells had been actively used by inhabitants of the communities to prevent sampling stagnant water (Lutterodt et al., 2021). Thirty (30) groundwater points were each sampled in Essiama, Winneba, and Keta, while 27 were sampled in Accra (Figure 4). The samples were collected into 500 ml sterile plastic containers as described by US EPA (2002) and transported in an ice chest to the laboratory, where they were stored at 4 °C until they were analyzed.

Laboratory analyses

The membrane filtration method was used for the analysis of total coliform and *E. coli* as previously described by (Lutterodt et al., 2014, 2021; U.S. EPA, 2002). One hundred milliliters of water samples were filtered through 0.45 µm cellulose ester filter paper (diameter 47 mm), after which the filter paper was placed on a Chromocult agar plate and incubated at 37 °C between 21 and 24 hours. All dark blue to purple-coloured colonies present on each plate were counted as *E. coli* count (U.S. EPA, 2002). All salmon red-coloured colonies were counted and recorded as other coliforms present. An oxidase-based test strip was used to confirm the coliform bacteria. All analyses were done in duplicate.

Quantitative microbial risk assessment

Quantitative microbial risk assessment (QMRA) was performed for *E. coli* O157:H7 using the following steps:

a) Hazard identification

E. coli was chosen because it is a common water quality indicator used in assessing faecal contamination and a significant cause of water-borne disease, particularly in developing countries. Furthermore, *E. coli* is easy and more economical to analyze. The O157:H7 was chosen because it is the most important serotype of *E. coli* in terms of public health concerns.

b) Exposure assessment

The concentration of *E.coli* O157:H7 was determined by multiplying the overall mean values of *E. coli* in a community by 8% (0.08), which represents the percentage of *E. coli* known to be pathogenic (Ngubane et al., 2022). The exposure pathways considered were ingestion (drinking) and incidental ingestion during showering. Incidental ingestion pathway (showering) was considered in this study because, in the Korle lagoon catchment area, groundwater is generally presumed to be polluted. Hence, groundwater in the Korle lagoon catchment area is mostly used for bathing and washing. As the groundwater in these towns is not treated before use, pathogen reduction measures were not considered.

Exposure or dose was calculated as:

$$D = V_{Consumed} \times C_{E\ coli\ \mathrm{O157:H7}} \quad (4)$$

Where D is the dose per day, $V_{consumed}$ is the volume of water consumed per day, and $C_{E.\ coli\ \mathrm{O157:H7}}$ is the mean concentration of *E. coli* in a community multiplied by 0.08.

For direct ingestion, the volume of water drank directly ($V_{consumed}$) was based on WHO's recommended water intake of 2L per day (Uprety et al., 2020); for incidental ingestion during showering, $V_{consumed}$ of 1.43mL per day was used based on the 10mL/week reported by Westrell (2004).

c) Dose-response assessment

In this study, the beta-Poisson model was used for the dose-response assessment. The equation for single exposure was used as shown below (WHO, 2016). Single exposure assumes that every ingested pathogen acts independently of other ingested pathogens and has the possibility of resulting in infection (Haas, 1983). It is noted that this assumption may lead to an overestimation of the response as it does not take cognizance of the differences that are present between individual pathogens (Nilsen and Wyller, 2016).

$$Pinfection, day = 1 - \left(1 + D/N_{50}\left(2^{\frac{1}{\alpha}} - 1\right)\right)^{-\alpha} \quad (5)$$

Where, $P_{infection,\ day}$ is the possibility of an infection per day, D is the dose, and N_{50} is the number of pathogens that will infect 50% of the exposed population, i.e., the median infection dose.

α and N_{50} have the values 0.373 and 2.473, respectively (Genthe & Oberholster, n.d.; Strachan et al., 2005; Teunis et al., 2008; WHO, 2016).

d) Risk characterization

The possibility of infection per year was calculated using the formula (WHO, 2016).

$$P_{\text{infection,year}} = 1 - (1 - P_{\text{infection,day}})^{365} \quad (6)$$

The number of days in a year (365 days) was used as the exposure frequency because the exposure pathways considered are drinking and bathing. It was assumed that members of the population take their baths daily. This assumption is based on the fact that groundwater in the studied communities is readily accessible and free in most cases. Irrespective of free access to groundwater, some individuals may be affected by some economic and attitudinal factors such that they may not take their baths daily; our assumption may therefore lead to inconsequential overestimation of the number of infections per year. Although the above equation may overestimate the number of infections per year, as it is based on the assumption that infections occur daily, and that individuals do not build immunity to infection, it gives a good estimate of the yearly likelihood of infection (Health Canada, 2019; Petterson et al., 2015).

The probability of illness per year was determined using the formula (Health Canada, 2019)

$$P_{illness,year} = P_{infection,year} \times P_{ill/inf} \quad (7)$$

The probability of illness given an infection ($P_{ill/inf}$) with *E. coli* O157:H7 is 1 (Strachan et al., 2005).

Disability Adjusted Life Years (DALY) were calculated as years lived with disability (YLD) and years of life lost due to death (YLL). YLD and YLL were computed, respectively, as the product of incidence, severity, and duration of illness (Health Canada, 2019).

Durations for YLL were calculated by subtracting the age at death for an outcome from the life expectancy. Severity weighting, incidence, and duration of *E.coli* O157:H7 outcomes were obtained from Havelaar and Melse (2003), except incidence values for death due to diarrhoea, and severity of end-stage renal disease which were obtained from Howard et al. (2006) and (Health Canada, 2019), respectively. The calculation of years of life lost was based on the average life expectancy of 66.3 in Ghana, death from diarrhoea occurring at 12 months, and death from end-stage renal disease occurring at an average of 30 years based on a study in Ghana (Adjei et al., 2019; WHO, 2023b).

Data analysis

Statistical analysis was performed with SigmaPlot 14.0, Microsoft Excel, and Minitab Statistical Software. Risk levels were shown as percentages. Descriptive statistics were performed for total coliform and *E. coli* concentrations. Levene's test was used to check for equal variance. The Wilcoxon signed-rank test for paired data was used to compare the medians of the wet and dry season for Essiama, Accra, and Keta, while the Mann-Whitney test was used for the Winneba as the Winneba data did not meet the equal variance assumption needed for the Wilcoxon signed-rank test. The overall means of the raw data were used to calculate the microbial risk.

Results

Sanitary risk assessment

Figure 5 shows the results of the sanitary risk assessment in Essiama, Winneba, Korle Lagoon catchment area of Accra, and Keta. Sanitary risk assessment showed that 70% of well/boreholes in Essiama, 53.33% in Winneba, 70.37% in the Korle lagoon catchment area, and 90% in Keta were at intermediate risk. Groundwater points at high risk of contamination were 3.33%, 40%, 14.81%, and 3.33% in Essiama, Winneba, Korle Lagoon catchment area, and Keta, respectively. Very high-risk levels of groundwater contamination were observed in the Korle lagoon catchment area of Accra (3.7% of the wells and boreholes) as shown in Figure 5.

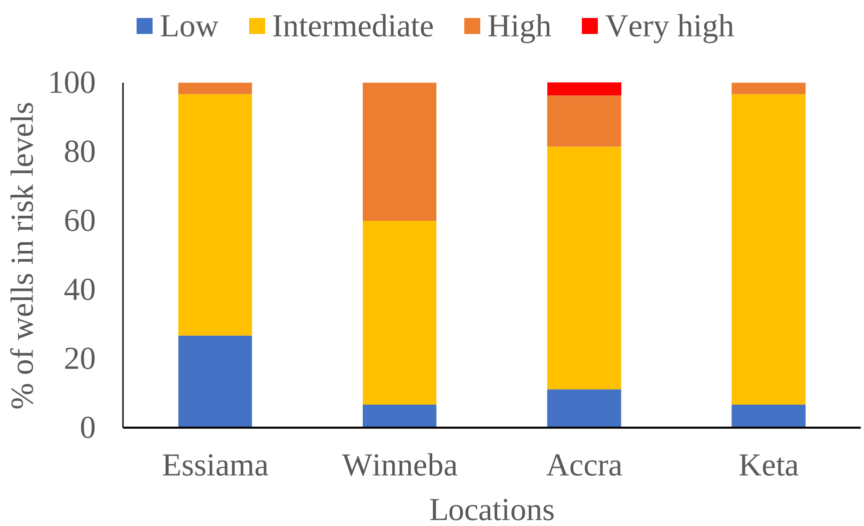

Figure 5: Spatial variations in risk levels

Sanitary risk assessment results (Figure 6) also showed that common risk factors to which groundwater points in Essiama were predisposed included the presence of animals or their waste within a 10 m radius of groundwater points, lack of well cover, use of rope and buckets, the presence of trees around wells, and absence of aprons/apron not more than 1.5 m/apron not sloping away from well/borehole as they affected, respectively, 86.67%, 73.33%, 70%, 53.33%, and 73.33% of the groundwater points. In Winneba, similar risk factors were observed in addition to the presence of abandoned materials in wells, wastewater drain within a distance of less than 10 m, bad drainage conditions, and collection of spilt water in the apron area, affecting 60-100% of the sampled groundwater points. An exception, however, was the presence of trees around wells. The presence of animals or their wastes within a 10 m radius of groundwater affected 85.19% of water points, whereas collection of spilt water in the apron area, drainage in bad conditions, and wastewater drain within a distance less than 10 m affected 74.07%, 66.67%, and 62.96%, of the water points, respectively in the Korle lagoon catchment area. In Keta, the use of ropes and buckets in fetching water, lack of well cover, apron-related risks (i.e., absence of aprons, aprons not more than 1.5 m, apron not sloping away from well/borehole), presence of animals and their wastes around wells and presence of trees around wells were the major risk factors that affected, respectively, 100%, 96.67%, 96.67%, 90% and 53.33% of the wells.

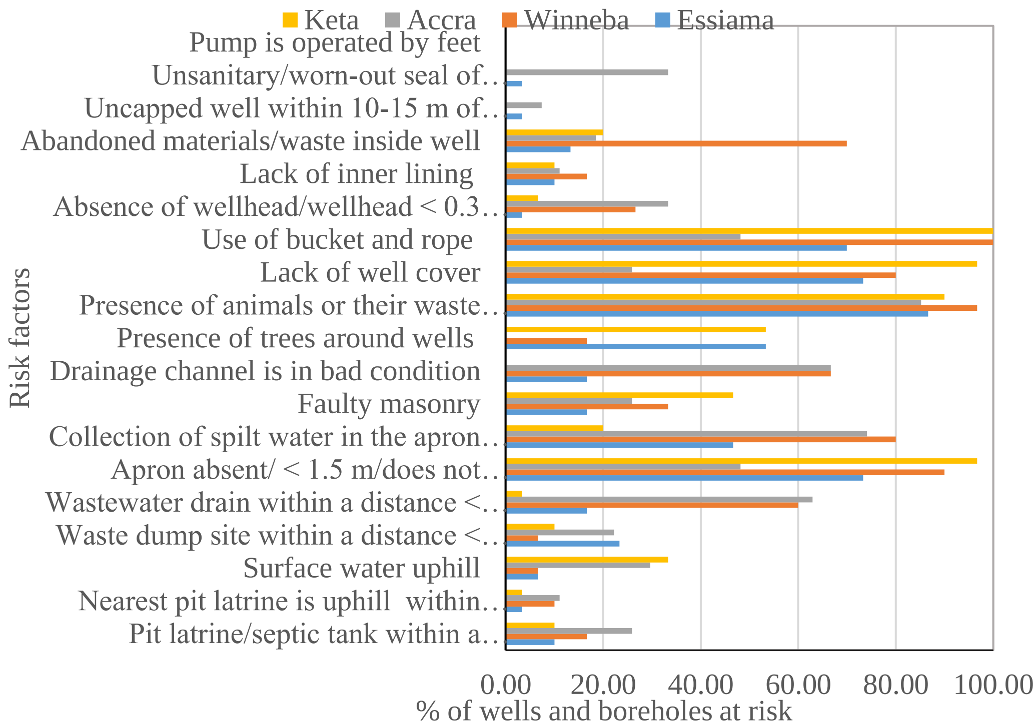

Figure 6: Spatial variation in risk factors

Microbial contaminations of groundwater and its seasonal variations

Mean *E. coli* counts for Essiama, Winneba, Korle Lagoon catchment area of Accra, and Keta were 30.98±6.34, 141.90±29.10, 62.00±26.90, and 36.92±5.85 CFU/100ml, respectively, for the entire sampling period (Table 4). The mean total coliform count was 123.40±17.50, 501.30±64.10, 245.40±55.10, and 171.70±18.20 in Essiama, Winneba, Korle Lagoon catchment area of Accra, and Keta, respectively. The mean *E. coli* and total coliform counts for all the study locations far exceeded the WHO and U.S. EPA standards of zero for drinking water throughout the sampling period.

Table 4: Summary statistics for *E. coli* and total coliform counts between April and December 2022

Location	Variable	Mean	SE Mean	St.Dev	Min	Median	Max	Range
Essiama	*E. coli*	30.98	6.34	49.10	0.00	13.00	285.00	285.00
Winneba	*E. coli*	141.90	29.10	225.10	0.00	34.00	930.00	930.00
Accra	*E. coli*	62.00	26.90	197.50	0.00	9.00	1400.00	1400.00
Keta	*E. coli*	36.92	5.85	45.31	0.00	22.00	265.00	265.00
Essiama	Total coliform	123.40	17.50	135.50	0.00	78.80	595.00	595.00
Winneba	Total coliform	501.30	64.10	496.90	10.00	327.50	1972.50	1962.50
Accra	Total coliform	245.40	55.10	405.20	0.00	133.80	2400.00	2400.00
Keta	Total coliform	171.70	18.20	141.20	10.00	125.30	725.00	715.00

Results on seasonal variations (Table 5) showed that during the wet season, Keta had the highest *E. coli* and total coliform counts (41.80 CFU/100 ml and 199.00 CFU/100 ml, respectively). For the dry season, Winneba had the highest *E. coli* counts and total coliform counts (243.80 and 860.80 CFU/ml, respectively). Wilcoxon signed-rank test and Mann-Whitney test results on seasonal variations in *E. coli* showed that the median *E. coli* counts for the dry season were significantly higher than that of the wet season in Winneba ($p = 0.001$) and Accra ($p = 0.040$). *E. coli* counts in Essiama and Keta showed no significant differences ($p = 0.145$ and 0.495), respectively. For total coliform, counts were also significantly higher during the dry seasons in Winneba (0.000) and Accra (0.045), except in Essiama, where a significant decrease was seen during the dry season (0.018). Total coliform in Keta showed no significant differences ($p = 0.188$).

Health risk assessment

Quantitative microbial risk assessment results showed that exposure to *E. coli* O157:H7 via drinking water from groundwater sources in the study locations ranged from 5 to 23 *E. coli* O157:H7 per day, with the highest exposure occurring at Winneba (Figure 7). Exposure to *E. coli* from the use of groundwater sources for bathing was less than 1 *E. coli*/day in all study locations. However, water users were exposed to at least one *E. coli* O157:H7 every 62, 141, 237, and 282 days in the Winneba, Korle lagoon catchment area, Keta, and Essiama, respectively, from showering (Figure 8).

Table 5: Seasonal variations in E. coli and total coliform counts

Location	Season	Mean	SE Mean	StDev	Min.	Median	Max.	Range	p-value
				E. coli					
Essiama	Wet	37.67	8.40	46.01	0.00	18.75	212.50	212.50	0.145
	Dry	23.83	9.47	51.85	0.00	8.75	285.00	285.00	
Winneba	Wet	39.60	13.20	72.40	0.00	21.30	395.00	395.00	0.001
	Dry	243.80	50.40	276.20	0.00	108.80	930.00	930.00	
Accra	Wet	23.98	8.08	41.99	0.00	5.00	127.50	127.50	0.040
	Dry	99.80	52.60	273.50	2.50	16.00	1400.00	1397.50	
Keta	Wet	41.80	10.40	57.20	0.00	20.00	265.00	265.00	0.495
	Dry	31.53	5.30	29.03	2.50	22.00	102.50	100.00	
				Total coliform					
Essiama	Wet	150.70	21.40	117.30	2.50	127.50	372.50	370.00	0.018
	Dry	96.10	27.10	148.60	0.00	35.00	595.00	595.00	
Winneba	Wet	141.80	23.10	126.60	10.00	122.50	600.00	590.00	0.000
	Dry	860.80	85.40	467.90	220.00	781.30	1972.50	1752.50	
Accra	Wet	181.70	63.50	330.10	0.00	90.00	1727.50	1727.50	0.045
	Dry	309.20	89.70	466.20	10.00	178.00	2400.00	2390.00	
Keta	Wet	199.00	30.80	168.50	17.50	147.50	725.00	707.50	0.188
	Dry	144.50	18.80	103.10	10.00	123.00	392.50	382.50	

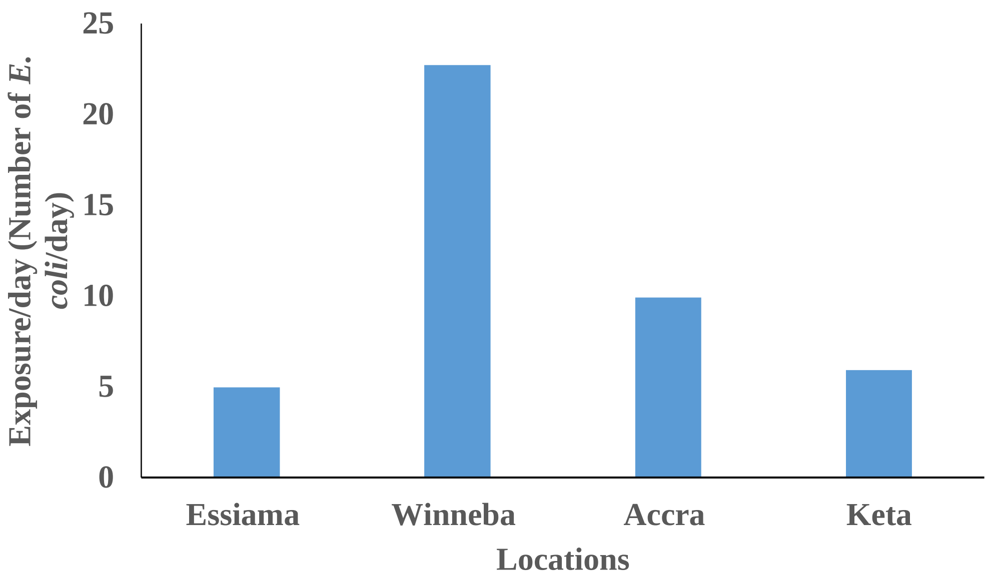

Figure 7: Spatial variation in exposure to *E. coli* from drinking

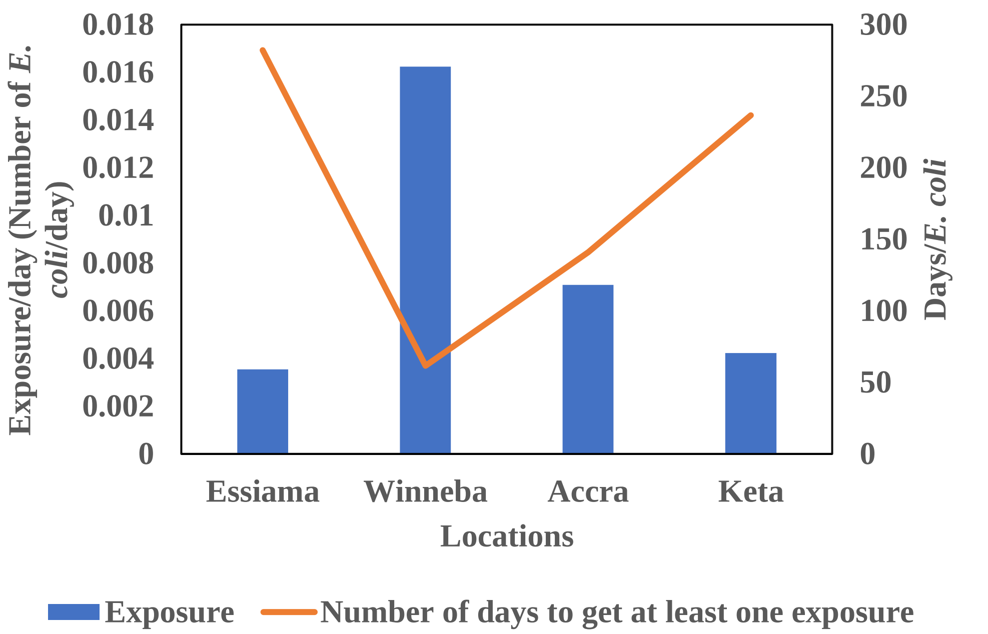

Figure 8: Spatial variation in exposure to *E. coli* from incidental ingestion while bathing

Results for the probability of infection/day, probability of infection/year, and probability of illness/year are shown in Figures 9 and 10, where the respective probability of infection/day for drinking groundwater from the study locations is 0.60, 0.77, 0.69, and 0.63 in Essiama, Winneba, Korle lagoon catchment area, and Keta. On the one hand, the probability of infection/year and illness/year for drinking are 1 in all study locations, whereas, on the other hand, the probability of infection/day for showering with groundwater in the study locations ranged from 0.0029 to 0.0129, with Winneba having the highest risk. The probability of infection/year and illness/year for bathing with groundwater ranged from 0.65 to 0.99, and Winneba also had the highest risk.

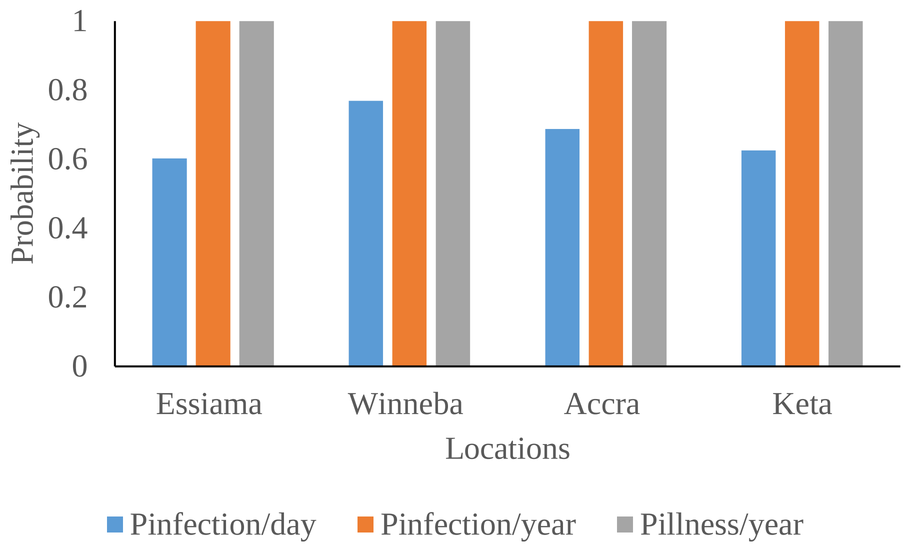

Figure 9: Spatial variations in health risks associated with *E. coli* from drinking water

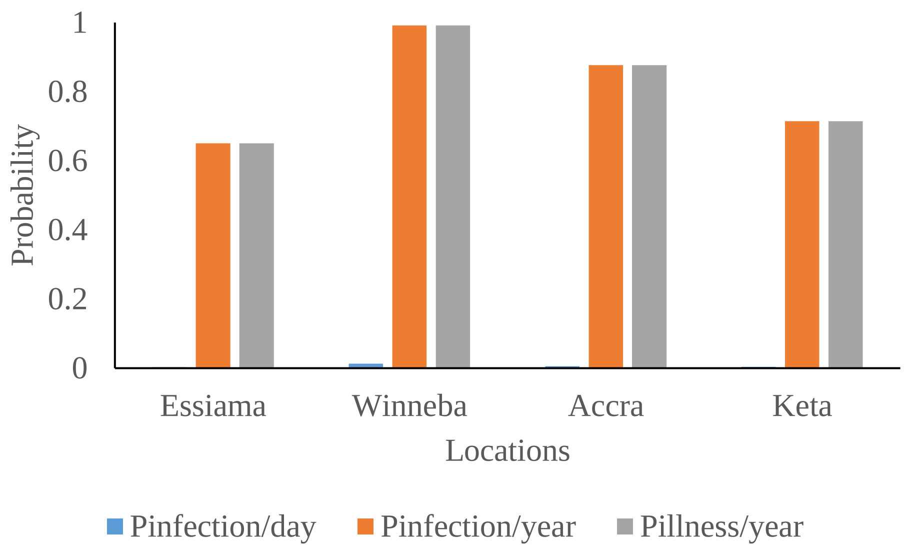

Figure 10: Spatial variations in health risks associated with *E. coli* from bathing

Table 6 presents the results for the Disability-Adjusted Life Years (DALY). The DALY obtained for this study was 0.49938. This value is far higher than the WHO-acceptable DALY of 10^{-5}-10^{-4}.

Table 6: Incidence, severity, duration, and estimated DALY

Years of Life Lived with Disability				
E. coli O157:H7 outcomes	Incidence	Severity	Duration	DALY
Watery Diarrhea	0.53000	0.067	3.4 days (0.009 years)	0.00032
Bloody diarrhea	0.47000	0.390	5.6 days (0.015 years)	0.00275
Hemolytic uremic syndrome	0.01000	0.930	21.0 days (0.057years)	0.00053
End stage renal disease	0.00118	0.950	9.350 years	0.01048
Years of Life Lost				
Death due to diarrhea	0.00700	1	65.3 years	0.45710
Death due to hemolytic uremic syndrome	0.00104	1	26.2 years	0.02725
Death due to end stage renal disease	0.00003	1	36.3 years	0.00109
DALY				0.49952

Discussion

Sanitary risk assessment

Results from the study showed that most of the wells were at intermediate risk levels of microbial contaminations, which raise some concerns for the safe use of groundwater in the coastal communities of Ghana. Moreso, the results show that 40% of the groundwater points in Winneba were at a high-risk level, while 3.7% of groundwater points in the Korle Lagoon catchment area were at a very high-risk level of contamination. These records in the present study are higher than other findings, where it was reported that 15.9% of groundwater points in the largest region of Ethiopia were at a high-risk level and 1.5% were at a very high-risk level (Alemayehu et al., 2020). The high-risk levels of contaminations in Winneba and the Korle Lagoon catchment area reported in this study may be due to sanitary conditions in the communities. Amongst the studied coastal communities, Winneba and the Korle Lagoon catchment area were the most populated and have the least sanitary conditions. Most houses in these communities lack toilet facilities. Also, wells are sited close to drainages. For example, 60% of wells are sited close to drainages in Winneba, as 62.96% of wells are sited close to drainages in Accra. Curiously, 66.67% of drainages in both Winneba and Accra are faulty and most of them contain stagnant wastewater with solid wastes; improper solid waste disposal in these communities is rampant. As a result, residents in these communities are at risk of consuming contaminated water.

Figure 6 shows that activities within the study area pose some threats to groundwater in the studied communities. For example, the use of ropes and buckets in fetching water, a long-aged practice, was one of the common risk factors in the studied communities. Findings reported by Genter et al. (2022) confirm our findings, where the use of ropes and buckets was a major factor that led to the contamination of wells in some cities in Indonesia. This practice of using ropes and buckets to fetch water from wells tends to contaminate well water, especially when many people within a community handle the ropes and buckets as they draw water, and, in the process contaminate the well water. In other circumstances, the ropes and buckets are left on the ground around the wells and are contaminated. Interestingly, another study (Weiss et al., 2016) reported that the use of a rope pump instead of a rope and bucket greatly decreased the geometric mean of *E. coli* contamination by 64.1%.

It was observed in this present study that the presence of animals and their wastes within a 10 m radius of groundwater points was another common risk factor prevalent in all the communities sampled for this work. Thus, there is a need to protect groundwater sources from stray animals in the communities. This is because, *E. coli*, found naturally in the intestines of warm-blooded animals is spread through their stools. Other common risk factors such as (i) the absence of aprons (impermeable concrete floors built around wells and boreholes to prevent spilt water from seeping into the ground), (ii) aprons not sloping away from water points, and (iii) the absence of well covers, were related to poor design and construction of wells and boreholes. In Adamawa, Cameroun, microbial contaminations of groundwater were attributed to poor design and construction of aprons and the absence of well covers (Viban et al., 2021). This notwithstanding, groundwater in the communities can be protected by strict observation and adherence to standards for the construction of wells and boreholes, as well as properly training artisanal masons, most of whom construct these wells, but are not well-versed in the standards of construction of wells, to be able to construct wells that are befitting of set standards.

Microbial contaminations of groundwater and its seasonal variations

Results also showed that mean *E. coli* and total coliform counts exceeded the WHO guideline values of zero (WHO, 2017a). Dzodzomenyo et al. (2022), Elisante and Muzuka (2016), and Pathak et al. (2011), respectively, reported similar findings from studies conducted in wells and boreholes in

Ghana, Tanzania, and Nepal. The results in this study are in agreement with the findings of Close et al. (2008), from which the mean *E. coli* of 40 MPN/100 ml and mean total coliform of 757 MPN/100 ml in wells in New Zealand were reported. The high *E. coli* counts reported in this study may be attributed to poor sanitary conditions around wells in the communities.

Results of this study also showed great variability in the seasonal variations of *E. coli* and total coliform counts across the four study locations, where no clear pattern was established. For example, while a significant ($p<0.05$) increase was seen in *E. coli* and total coliform count at Winneba and Accra during the dry seasons, and a significant ($p<0.05$) decrease was observed for the total coliform count in Essiama, no significant change was seen in Keta. Such varying patterns have been reported in other studies, where, no seasonal variations in faecal and total coliform of groundwater in Iran were observed, and significant increases during the wet season were reported from Ghana, South Africa, and Kenya respectively (Dzodzomenyo et al., 2022; Enitan-folami et al., 2018; Olonga et al., 2014; Sheikhy et al., 2014). Conversely, higher aerobic plate counts were observed during the dry season (Thomas et al., 2011). Run-off and seepage are major causes of groundwater contamination with faecal bacteria during the wet season and this may account for the high *E. coli* and total coliform counts reported for Keta during the wet season. Because Keta is characterized by loose sandy soils with larger pore sizes, its soils have a reduced ability to prevent the movement of microbes into aquifers (Dakheel Almaliki et al., 2022; Robertson, 1997). Site-specific conditions may be the reason for an increase in *E. coli* and total coliform in Winneba and Accra in the dry season. During the sampling period, it was particularly noted that 60% of the wells in

Winneba (Figure 6) were sited close to gutters that were extremely dirty during the dry season. Similarly, the Korle Lagoon catchment area of Accra was characterized by poor sanitary conditions, which predispose groundwater in the community to contamination and its inhabitants to water-borne diseases. Site-specific factors have been reported to have more influence on groundwater quality than seasonal effects in Finland (Korkka-Niemi, 2001). The concentration effects of microbes due to a decrease in water volumes may also be responsible for the increase in cell counts observed during the dry season (Dzodzomenyo et al., 2022; Thomas et al., 2011).

Health risk assessment

High counts of *E. coli* pose a great risk to human health, as it is associated with gastrointestinal diseases. It is, therefore, not far-fetched that the daily risk of infection ranged from 0.60 to 0.77, and the annual probability of infection and probability of illness was 1 for drinking water in all the communities. The daily risk of infections observed in this study is higher than 0.325 which was reported in Afikpo, Nigeria (Amatobi and Agunwamba, 2022), but the annual probability of infection is the same for both studies. A much lower daily risk of infection (6.9×10^{-6}) and annual risk of infection (2.5×10^{-3}) has been reported in Ghana (Yeboah et al., 2022). In another study by Barragán et al. (2021), a mean daily risk of illness of 6.29×10^{-3} and an annual risk of illness of 0.655 for ETEC (a related serotype of *E. coli* O157:H7) was reported in five rural areas of Villapinzon, Columbia; compared to this study, lower risk values were found in that study. The high risk of infection obtained in this study shows that there is an urgent need to protect groundwater sources in the four coastal communities sampled for this study.

Curiously, on one hand, residents of Essiama, Winneba, and Keta believe strongly that the groundwater sources in their communities are safe for domestic use (drinking, cooking, bathing, washing, etc.). Because of this belief, some of them consume groundwater directly from these sources without treatments such as boiling before consumption; on the other hand, residents of the Korle lagoon catchment area, are fully aware that groundwater sources in the area are not safe for domestic consumption. Hence, some members of the community use the water for only bathing and washing but rely on industrially-treated and packaged sachet water for drinking water. Irrespective of using the groundwater for bathing, the residents are still exposed to at least one *E. coli* cell every 141 days. This is higher than the acceptable risk level of 0.03-0.06/100 bathing events set by the U.S. EPA for recreational waters (U.S. EPA, 2012).

DALY represents the total burden of a disease in terms of mortality and morbidity. The estimated DALY for *E. coli* O157:H7 in this study was 0.49952 per person per year, which exceeded the set DALY of 10^{-5}-10^{-4} by the World Health Organization (WHO, 2008). The burden of disease for *E. coli* O157:H7 alone is higher than the total acceptable burden of disease per person per year. This implies that the pathogen has serious health consequences for members of the communities. One DALY indicated the loss of one year of full health (WHO, 2023a). A DALY of 0.49952 per person per year implies that about 182 days of full health are lost per person annually due to infection by *E. coli*, indicating increased morbidity and/or mortality, as well as reduced quality of life for the inhabitants of the study communities. This finding is similar to the findings of Machdar et al. (2013), where a DALY of 0.4 for *E. coli* O157:H7 was reported. Uprety et al. (2020) also observed DALYs higher than acceptable DALY in Nepal, particularly in the low-lying regions. There are several disease outcomes for *E. coli* ranging from mild diarrhoea, bloody diarrhoea, and hemolytic uremic syndrome, to end-stage renal disease. About 297,000 children under the age of five die each year from diarrhoea (WHO, 2019). Data on diarrhoea due to *E. coli* O157:H7 are, however, scarce, as in most cases, diarrhoea patients are not screened for the exact causative agents. Children below five years have a higher risk of developing hemolytic uremic syndrome (WHO, 2008). End-stage renal disease is also an important outcome of *E. coli* O157:H7 infection. A study in Ghana reported that 45% of renal disease death cases were due to end-stage renal disease (Adjei et al., 2019).

Conclusion

This study assessed the bacteriological quality of groundwater sources in Essiama, Wiineba, Accra, and Keta in Ghana, the seasonal variations in microbial contaminations, and the potential health risks associated with the use of these groundwater sources. The bacteriological quality assessment indicates that water from all groundwater points is not potable. The study showed that the presence of animals and their waste within a 10 m radius of the water, bad drainages, absence of aprons, absence of well covers, and use of ropes and buckets are common risk factors that predisposed groundwater to contamination in the studied locations. Seasonal variations in *E. coli* counts in Winneba and Accra were significantly higher in the dry season than in the wet season;

Essiama and Keta showed no significant seasonal variations. The annual risk of infection and illness from drinking groundwater in the communities was 1; and the estimated DALY far exceeded the WHO-acceptable DALY, implying a high disease burden. Urgent action is needed to protect groundwater sources in these coastal communities. Public education on the importance of environmental sanitation must be intensified. Lastly, artisanal masons must be trained to construct wells that are befitting of set standards.

CHAPTER FOUR

GROUNDWATER IN THE COASTAL AREAS OF GHANA: QUALITY AND ASSOCIATED HEALTH RISKS

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Abstract

Self-supply water sources, particularly groundwater sources, play key roles in the water supply ecosystem of developing countries. Recent studies indicate that groundwater sources in coastal communities in Ghana are under threat from improper waste management practices in the neighborhoods, seawater intrusion, and atmospheric aerosol deposition. In this study, the Water Quality Index (WQI) and Nemerow's Pollution Index (NPI) were employed to assess groundwater quality in four communities along the coast of Ghana. In addition, the health risks likely to be associated with metal pollution of groundwater were investigated using the incremental life cancer risk and the hazard quotient. pH of groundwater in all the studied communities was acidic during the rainy season. EC ranged from 0.44 to 2.61 mS/cm in the rainy season and from 0.43 to 2.45 mS/cm in the dry season for the four studied locations. Results also showed brackish conditions and mineralization of groundwater in Winneba, Accra, and Keta. Mean nitrate concentrations in Winneba and Accra were higher than the WHO standards for both the rainy and the dry seasons. Arsenic was higher than the acceptable level in Accra and Keta during the dry season, while iron was higher than the acceptable levels in Accra in both the rainy and dry seasons. Principal Component Analysis showed that Pb, As, and Fe had the highest loading in the first component in Essiama while phosphate and lead had the highest loading in the second component in Accra. WQI showed that the quality of groundwater in all the studied communities ranged from marginal to poor water quality indicating that groundwater in the coastal area often or usually departs from desirable levels. NPI revealed that nitrate, arsenic, and iron contribute to groundwater deterioration in the area. Health risk assessment showed that arsenic posed non-cancer health risks in Accra and Keta. The findings of this study showed that urgent regulations and monitoring strategies must be put in place to improve groundwater quality in the coastal areas of Ghana.

Keywords: Groundwater quality, water quality index, Nemerow's pollution index, cancer and non-cancer health risk assessment.

Introduction

Water supply is key to the development of resilient cities and communities, but global water supplies are dwindling. Currently, almost 50% of the global population lives in places where scarcity of water is experienced for at least one month annually (United Nations World Water Assessment Programme, 2018). The number of persons who experience water scarcity is expected to increase to 57% by 2050 (UN World Water Assessment Programme, 2018). Water scarcity is driven by an increase in water use due to population growth; an increase in the pollution of water resources; and a decrease in water resources (Boretti & Rosa, 2019). Water scarcity is already a major problem in developing countries (Boretti & Rosa, 2019). Future stress on water resources is expected to be higher in these countries due to population growth (Boretti & Rosa, 2019).

Self-supply of water plays a vital role in the water supply ecosystem of developing countries and has the potential to pivot the pace toward the achievement of SDG target 6.1 (Foster et al., 2021). Self-supply comprises water sources (both groundwater and rainwater) within the premises of individual households, that are owned and managed by these households

(Grönwall & Danert, 2020). Groundwater is the fastest-growing means of meeting water demands in sub-Saharan African cities; over 1.5 billion urban residents depend on groundwater for their water supplies (Foster et al., 2010). As is the case throughout the world, the majority of these sub-Saharan African cities are located in coastal areas where groundwater resources are vulnerable to the influence of seawater intrusion, atmospheric sea aerosol deposition, and pollution due to population pressure.

Since self-supply mechanisms play a key role in bridging the water supply gaps in urban, peri-urban, and rural areas, there is a need to include self-supply water sources in strategic planning. Concerted actions must be taken by water users and water managers of water resources to protect and effectively manage the key source of self-supply for communities. Because most self-supply sources are owned by individuals and are within their premises, they present opportunities such as willingness and ease to manage and protect them. Such management strategies require a clear understanding of the current state of groundwater resources and the possible risks posed to groundwater users. It also requires that water managers as well as groundwater users, as well as water managers understand the water quality data of their wells and boreholes. However, water quality parameters are numerous and data obtained from water quality measurements can be bulky. Also, a given source of water can meet the criteria for some parameters while not meeting others, making the communication of water quality information difficult. For these reasons, water quality indices (WQIs) are used in evaluating and communicating water quality data. The WQIs serve as tools for summarizing numerous water quality data into a single number that can be easily understood by a wide range of data users including water professionals and non-professionals (Canadian Council of Ministers of the Environment, 2017). Similarly, the Nemerow Pollution Index (NPI) is an effective tool for evaluating and communicating the overall water quality status to water users and policymakers (Shankar, 2018). It emphasizes the factors contributing most to the contamination of groundwater while considering the contribution of other factors (Su et al., 2022). The WQIs have been employed across the globe to assess and communicate water quality information (Adimalla & Qian, 2019; Adimalla, 2021; Akter et al., 2016; Faseyi, et al., 2022; Gao et al., 2020; Haider et al., 2019; Miyittah et al., 2020; UNEP GEMS/Water, 2007; Zhang et al., 2021).

In Ghana, the institutions in charge of water supply and distribution are overburdened and are unable to meet the needs of water users, hence, self-supply water from wells and private boreholes is common (Adams & Vásquez, 2019; Adams et al., 2016; Grönwall, 2016; Peprah et al., 2015). Furthermore, Ghana is currently experiencing a high rate of urbanization, particularly in its coastal areas, as four out of its six largest cities are situated along the coast (Owusu & Oteng-Ababio, 2015). The implication of this is that more pressure is mounted on water infrastructure in the coastal areas. The negative impact of such pressures is often borne by the poor. While water managers may routinely monitor the quality of water in their distribution lines, individuals served through self-supply mechanisms do not carry out such checks. One implication of this is that in cases where these self-supply sources are contaminated, water users will continue to consume water from these sources, which may lead to negative health consequences. Despite this, not much has been done to fully assess the quality of self-water supply sources in the coastal areas of Ghana.

Moreso, most studies have been focused on the use of hydrochemical plots, descriptive statistics, and other methods that provide information that are mostly only understood by scientists, and not the self-supply water users who need this information the most (Asare et al., 2021b; Asare et al., 2016; Awo et al., 2017; Daanoba et al., 2019; Fianko et al., 2010; Ketadzo et al., 2021). Indices such as the WQI and NPI that provide an overall picture and easy-to-understand information on self-supply water sources have found limited use in these areas. Furthermore, some studies have reported the contamination of groundwater sources in the coastal areas with heavy metals (Affum et al., 2015; Appiah-Opong et al., 2021; Avi et al., 2014; Dorleku et al., 2018; Ketadzo et al., 2021). However, the assessment of the health risks posed by heavy metals in the region regarding drinking water from groundwater sources is limited. Therefore, this study seeks to assess groundwater quality from self-supply water sources in the coastal areas of Ghana using a WQI and the Nemerow Pollution Index. The study also seeks to assess the health risks associated with the use of groundwater in the area.

Materials and Methods

Description of study sites

Four coastal communities (Essiama, Winneba, Korle Lagoon catchment of Accra, and Keta town) were selected for the study (Figure 11).

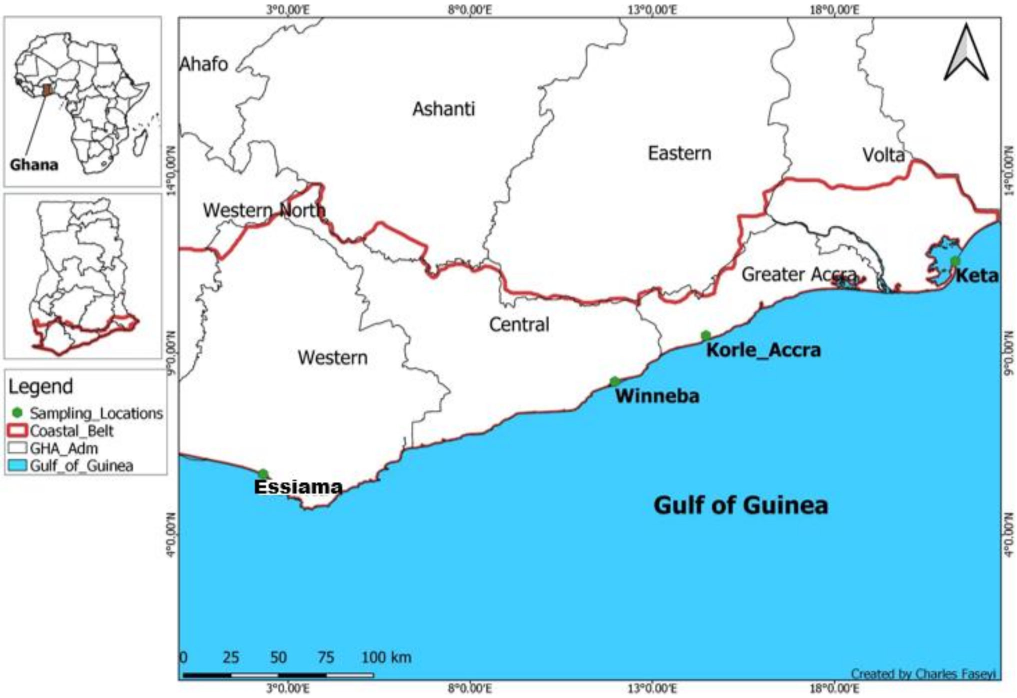

Figure 11: Map showing the study locations

Essiama is located in the Ellembelle district, in southwestern Ghana. The district lies within the wet semi-equatorial climate zone and experiences a bimodal rainfall regime with February to July as its peak and August to November as its trough (Aduah et al., 2015; Edjah et al., 2015). Mean temperatures range from 22-32 ^{o}C (Aduah et al., 2015). The town is mainly covered by moist semideciduous rainforest which has turned into a secondary forest due to activities such as tree felling (Edjah et al., 2015). The geology of Essiama is mainly of the Birimian Supergroup and the Apollonian group (Edjah et al., 2015, 2021). The Apollonian group consists of Cretaceous-Eocene marine sedimentary rocks such as siltstone, sandstone, shale, mudstone, conglomerate, and limestone which overlie the Birimian rocks (Kesse, 1985). Some of the shale rocks have iron sulfide content and are carbonaceous (Tsidzi, 1997). The Birimian rocks consist of evenly spaced N-E belts made up of both metasedimentary and metavolcanic rocks (Edjah et al., 2015). They are made up of alternating shales, phylitities, greywacke, and argillaceous beds with tuffs and lavas. The metavoltic rocks are of volcanic and pyroclastic origin (Edjah et al., 2015). The Birimian rocks are known to store considerable amounts of water that flows through foliations, joints, and fractures (Kesse, 1985). The major economic activities in the town are fishing, farming, trading, and services in the petrochemical and mining industries. The presence of petrochemical and mining industries in communities around Essiama has turned the town into a cosmopolitan town.

Winneba is located in the Central Region of Ghana and is the capital of Effutu Municipal Assembly. The town is 140 km east of Cape Coast. Winneba lies in the dry-equatorial climate zone and has a tropical climate (Dadson, 2012). The town has a long dry season of about 5 months. The rainfall regime is bimodal, with April to July being the peak months (Ankrah, 2020). Average temperatures range from 22℃ to 28℃ (Ankrah, 2020). The geology of the area is mainly of the Birimian Supergroup which comprises the metasediments which form a sedimentary basin, and metavolcanic rocks which form a volcanic belt (Nyarko et al., 2012). Granites and pegmatites intrude the metasediments (Nyarko et al., 2012). Fishing, trading, and services are the major economic activities in the town (Akutse & Samey, 2015; Ayeta et al., 2023b).

The Korle lagoon catchment area is situated in the southwestern part of Accra, the capital city of Ghana. The Korle Lagoon has a total surface area of approximately 0.6 km^2 while the catchment area drained by it is approximately 400 km^2 (Karikari et al., 2009). 60% of the floodwater of Accra is drained by the lagoon and its catchment area (Abraham et al., 2006). The Korle Lagoon lies in the tropical savannah climate zone which has a bimodal rainfall regime with the highest rainfall occurring between April and July (Clottey et al., 2022). Annual temperatures range from 27.6°C to 25.9°C (Clottey et al., 2022). The geology of the area is that of the Accraian series which consists mainly of sandstone, shale, and mudstone with some ironstone and grit (Antjony Woode, 2013; Clottey et al., 2022; Kutu et al., 2013). The Accraian series is part of the coastal sedimentary rocks. The area is home to popular slums such as Agbogbloshie, Old Fadama, Sabon Zongo, and Jamestown. In this study, samples were collected from Agbogbloshie, Old Fadama, and Jamestown.

Keta town is a municipality located in the southeastern part of Ghana (Figure 11). The municipality lies in the dry equatorial climate zone and has an average temperature of 28^{o}C (Kortatsi et al., 2005). The area experiences two rainfall regimes with the major rainy season occurring between April and July (Jørgensen & Banoeng-Yakubo, 2001). The Keta area falls within the Keta basin which is a Mesozoic/Tertiary sedimentary basin along the coast of the Gulf of Guinea and characterized by block-faulting (Jørgensen & Banoeng-Yakubo, 2001; Kesse, 1985). The basin mainly comprises sedimentary rocks formed in the Mesozoic/tertiary and comprising of Cretaceous – Eocene marine sediments: limestone, shale, and glauconitic sandstone exposed towards the east near the boundary between Ghana and Togo; and the Paleozoic era within the Lower to Middle Devonian period and comprises of marine shale, sandstone, and siltstone, overlain by Jurassic dolerites and sills (Akpati, 1978; Jørgensen & Banoeng-Yakubo, 2001). The Keta area is underlain by limestone which forms the lower layer of two limestone horizons in the subsurface of the Keta basin (Yidana et al., 2007). Fishing is the major economic activity in Keta while communities surrounding the town are involved in farming (Ayeta et al., 2023b). The town is also home to the largest lagoon in Ghana: the Keta Lagoon (Brempong et al., 2023).

Sample collection

Water samples were collected from wells and boreholes in each location for spatial and temporal comparison of physicochemical parameters, nutrients, and heavy metals. A total of thirty (30) water samples were collected in each community except in the Korle Lagoon catchment area where twenty-seven (27) samples were collected. For heavy metals, three (3) composite samples were collected from each community due to the high cost of analysis. This was done by dividing the number of the sampled wells and boreholes in each location into 3 equal parts and compositing equal volumes of water in each part. Salinity, pH, and Total Dissolved Solids (TDS) were measured *in situ* with the use of a EUTECH Multi-Parameter probe while turbidity was measured with an Oakton T-100 turbidimeter. Water samples for heavy metals and nutrients analysis were collected in pre-washed polyethylene bottles. All sample bottles were rinsed several times with the sampled water before about 500ml of water was collected. To prevent sampling stagnant water, hand-dug wells were sampled after the wells had been actively used by the communities (Lutterodt et al., 2021) while boreholes were purged for about 5 minutes before samples were collected. Samples for heavy metal analyses were preserved by the addition of 1 ml of concentrated nitric acid. This was to prevent the heavy metals from adsorbing onto the surface of the polyethylene bottles. Samples were stored at 4 ^{o}C and transported to the Laboratory of the Department of Fisheries and Aquatic Sciences, University of Cape Coast.

Laboratory analyses

Nitrate (NO_3) and phosphate (PO_4) were analyzed by the cadmium reduction and ascorbic acid methods, respectively, using the HACH DR 900 Spectrophotometer (Hach, 2017, 2019). To do this, 100 mL of groundwater samples were filtered through 0.45 µm pore size lead acetate paper into sterile sampling bottles. For each parameter, 10 mL of the filtered sample was transferred into a HACH sample cell followed by the addition of a reagent (NitraVer® 5 Nitrate reagent powder pillow and PhosVer 3 Phosphate powder pillow reagent for the analysis of NO_3- and PO_4, respectively). Samples for nitrates were then shaken for a minute and allowed to stand for 5 minutes to react while samples for phosphate were shaken for 30 seconds, and thereafter, left to react for 2 minutes. In all cases, a blank filtered water sample was used to calibrate the HACH-DR 900. The prepared samples were then placed in the cell holder of the HACH-DR and readings were taken at an absorbance of 520 nm and 880 nm, respectively for NO_3-N and PO_4. NO_3-N content in the samples was converted to NO_3 in mg/l by multiplying the reading by 4.43 (Hach, 2019).

Heavy metals (As, and Pb) were determined using Inductively Coupled Plasma - Mass Spectrometry (US EPA200.8) (Creed et al., 1994) while Fe was determined by Inductively Coupled Plasma- Optical Emission Spectrometry (APHA 3120B). The accuracy of analytical results was ensured by incorporating methods blanks and matrix spikes. The heavy metal analysis was performed at the SGS Laboratory in Accra.

Data analyses

Groundwater data from the four (4) study locations were analysed statistically for the mean ± standard deviation (SD) and range (min-max) Pearson correlation was used to assess the possible association/relation between the parameters (physicochemical and metal) measured in groundwater samples. Principal component analysis (PCA) was used to ascertain the contribution of physicochemical parameters and metals to variations in the dataset. Microsoft Excel and Past software (Version 4.13) were used for the analyses.

Water quality index

The Canadian Council of Ministers of the Environment (CCME) WQI was employed in this study. The choice of the CCME WQI was due to its flexibility as the parameters, time, and guidelines (standards to be used) are not defined. This makes it applicable in assessing the water quality in different regions, at different times, and in different water use scenarios. Parameters, standards and sampling time can be chosen based on prevailing local conditions, the purpose for which the water is used, and the existing water quality issues (Canadian Council of Ministers of the Environment, 2017). The CCME water quality categories are shown in Table 7.

In this study, seven (7) parameters (pH, TDS, turbidity, nitrate, As, Pb, and Fe) were used in estimating water quality and sampling was done for both the wet and the dry season. Although the CCME recommends that at least four parameters monitored at least four times be used in the estimation of water quality, it states that in some cases, monitoring can be done once per season.

Table 7: CCME water quality categories

WQI Category	Index Value	Description
Excellent	95-100	All measurements are within the objectives all the time
Good	80-94	Conditions rarely depart from desirable levels
Fair	65-79	Conditions sometimes depart from desirable levels
Marginal	45-64	Conditions often depart from desirable levels
Poor	0-44	Conditions usually depart from desirable levels

CCME- Canadian Council of Ministers of the Environment

Additionally, several samples (at least 27 in each community except for the heavy metals samples) were collected to compensate for any effects that the reduction in sample times might have.

CCME WQI was calculated as:

$$CCME - WQI = 100 - \frac{\sqrt{FI^2 + F2^2 + F3^2}}{1.732} \quad (8)$$

Where

$$F1 = Scope = \frac{Number\ of\ failed\ parameters}{Total\ number\ of\ parameters} \times 100$$

$$F2 = Frequency = \frac{Number\ of\ failed\ test}{Total\ number\ of\ test} \times 100$$

$$F3 = Amplitude = \frac{NSE}{0.01\ NSE + 0.01}$$

The scope represents the percentage of parameters that fail to meet the guideline at least once during the period under consideration; the frequency is the percentage of individual tests that fail to meet the guideline; and the amplitude is the amount by which the failed test values do not meet their guidelines. NSE is the normalized sum of excursion. The excursion represents the number of times by which an individual concentration is greater than the guideline. NSE was calculated as follows

$$\text{Excursion}_{i} = \left(\frac{\text{Failed test value}}{\text{Objective } j}\right)-1 \quad (9)$$

$$\text{NSE}= \sum_{i=1}^{n}\left(\frac{\text{Excursioni}}{\text{Number of tests}}\right) \quad (10)$$

Nemerow's pollution index

Nemerow's pollution index (NPI) is a simple pollution index that was introduced by Neme (Rathod et al., 2011) also referred to as Raw's pollution index. It unveils the extent of contamination for a given water quality parameter with reference to its standard/recommended value. The calculation and analysis of NPI values of different water quality parameters for an area help in the identification of principal contaminants in that area which is very useful for the enhancement of water quality in the area (Swati & Umesh, 2015).

Nemerow's pollution index is a very effective tool for communicating the overall water quality status to water users and policymakers (Shankar, 2018). It is also very useful in conveying raw environmental information to managers, decision-makers, technicians, and the general public (Caeiro et al., 2005).

NPI was calculated using the equation applied by (Rathod et al., 2011; Shankar, 2018; Swati & Umesh, 2015)

$$NPI = \frac{Ci}{Li} \quad (11)$$

Where:

Ci represents the measured concentration of the ith parameter while

Li represents the permissible limit of the ith parameter.

Each value of NPI represents the relative pollution contributed by a given parameter and should be less than or equal to one (Rathod et al., 2011). If the

NPI values exceed one for a given parameter, it is an indication of impurity (Rathod et al., 2011).

Health risk assessment

Cancer risk (CR) and hazard quotient (HQ) were respectively used to determine the carcinogenic and non-carcinogenic health risks of heavy metals in children and adults. As and Pb have been classified as group 1 and group 2A carcinogens, respectively, by the International Agency for Research on Cancer (International Agency for Research on Cancer, 2016). The carcinogenic risk of As and Pb was calculated using the formula described by ATSDR (2022)**.**

$$\text{CR} = \text{D} \times \text{SF} \times (ED/LY) \quad (12)$$

$$D = \frac{C \times IR \times EF}{BW} \quad (13)$$

Where D is the exposure dose (in mg/kg/day), SF is the cancer slope factor for the given heavy metal:1.5 × 10^{-3} for As and 8.5 × 10^{-3} for Pb (U.S. EPA IRIS, 2011), ED is the exposure duration (years), LY is the lifetime in years, C is the heavy metal concentration (mg/L), IR is the ingestion rate, EF is exposure factor (= 1 unitless; 1 because exposure is daily and chronic), and BW is body weight. Cancer risk was calculated for children aged 6 to < 11 years using ATSDR-recommended age-specific water intake rates and body weights of 0.455 L/day and 31.8 kg, respectively (ATSDR, 2023a, 2023b). For adults, incremental lifetime cancer risk was calculated using ingestion rate (= 2.2 L/day), exposure duration (= 70 years), and body weight (= 70 kg) (Wongsasuluk et al., 2014). A lifetime of 70 years was used in computing CR for both children and adults. When CR is equal to or less than 10^{-6}, it indicates that there is no concern for increased cancer risk. CR between 10^{-6} and 10^{-4} indicates that there is either a concern or no concern for increased cancer risk (further evaluation is needed; other factors need to be considered to make a decision). CR higher than 10^{-4} indicates a concern for increased cancer risk (ATSDR, 2022b).

The Hazard quotient (HQ) for As, Pb, and Fe was calculated using the formula described by ATSDR (2022).

$$HQ = \frac{D}{RfD} \tag{14}$$

Where RfD is the oral reference dose of the heavy metal in mg/kg/day. Established oral reference doses from U.S. EPA were used: 3.0×10^{-4} for As, 3.6×10^{-3} for Pb, and 7×10^{-1} for Fe (U.S. EPA IRIS, 2011). Hazard quotients less than 1 indicate that there is no risk of a non-cancer hazard, while hazard quotients greater than 1 indicate that there is a risk of non-cancer adverse health effects.

Results

Water quality parameters

The mean and range of values for all the parameters for both wet and dry seasons are presented in Table 8. Results of water quality analyses show acidic groundwater for all communities during the rainy season. The mean pH values of groundwater samples in all the studied communities were outside of the pH range recommended by the World Health Organization and below the lower limit of 6.5. A mean pH value of 3.22 was recorded for Essiama with a range between 0.26 and 6.54; in Winneba, a mean value of 4.08 and a range between 2.02 and 7.12 was recorded; in Accra, a mean of 3.11 and range between 0.00 and 7.20 was recorded while in Keta a mean of 4.57 and range between 2.43 and 8.43 was recorded. Dry season results show comparatively less acidic conditions in all communities with mean values reflecting neutral conditions and most values falling within acceptable standards for drinking water with the exception of Keta where values were slightly higher than the upper limit of 8.5. Values of pH ranged between 5.18 and 9.18 with a mean of 7.0 for Essiama. For Winneba, pH ranged from 7.70 to 8.77 with a mean of 8.25. For Accra, pH ranged from 5.55 to 9.05 with a mean of 7.67. Whereas, for Keta pH ranged between 8.05 and 9.22 with a mean of 8.54.

Similarly, mean values higher than the standard were recorded for electrical conductivity (EC) in Winneba (0.77-5.24 mS/cm, mean 2.54 mS/cm) and Accra (0.22-4.91 mS/cm, mean 2.61 mS/cm) during the rainy season. During the dry season, EC values for all the studied communities were at acceptable levels. Total dissolved solids (TDS) in Essiama was at an acceptable level for the two seasons. For the other study locations, the values for TDS were above acceptable levels for both seasons, although the rainy season values were generally higher than the dry season values. Mean turbidity was also above the acceptable level in most of the studied communities during the rainy season (except in Winneba), while during the dry season, mean turbidity was at acceptable levels in most of the studied communities (with Accra as the only exception).

Mean nitrate concentrations were found to be higher than the WHO standards in Winneba and Accra for both the rainy and the dry season while in Essiama and Keta the concentrations were at acceptable levels for both seasons.

In all the studied communities, lead was at an acceptable level during the rainy and dry seasons. Arsenic was however found to be higher than the acceptable level in Accra and Keta during the dry season, while iron was higher than the acceptable levels in Accra in both the rainy and dry seasons.

From the results, we conclude that variations exist in the water quality parameters (EC/TDS, Turbidity, pH, salinity) over the seasons and amongst the study sites. Average pH values indicate groundwater is acidic in the rainy season and less acidic in the dry season with more basic groundwater conditions in the Keta area. EC/TDS/Salinity values are higher in the rainy season than the dry season for Winneba and Accra, invariable over the seasons for Essiama, and high in the dry season for Keta. EC/TDS/Salinity values indicate mineralisation in the various aquifers under study. Groundwater in the studied communities may be contaminated with fecal matter; nitrate content is comparatively high in the rainy season with average values above the WHO standards for Keta and Accra.

Relationship between water quality parameters

Pearson correlation of physicochemical parameters and metals is presented in Figure 12-15. In almost all the studied communities, EC, TDS, and salinity had strong positive correlations as expected. In Essiama, there were strong positive correlations of pH with Pb and As, NO_3 with Pb and As, PO_4 with As, and Pb with As. Strong positive correlations were also recorded in Winneba for pH with As, and As with Pb. Also, in Accra, turbidity and Pb, PO_4, and Pb, and As and Pb had strong positive correlations while pH with As and Fe had strong negative correlations.

Table 8: Statistical summary of parameters metals concentration of groundwater sources in the coastal area of Ghana
*European Union Guideline; BDL: Below Detection Level; DL for Fe- 0.1 mg/L; DL for Pb and As- 0.5 µg/L

Parameters	Rainy				Dry				WHO 2017
	Essiama	Winneba	Accra	Keta	Essiama	Winneba	Accra	Keta	
pH	3.22±1.89	4.08±1.72	3.11±2.41	4.57±2.16	7.00±0.78	8.25±0.26	7.67±0.78	8.54±0.31	6.5–8.5
	0.26-6.54	2.02-7.12	0.00-7.20	2.43-8.43	5.18-9.18	7.70-8.77	5.55-9.05	8.05-9.22	
EC (mS/cm)	0.44±0.25	2.54±1.14	2.61±1.18	1.57±0.91	0.43±0.24	2.41±1.04	2.45±1.25	1.77±1.53	2.5*
	0.16-1.05	0.77-5.24	0.22-4.91	0.30-3.56	0.14-0.99	0.75-5.02	0.27-5.67	0.28-7.74	
TDS (g/L)	0.29±0.16	1.63±0.72	1.61±0.70	1.29±1.18	0.29±0.16	1.50±0.71	1.57±0.79	1.13±0.97	0.6
	0.10-0.97	0.49-3.30	0.14-3.14	0.19-5.86	0.091-0.64	0.11-3.16	0.18-3.57	0.18-4.87	
Salinity (ppt)	0.28±0.44	1.31±0.61	1.30±0.60	1.05±1.05	0.22±0.13	1.24±0.57	1.27±0.68	0.91±0.84	
	0.07-2.50	0.37-2.81	0.10-2.62	0.14-5.20	0.06-0.55	0.36-2.69	0.13-3.05	0.13-4.26	
Turbidity (NTU)	5.09±8.09	4.37±4.93	11.63±18.65	8.83±7.36	4.63±7.80	2.37±4.37	15.20±25.49	0.43±0.57	5.0
	0.00-27.00	0.00-18.00	0.00-60.00	0.00-24.00	0.00-39.00	0.00-18.00	0.00-114.00	0.00-2.70	
Phosphate (mg/L)	0.14±0.19	1.35±1.13	0.31±0.44	1.63±1.86	0.28±0.83	1.41±1.14	0.65±1.27	1.50±1.88	
	0.00-0.74	0.10-3.54	0.04-2.31	0.00-5.58	0.00-4.55	0.11-4.18	0.00-5.23	0.07-6.23	
Nitrate (mg/L)	37.10±31.19	135.41±66.87	92.24±80.72	40.76±52.51	46.74±43.65	150.50±67.17	74.56±88.40	41.95±50.13	50
	1.33-112.21	3.99-233.02	0.00-210.87	0.00-171.00	3.10-173.88	10.19-287.51	0.00-249.85	1.77-178.53	
Pb (mg/L)	BDL	BDL	BDL	BDL	0.0008±0.0003	0.0012±0.00	0.0006±0.00	0.0006±0.00	0.01
	BDL	BDL	BDL	BDL	0.0006-0.0011	BDL-0.0012	BDL-0.0006	BDL-0.0006	
As (mg/L)	BDL	BDL	0.01±0.00	BDL	0.005±0.002	0.0033±0.0020	0.062±0.00	0.011±0.00	0.01
	BDL	BDL	BDL-0.01	BDL	BDL-0.0067	0.0011-0.005	BDL-0.062	0.011-0.011	
Fe (mg/L)	0.27±0.21	0.1±0.00	3.65±1.06	0.15±0.07	0.10±0.00	BDL	1.27±2.02	0.30±0.17	0.3
	0.10-0.50	BDL-0.10	BDL-4.40	BDL-0.20	BDL-0.10	BDL	0.10-3.60	0.20-0.50	

There were strong positive correlations of pH with As in Keta groundwater sources.

Principal component biplots of groundwater quality variables are shown in Figure 16-19. In Essiama, PCA revealed that Component 1 explained 24.89% and Component 2 explained 20.94% of the 45.83% cumulative variance in the groundwater sources. Pb, As, and Fe had the highest loading in the first component while EC and TDS were highly loaded in the second component. A cumulative percentage variance of 57.17% was recorded for the first two components in Winneba, where Component 1 explained 36.65% and Component 2 explained 20.52% of the entire variance in the groundwater sources. The loadings of EC, TDS, and salinity were highly loaded in the first component whereas Pb and As were highly loaded in Component 2.

In Accra, Component 1 explained 31.07% while Component 2 explained 21.89% of the total variance in the dataset. Cumulatively, the first two (2) components in the principal component analysis of groundwater quality properties were responsible for about 52.96% of the variation in the system. Similar to Winneba, EC, TDS, and salinity were highly loaded in the first component. On the other hand, phosphate and lead were highly loaded in the second component. Of the 50.13% cumulative variance explained by the first 2 components in Keta, Component 1 was responsible for 29.94% and Component 2 was responsible for 20.19%. Like in the case of Winneba and Accra, EC, salinity, and TDS were highly loaded in the first component. As and Fe were highly loaded in the second component in Keta.

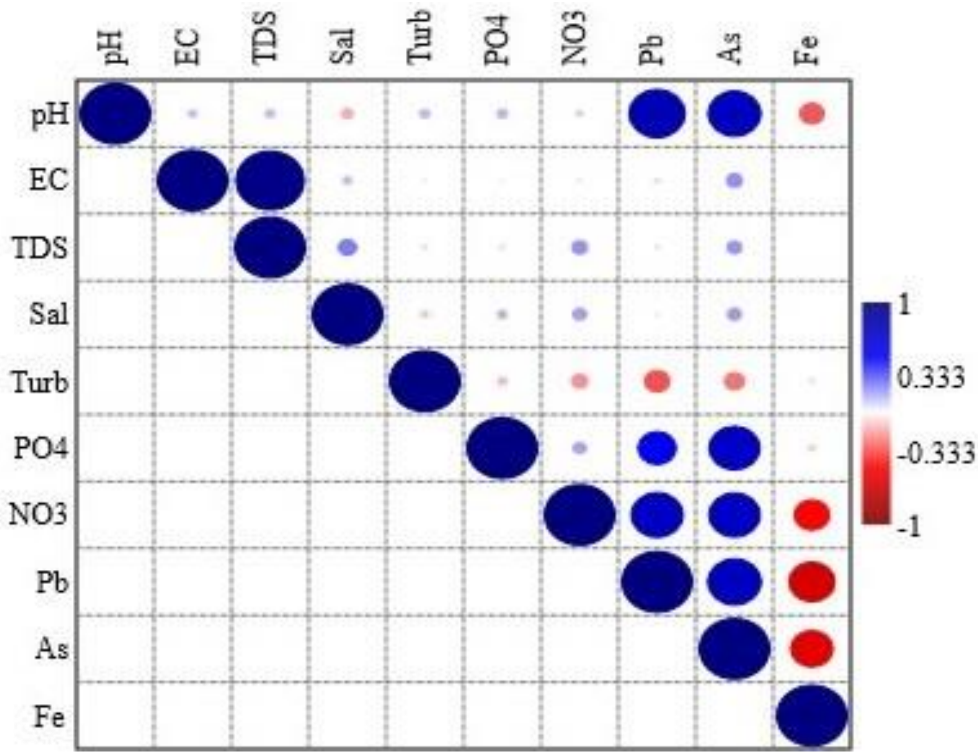

Figure 12: Pearson correlation of physicochemical parameters and metals of groundwater sources in Essiama

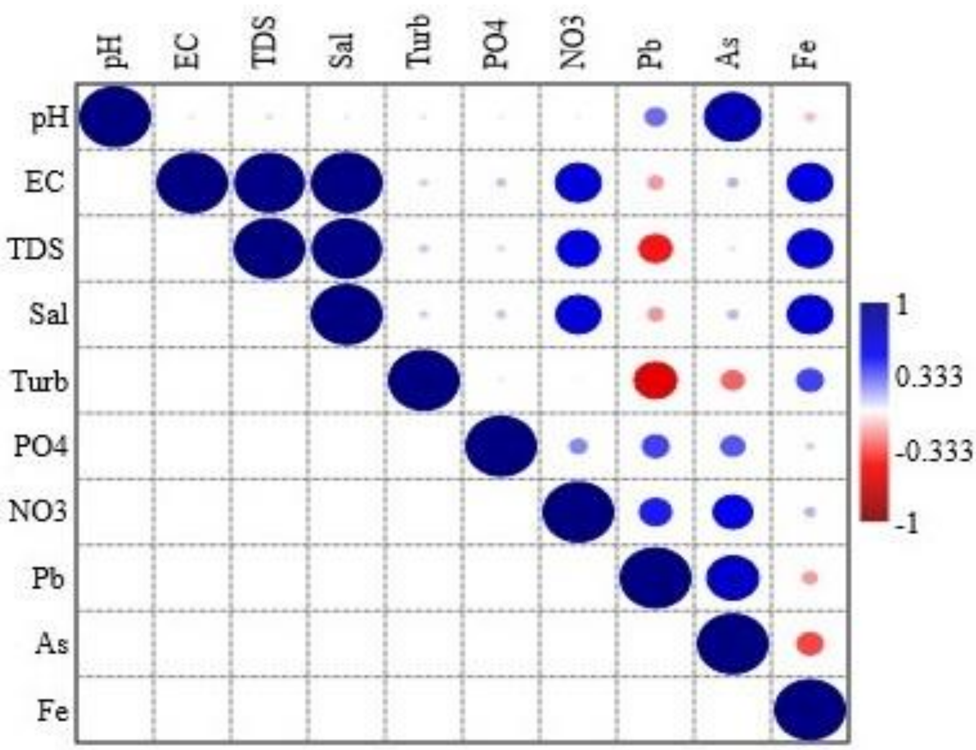

Figure 13: Pearson correlation of physicochemical parameters and metals of groundwater sources in Winneba

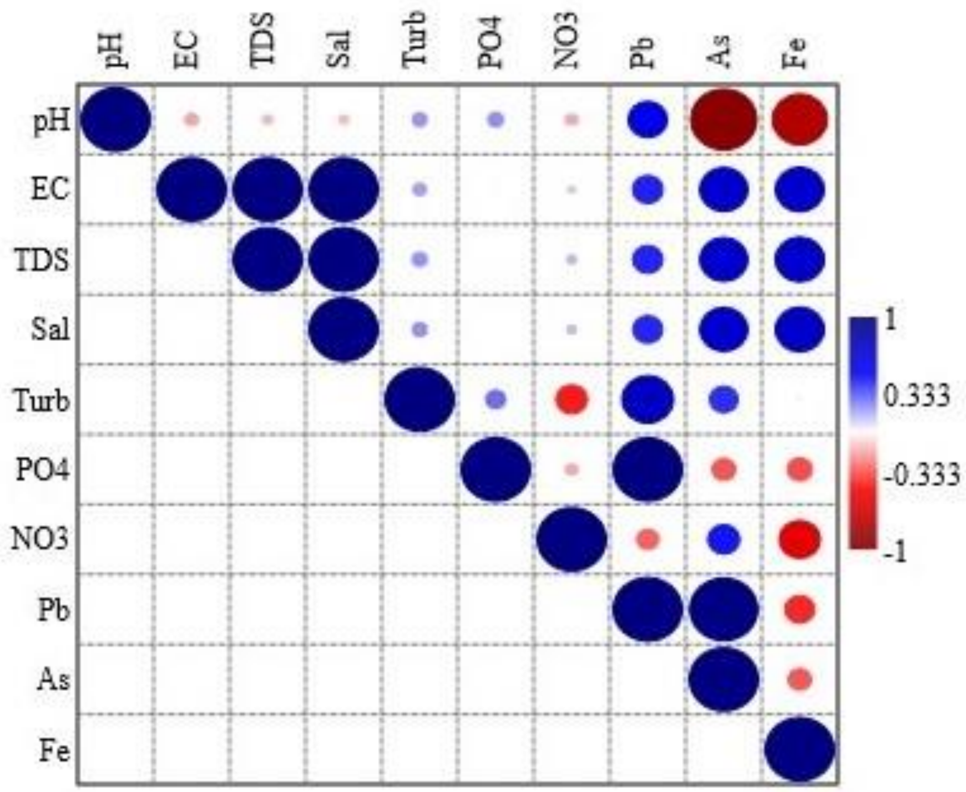

Figure 14: Pearson correlation of physicochemical parameters and metals of groundwater sources in Accra

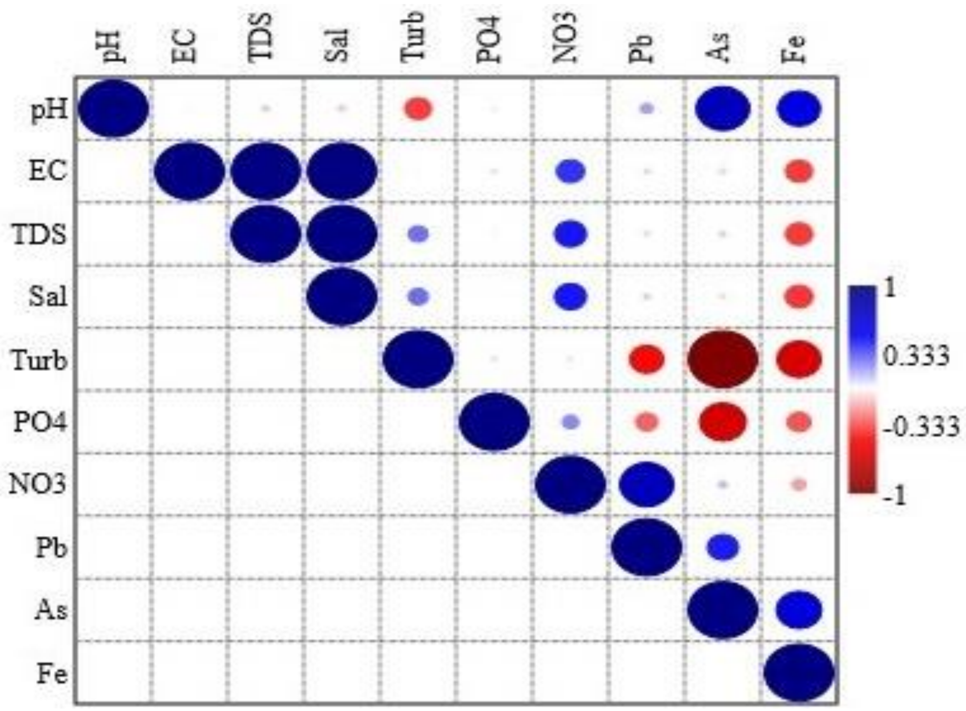

Figure 15: Pearson correlation of physicochemical parameters and metals of groundwater sources in Keta

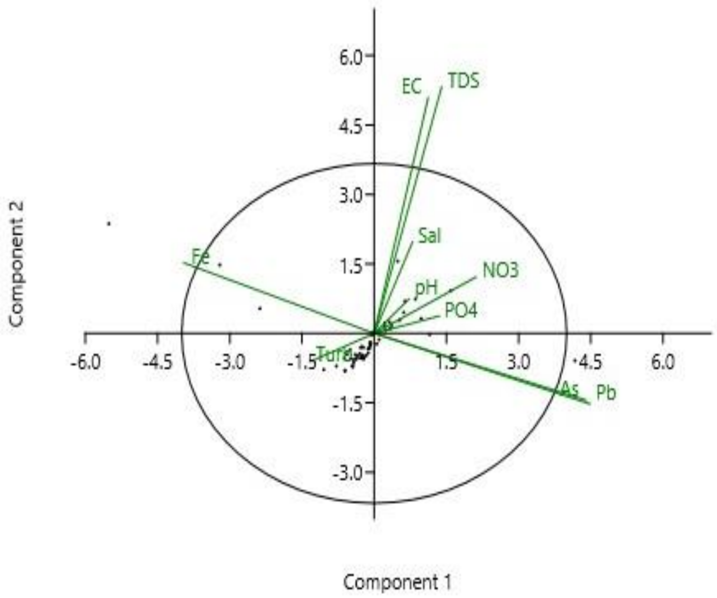

Figure 16: Principal component analysis biplots for physicochemical parameters and metals of groundwater sources in Essiama

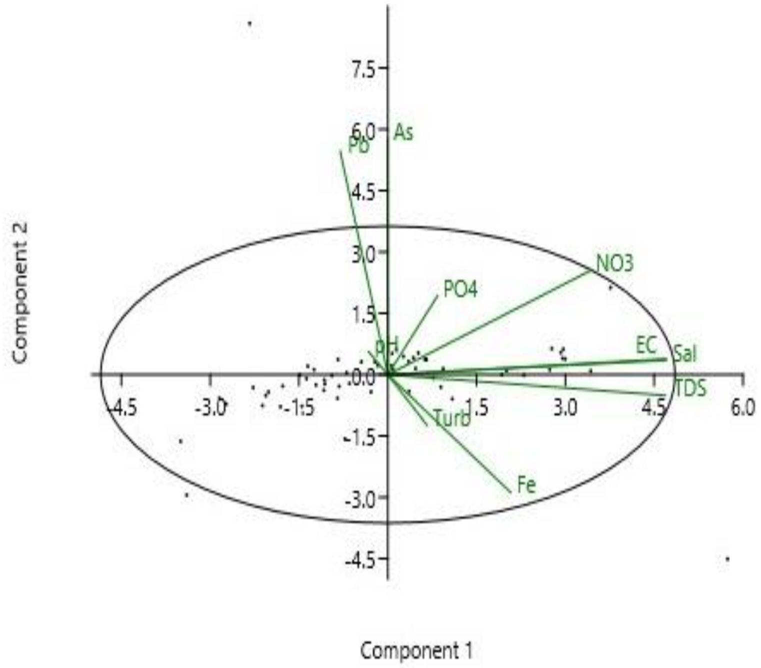

Figure 17: Principal component analysis biplots for physicochemical parameters and metals of groundwater sources in Winneba

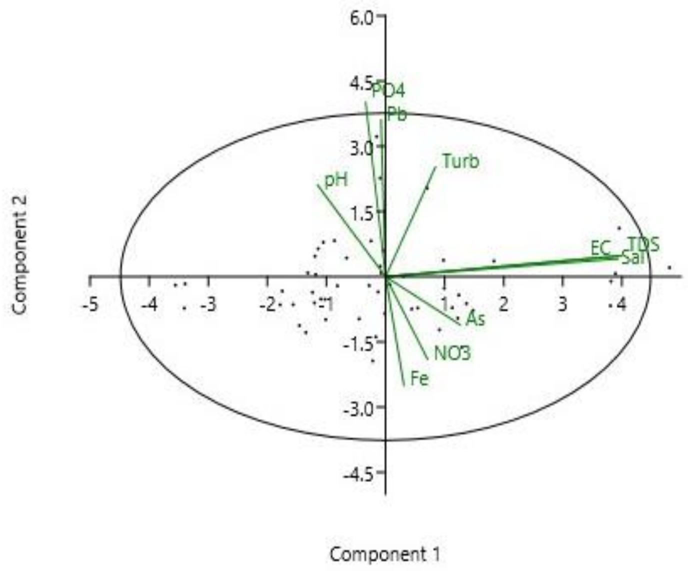

Figure 18: Principal component analysis biplots physicochemical parameters and metals of groundwater sources in Accra

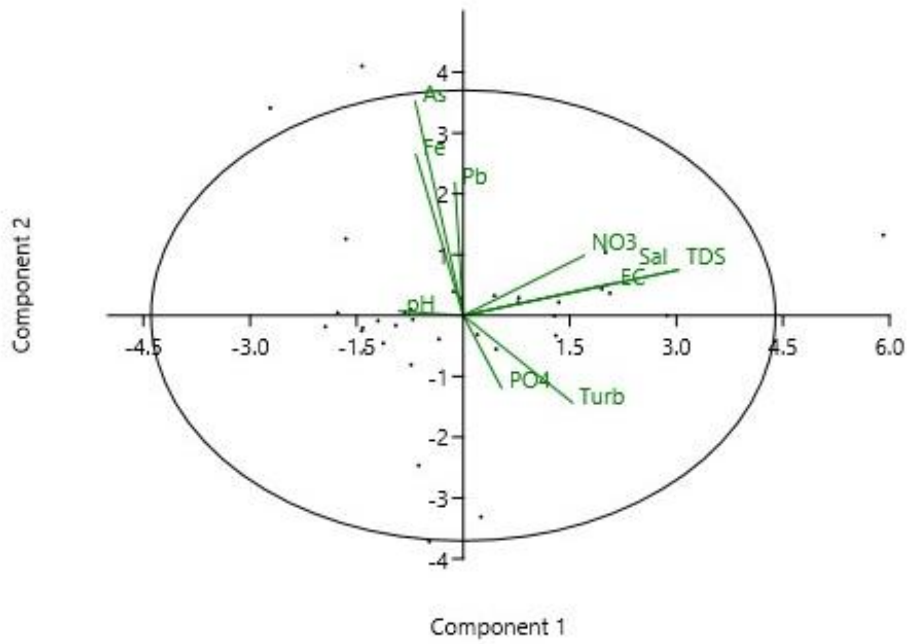

Figure 19: Principal component analysis biplots for physicochemical parameters and metals of groundwater sources in Keta

Water quality and pollution indicators

Details of the CCME-Water quality index of groundwater sources in the four locations along the coast of Ghana are shown in Table 9. The index showed that marginal water quality category was recorded in Essiama while the groundwater sources in Accra, Winneba, and Keta were categorised in the poor water quality category. Essiama recorded the highest CCME-WQI: (51.10), followed by Winneba (44.70) and Keta (40.00) while the least was recorded in Accra (32.20). The marginal groundwater quality recorded in Essiama indicates that groundwater in the community often departs from desirable levels. The poor groundwater quality recorded in Accra, Winneba, and Keta indicates that groundwater in these communities usually departs from desirable levels.

Results of the Nemerous Pollution Index (NPI) are shown in Table 10. Results showed that nitrate contributed to the pollution of groundwater sources in Winneba (rainy-2.71, dry-3.01) and Accra (rainy-1.84, dry-1.49), while arsenic only contributed to the contamination of groundwater in Accra (6.20) and Keta (1.10) in the dry season. Also, iron contributed to the contamination of groundwater sources in Accra in the rainy (12.17) and dry (4.23) seasons, and in Keta during the dry season (1.00).

Table 9: CCME-WQI of groundwater sources in the coastal area of Ghana

WQI	Locations			
	Essiama	**Winneba**	**Accra**	**Keta**
F1	71.40	57.10	85.70	85.70
F2	31.10	58.50	53.30	46.50
F3	33.00	49.70	60.00	35.90
CCME WQI	51.10	44.70	32.20	40.00
WQI Category	Marginal	Poor	Poor	Poor
Sum of Failed Tests	126.50	254.60	321.40	137.00
Normalized Sum of Excursion	0.50	1.00	1.50	0.60
Total Samples	60.00	60.00	50.00	60.00
Total Variables	7.00	7.00	7.00	7.00
Actual Variables Tested	7.00	7.00	7.00	7.00
Total Tests	257.00	258.00	214.00	245
Number of Failed Tests	80.00	151.00	114.00	114.00
Number of Passed Tests	177.00	107.00	100.00	131.00
Number of Less than Detected	8.00	13.00	10.00	8.00

CCME- Canadian Council of Ministers of the Environment; WQI- Water Quality Index; F1- Scope; F2- Frequency and F3- Amplitude

Table 10: Nemerow's Pollution Index (NPI) of groundwater sources in the coastal area of Ghana

Parameters	Rainy				Dry			
	Essiama	Winneba	Accra	Keta	Essiama	Winneba	Accra	Keta
Nitrate	0.74	**2.71**	**1.84**	0.82	0.93	**3.01**	**1.49**	0.84
Pb (mg/L)	0.12	0.00	0.00	0.00	0.08	0.12	0.06	0.06
As (mg/L)	0.00	0.00	0.00	0.22	0.50	0.33	**6.20**	**1.10**
Fe (mg/L)	0.90	0.33	**12.17**	0.50	0.33	0.00	**4.23**	**1.00**

Health risk assessment

The health risk associated with the use of groundwater sources in the studied communities is presented in Table 11. For adults, the incremental lifetime cancer risk (ILCR) recorded across the studied communities is 0 for both Pb and As in the rainy season except in Accra where an ILCR of 4.71×10^{-7} was recorded for As. On the other hand, during the dry season, an ILCR of 1.60×10^{-7} was recorded for Pb in Accra and Keta while Essiama and Winneba had ILCR of 2.14×10^{-7} and 3.21×10^{-7} respectively. For As, ILCR of 2.36×10^{-7}, 1.56×10^{-7}, 2.92×10^{-6}, and 5.19×10^{-7}, respectively, were recorded in Essiama, Winneba, Accra and Keta. Similar to the findings for adults, cancer risk in children aged 6 to < 11 years was 0 for both Pb and As across the studied communities in the rainy season except in Accra where a cancer risk of 1.53×10^{-8} was recorded for As. During the dry season, a cancer risk of 5.21×10^{-9} was recorded for Pb in Accra and Keta while Essiama and Winneba had a cancer risk of 6.95×10^{-9} and 1.04×10^{-8}, respectively. For As, cancer risk in children aged 6 to < 11 years was 7.67×10^{-9}, 5.06×10^{-9}, 9.50×10^{-8}, and 1.69×10^{-8}, respectively, in Essiama, Winneba, Accra and Keta.

For adults, a hazard quotient (HQ) of 0 was recorded for Pb and As across all the communities in the rainy season except in Accra where HQ for As was 1.05. For Fe, HQ was 1.21×10^{-2}, 4.49×10^{-3}, 1.64×10^{-1} and 6.74×10^{-3} in Essiama, Winneba, Accra, and Keta, respectively in the rainy season implying the absence of non-cancer risks. HQ for Pb was 6.98×10^{-3}, 1.05×10^{-2}, 5.24×10^{-3}, and 5.24×10^{-3} in Essiama, Winneba, Accra, and Keta, respectively during the dry season. HQ for As was 5.24×10^{-1}, 3.46×10^{-1}, 6.50, and 1.15 in Essiama, Winneba, Accra, and Keta, respectively while HQ for Fe were 4.49×10^{-3}, 0.00,

Table 11: Human health risk indicators of metals in the groundwater sources

Metal	Exposure Group	Rainy				Dry			
		Cancer Risk							
		Essiama	Winneba	Accra	Keta	Essiama	Winneba	Accra	Keta
Pb	Children	0.00	0.00	0.00	0.00	6.95×10^{-9}	1.04×10^{-8}	5.21×10^{-9}	5.21×10^{-9}
	Adult	0.00	0.00	0.00	0.00	2.14×10^{-7}	3.21×10^{-7}	1.60×10^{-7}	1.60×10^{-7}
As	Children	0.00	0.00	1.53×10^{-8}	0.00	7.67×10^{-9}	5.06×10^{-9}	9.50×10^{-8}	1.69×10^{-8}
	Adult	0.00	0.00	4.71×10^{-7}	0.00	2.36×10^{-7}	1.56×10^{-7}	2.92×10^{-6}	5.19×10^{-7}
		Hazard Quotient							
Pb	Children	0.00	0.00	0.00	0.00	3.18×10^{-3}	4.77×10^{-3}	2.38×10^{-3}	2.38×10^{-3}
	Adult	0.00	0.00	0.00	0.00	6.98×10^{-3}	1.05×10^{-2}	5.24×10^{-3}	5.24×10^{-3}
As	Children	0.00	0.00	4.77×10^{-1}	0.00	2.38×10^{-1}	1.57×10^{-1}	2.96	5.25×10^{-1}
	Adult	0.00	0.00	1.05	0.00	5.24×10^{-1}	3.46×10^{-1}	6.50	1.15
Fe	Children	5.52×10^{-3}	2.04×10^{-3}	7.46×10^{-2}	3.07×10^{-3}	2.04×10^{-3}	0.00	2.60×10^{-2}	6.13×10^{-3}
	Adult	1.21×10^{-2}	4.49×10^{-3}	1.64×10^{-1}	6.74×10^{-3}	4.49×10^{-3}	0.00	5.70×10^{-2}	1.35×10^{-2}

5.70×10^{-2} and 1.35×10^{-2}. HQ recorded for children for Pb, As, and Fe were less than 1 across the studied locations both during the rainy and the dry season, except in Accra where HQ of 2.96 was recorded for As during the dry season.

Discussion

Water quality parameters

The results of this study showed that seasonal variations exist in the water quality parameters and amongst the study sites. Groundwater in the study areas is mineralised with high EC/TDS/Salinity in addition to the presence of fecal matter in groundwater inferred by nitrates in water samples.

Groundwater was found to be acidic and near neutral pH conditions, respectively, during the rainy and dry seasons for the four coastal communities. These conditions have previously been reported in shallow (wells) and deep groundwater (boreholes) sources within communities along the coast of Ghana (Asare et al., 2021b; Ganyaglo et al., 2017; Lutterodt et al., 2021; Osiakwan et al., 2021; Zume et al., 2021) and have variously been attributed to wastewater infiltration (Lutterodt et al., 2021) and the geology (Asare et al., 2021b). In our case, we attribute the acidic conditions observed in the sources to both wastewater infiltration and dissolution of granitoid minerals. All four communities under study are densely populated municipalities and in many cases without proper wastewater management practices as is the case in many parts of Ghana (Rossiter et al., 2010). This assertion is reflected in the high nitrate content in groundwater sources within the Winneba and Accra areas. The sources of the nitrates may be poor sanitary conditions around the wells especially, the presence of pit latrines, septic tanks, and waste dumps that are located at short distances from the groundwater sources; a more common observation that affects groundwater quality in many high population communities (slums and peri-urban) in parts of the Sub-Saharan Africa region (Chaúque et al., 2021; Ferrante et al., 2018; Lutterodt et al., 2023). Septic tanks for example have been implicated as the main source of nitrate pollution in communities that lack central wastewater systems (Górski et al., 2019) as is the case in all four communities. Additionally, mineral dissolution might have contributed to the acidic conditions, especially within two of the communities (Winneba and Essiama) underlain by sediments intruded by granitoids which are known to produce acidic groundwater (Asare et al., 2021b).

Our results indicated that average EC values ranged between 0.44 and 2.61 mS/cm during the rainy season and from 0.43 to 2.45 mS/cm in the dry season for the four study locations. Note that as high as 7.74 mS/cm was measured in a well in Keta. These values can be considered to be fresh to brackish waters according to the classification scheme by (Park et al., 2012). From the results, only Essiama with an average EC of 0.44 and 0.43 (< 1 mS/cm) indicated fresh water according to the classification by Park and co-workers (2012). EC values for the rest of the communities showed brackish conditions i.e., 1.5 mS/cm < EC< 3 mS/cm (Park et al., 2012) indicating that groundwater in the three communities is mineralized. Our results are comparable to previous findings in coastal aquifers within the country. For instance, Zume et al. (2021) reported EC values in the range of 0.4 to 6.7 mS/cm and a mean of 1.85 mS/cm. Lutterodt et al. (2021) also reported EC values in the range of 0.2 to 2.7 mS/cm. Likewise, Asare et al. (2016) reported EC values in the range of 0.71 to 9.76 mS/cm, and a of mean 1.1 mS/cm. We attribute the brackish nature of water to the influence of the sea through seawater intrusion and/or deposition of atmospheric sea aerosol, dissolution of minerals, and infiltrating wastewater in the neighborhood of the wells. Similar, to our findings for Accra and Winneba; Norvivor (2017) reported higher values of EC/TDS in the wet season compared to the dry season in their work in the Keta area. It is difficult to explain the observed higher EC/salinity values in the rainy season compared to the dry season for Accra and Winneba; it is common for the vice versa to be observed and usually attributed to dilution in concentrations of chemicals and other physical water quality parameters during the wet season and evaporation in the dry season increasing concentrations of chemical parameters and physical quality values. We speculate the possibility of plug flow conditions within the neighborhood of the wells: low chemical content recharging water pushing stagnant and chemically modified water into wells.

The high turbidity recorded for most of the study locations in the rainy season may be due to the effects of runoff, seepage, and re-suspension of particles which may be due to the effect of groundwater flow rate changes in the neighborhood of the wells. Some of the wells in the study locations lack wellheads, a condition that can lead to the direct inflow of runoff into those wells; this was a common incidence in Keta, in addition to the shallow nature of the water table in the study area in Accra. Apart from the Accra area which recorded high average turbidity in the dry season compared to the rainy season values, the observation for the rest of the communities was vice versa. Turbidity is known to affect the acceptability/potability of water and can pose a health concern, as the suspended particles in turbid water can serve as food, shelter, and surfaces for the attachment of microbes, thus aiding their survival (U.S.

Geological Survey, 2018c). Furthermore, suspended particles can provide attachment for heavy metals. High turbidity values for the other three communities during the rainy season can be linked to two possibilities: (1) direct inflow of run-off water into especially large diameter hand-dug wells that lack protective apron walls which was a common observation in the Keta area. Note that the Keta area is known to experience seasonal flooding (Awo et al., 2017) and therefore compliments the assertion that run-off may flow directly into some of the wells, and/or (2) rapid changes in hydrodynamic conditions within the aquifer in the neighborhood of the wells and boreholes during the rainy season. Increased groundwater flow rates can result in the dislodging of sediments from the surfaces of aquifer media and re-suspension of these sediments together with quartz colloids in water within groundwater flow lines. Note that, the two communities (Accra and Keta) that observed high turbidity in groundwater samples are underlain by sedimentary rocks. For example, the Keta area is made up of unconsolidated sediments with a high possibility of entrainment of these loosely held sediments into flowing water during the wet season. Awo et al. (2017) made similar findings in the Keta area. The high turbidity recorded in wells in Accra during the dry season cannot be explained, we speculate the possible seepage of wastewater into the shallow groundwater system of the area. Note that in the Agbogbloshie area, the depth to the water surface is short and close to the surface (< 0.3 m by visual inspection). Given the e-waste recycling in Agbogbloshie, which made it rank among the top ten most polluted areas in the world in 2013 (Blacksmith Institute, 2013), and the wastewater that flows freely through the area, groundwater in the area appears to be more vulnerable.

The high As content in groundwater samples in the Agbogbloshie area of Accra can be attributed to the e-waste recycling site. Previous studies in the area indicate significant enrichment of the soils in the area with As (Fosu-Mensah et al., 2017). The high concentrations of iron in Accra (Table 8) may be due to the natural sources, as the Accraian series which underlies the area contains some ironstone (Kutu et al., 2013). In addition, high iron levels in groundwater are a common situation in Ghana (Plumpton et al., 2020).

Generally groundwater quality was better during the dry season than the rainy season as most water quality parameters were within the WHO acceptable standard during the dry season. The pollution of groundwater during the rainy season can be attributed to wastewater infiltration, seepage of effluents from waste dumps, and direct run-off into wells with shallow depths to water surface as is the case in the communities under study.

Relationship between water quality parameters

The strong correlations between the various physicochemical parameters and metal concentrations (Figure 12-15) showed that there are associations between these parameters. Strong correlations between TDS, EC, and salinity are expected due to their theoretical links (Lutterodt et al., 2021). The ability of water to conduct electricity (electrical conductivity) increases as the amount of dissolved salts (salinity) in it increases. Similarly, measurements of electrical conductivity and salinity are strongly correlated with total dissolved solids, although the relationship is not directly linear (Rusydi, 2018).

Strong associations were also observed between pH and heavy metals. pH influences the movement of heavy metals into groundwater. Acidic conditions favour the leaching of heavy metals into groundwater (Król et al., 2020).

The high loading of EC, TDS, and salinity in Component 1 of Winneba, Accra, and Keta (Figure 16-19) is expected as the areas under study are coastal communities which often have high salt contents when compared to inland areas. However, the high loading of Pb, As, and Fe in Component 1 of Essiama may be due to the mining activities in neighbouring towns around the community. Nkroful and the Ankobra River Basin are major mining locations situated around Essiama. Mining as a major anthropogenic activity resulting in ground and surface water pollution has been reported in the area (Acheampong & Nukpezah, 2016; Faseyi et al., 2022).

The high loading of heavy metals in the second component in Winneba, Accra, and Keta (Figure 16-19) may be due to both geogenic and anthropogenic sources. Arsenic is an important geogenic groundwater contaminant; it affects millions of people in every continent in the world (UN Water, 2022). Anthropogenic pollution of groundwater results from agricultural activities, urbanization, increase in population, industrialization, and climate change.

The high loading of phosphate in Component 2 in Accra (Figure 18) may be due to the indiscriminate discharge of human, industrial, and household wastes in the area. Urbanization has a strong link with phosphate contamination of groundwater (Huang et al., 2020). The Korle lagoon catchment area of Accra is densely populated and lacks adequate toilet facilities; urine, kitchen waste, and other household wastes are often emptied into faulty water drains found within the area. Furthermore, the Odaw River which drains the area also drains some major industrial areas upstream. This may also serve as a conduit for contaminants to groundwater within the river basin.

Water quality and pollution indicators

The water quality category in this study ranged from poor to marginal category with implications for groundwater use for domestic purposes. The poor water quality category recorded in the Accra Korle-Lagoon Catchment may be due to the poor sanitary conditions in the area which result from improper waste management, high population density, and urbanization. Agbogbloshie, Old Fadama, and James Town in Accra where water samples were collected are characterized by informal settlements and inadequate sanitation infrastructure (Aglanu & Appiah, 2014). The poor water quality in Winneba may also have resulted from poor sanitation and siting of groundwater sources near septic tanks while the poor water quality recorded in Keta may be due to the absence of well covers and construction of wells without aprons. The marginal water quality category in Essiama could be a result of mining activities in the area. The results of PCA where Essiama was the only study location that had heavy metals loaded in the first component support this. Mining wastes have been reported to be associated with the contamination of groundwater in the western region of Ghana (Abanyie et al., 2023; Ato et al., 2010; Bhattacharya et al., 2012; Faseyi et al., 2023). Similar to the finding of this study, Egbi et al. (2019) reported marginal and poor groundwater quality for some groundwater sources in South Tongu and Ada East of Ghana. Poor and marginal groundwater quality categories have also been reported by workers in other jurisdictions (Al-Hamdani et al., 2021; Wagh et al., 2017).

The contribution of nitrate to the contamination of Winneba and Accra groundwater sources in both rainy and dry seasons is an indication of pollution from sewage waste disposals and improper siting of groundwater sources, especially wells and boreholes. The contribution of Fe and As to the contamination of Keta may be due to the natural enrichment of the underlying rock materials with these metals as there are no known human activities in the community that can result in such enrichment. Whereas, in Accra, the contribution of As to groundwater contamination may be due to both natural and anthropogenic sources as Agbogbloshie is a notable E-waste hub in Ghana. The contribution of Fe to the contamination of groundwater in Accra may be due to the naturally high Fe concentrations in most aquifers in Ghana (Plumpton et al., 2020).

Health risk assessment

Results of health risk assessment showed that there was no potential cancer and non-cancer risk for Pb in children and adults who consume groundwater in all the study locations and seasons. Mohammadi et al. (2019) who obtained hazard quotient values of 7.17×10^{-5} observed similar results for non-cancer risk of lead in Iran, but contrary to our findings, they observed potential cancer risk with a mean ILCR of 8.54×10^{-4}. Lead has been implicated in abnormal brain development, intellectual disability, anaemia, kidney diseases, hypertension, immunotoxicity, and toxicity to the reproductive system (WHO, 2022c).

In this study, HQ for iron was below 1 for both children and adults, showing that it had no significant non-cancer risk. This is similar to the findings of Luvhimbi et al. (2022) who reported an HQ value of 7.68×10^{-4}. The findings, however, contradict the findings of Maigari et al. (2016) in groundwater in Dadinkowa dam and Kwadon, Nigeria who reported HQ values of 1.27. Iron is an essential nutrient for humans, but excess iron in drinking water can affect its aesthetic quality and lead to health disorders such as cardiovascular diseases, Parkinson's disease, diabetes, Huntington disease, hyperkeratosis, body pigmentation, alzheimer's disease, kidney, liver, respiratory and neurological disorders (Ghosh et al., 2020).

Cancer risk estimate for arsenic in Accra showed that further evaluation is needed to decide whether or not arsenic poses a concern for increased cancer risk as ILCR was 2.92×10^{-6} (between 10^{-6} and 10^{-4}). Other factors such as how much natural background contributes to cancer risk, how much anthropogenic background contributes to cancer risk, and the availability of reliable health outcome data on cancer rates for the exposed population need to be considered to make a decision (ATSDR, 2022b). HQ estimation showed that arsenic poses non-cancer adverse health risks in Accra (for both children and adults) and Keta (for adults). Similar to our findings, Shah et al. (2020) observed non-cancer health risks in their study on groundwater in Pakistan with a mean hazard quotient of 3.9. Zhang et al. (2022) also reported a similar trend in groundwater in China. Arsenic is the most significant chemical contaminant in drinking water globally (WHO, 2022a). Arsenic has been classified as a Group I carcinogen. Prolonged exposures to arsenic can lead to cancer of the bladder, skin, lungs, liver, digestive tract, and lymphatic system (National Cancer Institute, 2022). Non-cancer-related effects of arsenic include adverse pregnancy outcomes, developmental impairment, lung diseases, diabetes, and arsenic-induced myocardial infarction (WHO, 2022a).

Conclusion

The current study assessed groundwater quality and associated health risks in four (4) coastal communities in Ghana. Turbidity, EC, TDS, nitrate, and As in the study locations were generally above WHO standard limits during the rainy season in some of the studied communities. Results of EC showed that groundwater in Essiama was fresh while that of the other Winneba, Accra, and Keta is brackish and mineralized. CCME-WQI also showed that groundwater quality in the studied communities ranged from marginal to poor water quality categories. Nemerow's Pollution Index showed that nitrate, arsenic, and iron are important groundwater contaminants in some of the studied communities. Health risk assessment showed that As poses non-cancer health risks in some of the studied communities. Urgent regulations and monitoring strategies must be put in place to improve groundwater quality in the coastal area of Ghana.

CHAPTER FIVE

GROUNDWATER GOVERNANCE AND A SNAPSHOT OF ASSOCIATED ISSUES IN SELECTED COASTAL COMMUNITIES IN GHANA

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Abstract

Groundwater is an important freshwater resource worldwide, particularly in coastal communities where freshwater is scarce, but often ignored. In Ghana, there is increasing dependence on groundwater, yet assessment of groundwater governance is rare. This study assessed the status of groundwater governance and identified existing gaps in Ghana. Also, groundwater-associated issues in four coastal communities (Essiama, Winneba, Korle Lagoon catchment area of Accra, and Keta) were assessed. Policy document review and expert-based assessment were employed to assess groundwater governance status and gaps while field observations, focus group discussions with community leaders, risk-priority matrix, and Nemerow's pollution index were employed to obtain a snapshot of local conditions that impact groundwater at the community level. Policy document review and expert-based assessment of groundwater governance capacity showed that technical capacity, cross-sector policy coordination, and operational capacity were incipient while legal and institutional capacity was acceptable. Overall groundwater governance capacity in Ghana was shown to be incipient. Major gaps identified were (i) low enforcement of groundwater policies, (ii) poor monitoring, (iii) poor technical and operational capacity, (iv) low cooperation within the water sector and across other sectors, and (v) poor public participation in water governance. The study revealed groundwater as an important resource in the studied coastal communities, where accessing potable water comes with some difficulties. Also, knowledge of groundwater policies was low within the communities and there was no groundwater monitoring network in the communities. Furthermore, poor microbiological and chemical status of groundwater was observed. These findings suggest a need to build capacity in groundwater governance and to ensure robust public education on groundwater governance in Ghana.

Keywords: Governance capacity, groundwater governance, coastal communities, expert-based assessment, SDG 6.

Introduction

Groundwater is a source of water for over 2.5 billion people globally (Shaji et al., 2021). It is a crucial freshwater resource worldwide, yet, it is often neglected (Foster & Cherlet, 2014; Vadiati et al., 2018). Many communities depend on ecosystems that are sustained by groundwater. Yet this important water resource is faced with precarious problems like over-abstraction and pollution (Lall et al., 2020; Shaji et al., 2021). Notwithstanding these numerous problems, groundwater can be managed through proper governance systems. While several countries have adopted the integrated water resources management framework, the groundwater component of these frameworks is often missing (Wijnen et al., 2012). In most cases where the frameworks are present, their implementation is often a challenge. Indeed, the innate characteristics of groundwater (invisibility and ease of individual exploitation) make its management more challenging and complicated when compared to surface water (Lall et al., 2020; Oguama et al., 2019). Despite these challenges, the discourse on groundwater governance has continued to expand as the relevance of groundwater is more glaring in the face of the increasing global water crisis (Gudaga et al., 2018a). The Groundwater Governance Project defined groundwater governance as “the promotion of responsible collective action to ensure control, protection and socially-sustainable utilisation of groundwater resources and aquifer systems for the benefit of mankind and dependent ecosystems" (FAO, 2016b). Groundwater governance is well ingrained in developed countries, whereas it is either weak or non-existent in many parts of the world, particularly in developing countries (FAO, 2016a).

Groundwater governance is dependent on local needs and conditions which differ greatly across the globe. For instance, Ananda and Aheeyar (2020) reported that the absence of formal institutions in charge of groundwater management and ill-defined well rights were the major problems hampering sustainable groundwater use in India, while Molle et al. (2017) reported that the fragmentation of agencies and lack of technical capacity were major challenges preventing effective groundwater governance in Lebanon. In the case of the Grootfontein aquifer in South Africa, inadequate governance arrangements were the major impediment to the potential of groundwater as a sustainable source of water supply despite in-depth knowledge of the hydrogeological properties of the aquifer (Cobbing & De Wit, 2018). It is seemingly clear that the assessment of groundwater management practices is vital in evaluating the effectiveness of existing frameworks and unraveling gaps and opportunities for groundwater governance (Akhmouch & Clavreul, 2018). There is a dearth of information on groundwater governance structures, frameworks, and institutions in Ghana. The literature is rather scant with few studies on groundwater governance in Ghana that have focused on water users and water resource governance in general (Frimpong et al., 2021; Kankam-Yeboah et al., 2011). Grönwall's (2016) work on groundwater governance which included water users and management institutions was also limited to a peri-urban town:

Dodowa. This study, therefore, sought to answer the following research questions: (i) what is the status of groundwater governance in Ghana? and (ii) what are the issues and local conditions that affect groundwater quality, use, and management in the coastal communities of Ghana? The study provides empirical data on groundwater governance in Ghana and guides policymakers and stakeholders to prioritize groundwater protection initiatives in needed areas. Additionally, it bridges the gap between science, policy, and the community, as groundwater research in Ghana has been mainly focused on microbial, physicochemical quality, hydrochemical, and hydrogeological appraisal of aquifers (Foppen et al., 2020; Opoku et al., 2020). Furthermore, by shifting attention to groundwater governance, this research would help to expand the debate on policy and institutional design which has been long confined to surface water in the country.

Materials and Methods

Conceptual framework

The conceptual framework of the study (Figure 20) is based on the premise that the assessment of the quality of groundwater and groundwater governance are interdependent (de Chaisemartin et al., 2017b). While groundwater assessment provides a sound knowledge of the quality of the resource, which is important in ensuring its effective management, groundwater governance provides the framework for groundwater monitoring and assessment (de Chaisemartin et al., 2017b). Adequate groundwater governance and assessment help to unveil the pollution status of groundwater and curtail activities that lead to groundwater pollution, which consequently helps to improve groundwater quality. Improvements in groundwater quality ultimately lead to the achievement of SDG 3 (target 3.3: '….end water-borne diseases'; target 3.9: 'reduce deaths and illnesses from….water…..pollution and contamination') and SDG 6 (target 6.1: 'access to safe and affordable drinking water for all'; target 6.3: 'improve water quality by reducing pollution'; and target 6.6: 'protect and restore water-related ecosystems including aquifers').

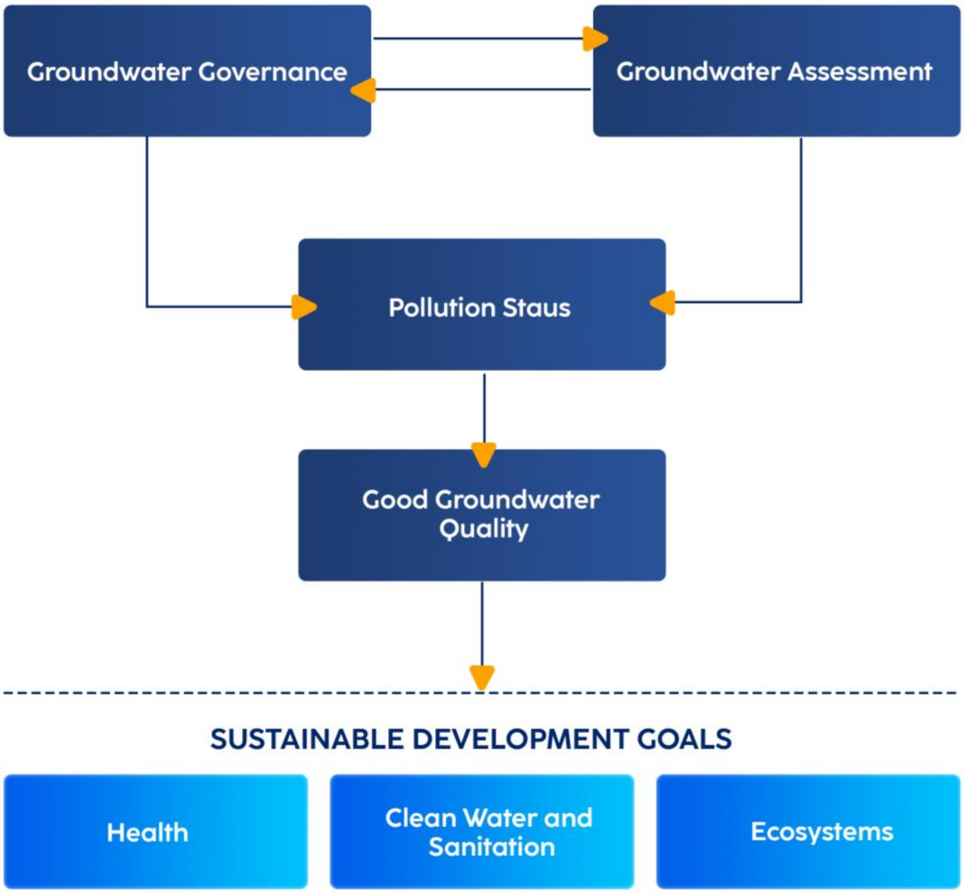

Figure 20: Conceptual framework of groundwater governance

Groundwater resource setting in Ghana

Groundwater in Ghana occurs in three major geological formations: (i) the basement complex, which covers about 54% of the country; (ii) the consolidated sedimentary formations, which cover about 45% of the country;

and (iii) the Mesozoic and Cenozoic sedimentary rocks, which cover about 1% of the country and are found in the extreme southwestern and southeastern corridors, along the coast of Ghana (Water Resources Commission, 2023). About 41% of Ghanaian households depend on groundwater; more than 95% of the total groundwater use is for domestic purposes (Plumpton et al., 2020).

Description of study locations

To have a snapshot of issues on local conditions surrounding groundwater in the coastal zone of Ghana, four coastal communities were studied (Figure 21). The study focused on the coastal zone because it is home to one-fourth of the population of Ghana and represents one of the areas identified to have problems with groundwater quality due to increased mineralization and saltwater intrusion. One coastal urban community was selected from each of the four administrative regions along the coast of Ghana namely: Essiama (Western Region); Winneba (Central Region); Korle Lagoon catchment area of Accra (Greater Accra Region); and Keta (Volta Region). Western and Greater Accra Regions are highly industrialized, while Central and Volta Regions are less industrialized.

Essiama is located in the Ellembelle District. The town has grown to become a cosmopolitan town due to the presence of petrochemical and mining industries in its neighboring towns. The town has a projected population of 13,161 for the year 2023 (Ghana Statistical Services, 2023). The major occupations of its residents are fishing, farming, trading, and services in the petrochemical and mining industries.

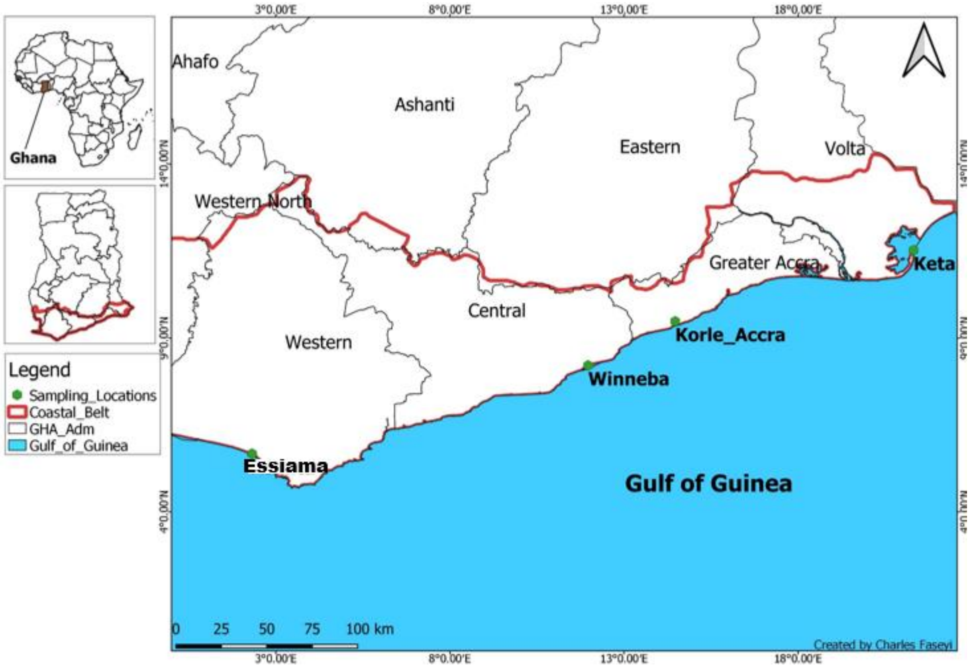

Figure 21: Map showing the study locations

Winneba is the capital of Effutu Municipal Assembly. Fishing is the main occupation of the population (Akutse & Samey, 2015). A baseline study in the community by USAID and *Hen mpoano*, a Ghanaian NGO, revealed that a major problem faced by the community is poor sanitation, leading to the outbreak of diseases such as cholera and typhoid (Akutse & Samey, 2015).

Keta is the capital of the Keta Municipal Assembly. The town is located near the Volta estuary and lies on a sand spit between the Keta Lagoon and the Atlantic Ocean (Hillmann & Spaan, 2017). The main livelihood activities of Keta residents are farming, fishing, copra production, salt production, and trading (Hillmann & Spaan, 2017). Keta is plagued with environmental issues that range from coastal erosion, subsidence, groundwater pollution, and groundwater depletion due to groundwater extraction for salt production (Hillmann & Spaan, 2017).

Korle lagoon catchment area is situated in the southwestern part of Accra, the capital of Ghana. The area houses about 60% of the city's population;

settlements in the area are mainly slums (Abraham et al., 2006; Ketadzo et al., 2021). Specifically, Old Fadama, Agbogbloshie, and James Town were selected for the study. Like most slums, these settlements lack access to clean water and basic sanitation facilities.

Data collection

Ethical approval (ethical approval ID- UCCIRB/CANS/2022/13) was given by the University of Cape Coast Institutional Review Board, Ghana, to undertake this study. An embedded mixed-method approach was employed in the study.

Groundwater governance in Ghana

A checklist developed by Foster et al. (2009) was adapted and used to assess the status of groundwater governance. The checklist was developed based on the experience of the Groundwater Management Advisory Team (GW.MATE) in assessing groundwater governance. To gather the needed information, a comprehensive review of the policies and legal framework, and an expert-based assessment of groundwater governance was carried out. Water experts from stakeholder agencies and institutions – Water Resources Commission (WRC), Environmental Protection Agency (EPA), Public Utilities Regulatory Commission (PURC), Community Water and Sanitation Agency (CWSA), Ministry of Sanitation and Water Resources, Council for Scientific and Industrial Research-Water Research Institute (CSIR-WRI), Ghana Atomic Energy Commission (GAEC), Coalition of Non-Governmental Organizations in Water and Sanitation (CONIWAS), the Institute of Environment and

Sanitation Studies of the University of Ghana, and the Department of Water and Sanitation of the University of Cape Coast – were involved in the study. These agencies and institutions included government institutions, non-governmental organizations, and local universities whose activities are within the water and sanitation sector The GAEC is actively involved in groundwater studies in Ghana. Other relevant institutions were contacted for the study, but they did not respond to our requests to take part in the survey. To recruit the experts for the study, the participating institutions were contacted and requested to recommend appropriate respondents with expertise in groundwater who can adequately respond to the items of the survey instrument. A questionnaire was administered to the experts using a Google Form after the experts had signed the Informed Consent Form. The questionnaire had both open-ended and closed-ended questions; the closed-ended questions were mainly on the 5-point Likert scale. In total, thirty-four (34) experts participated in the survey.

Snapshot of issues surrounding groundwater at the community level in the coastal area of Ghana

To gain insights into the issues surrounding groundwater, field observations and Focus Group Discussions (FGDs) were conducted in the selected coastal communities with community leaders that included chiefs, queen mothers, assemblymen, unit committee leaders, chief fishermen, and youth leaders. Participants in the FGD were contacted and recruited with the help of the assemblymen of the communities. Six to ten persons per community took part in the FGD, except in the Korle Lagoon catchment area, where only four participants were present. Purposive sampling was used to select respondents for both the expert survey and the FGDs because it was important to have respondents who were in the best position to provide the needed data.

The data obtained from field observations and FGD was complemented with a risk-priority matrix and Nemerow's Pollution Index (NPI), which were computed for microbial and chemical parameters, respectively. The risk-priority matrix combines information on sanitary assessment and microbial water quality data to assess the relative priority action needed for drinking water protection (WHO, 2012). Using the matrix, groundwater sources in the coastal communities were grouped into the following priority action needs: (i) no action required, (ii) low action priority, (iii) higher action priority, and (iv) urgent action required. The data used in computing the risk-priority matrix was obtained from Ayeta et al. (2023b). The NPI is a simple pollution index that was introduced by Neme (Rathod et al., 2011). It unveils the extent of contamination for a given water quality parameter with reference to its standard/recommended value. It is a very effective tool for communicating the overall water quality status to water users and policymakers (Shankar, 2018). In this study, NPI was used to assess the chemical status of groundwater. NPI was calculated using the equation applied by (Rathod et al., 2011; Shankar, 2018; Swati & Umesh, 2015).

$$NPI = \frac{Ci}{Li} \quad \text{(Shankar, 2018)} \quad (15)$$

where,

Ci represents the measured concentration of the ith parameter while

Li represents the permissible limit of the ith parameter.

If the NPI values exceed one for a given parameter, it is an indication of impurity (Rathod et al., 2011). Data used in computing NPI was obtained from Ayeta et al. (2023a).

Data analysis

Audio records from the FGDs were transcribed and thematic analysis was applied to analyze and group the participants' responses into themes such as main water supply, challenges in accessing clean water, awareness of groundwater policies at the regional and national level, etc. Descriptive statistics was performed for the expert-based assessment. Means were calculated for each Likert-scale item, and thresholds were set for mean occurrence per the recommendations by Pornel and Saldaña (2013): means of 0-1.49, for the first Likert item (e.g., not integrated at all); means of 1.50-2.49, for the second Likert item (e.g., limitedly integrated); means of 2.50-3.49, for the third Likert item (e.g., uncertain); means of 3.50-4.49, for the fourth Likert item (e.g., integrated); and means of 4.50-5.00, for the fifth Likert item (e.g., strongly integrated).

Foster et al. (2009) described four levels of groundwater governance capacity, namely, non-existent, incipient, acceptable, and optimal. To fit the 5-scaled mean values to the four levels described by Foster et al. (2009), mean values of 0-1.49, 1.50-3.49, 3.50-4.49, and 4.5-5.0 were, respectively, represented as non-existent, incipient, acceptable and optimal criterion. Assessments that were described as the 'uncertain' category were added to the incipient category. We assumed that if a given criterion existed at an acceptable or optimal level, experts would be well acquainted with it. We also assumed that experts' uncertainty with a level of governance criterion may not necessarily be due to the non-existence of such a criterion, but because that capacity is incipient, i.e., at its early stage of development.

Results

Groundwater governance in Ghana

Technical capacity

Figures 22-25 present results on the technical capacity of groundwater governance.

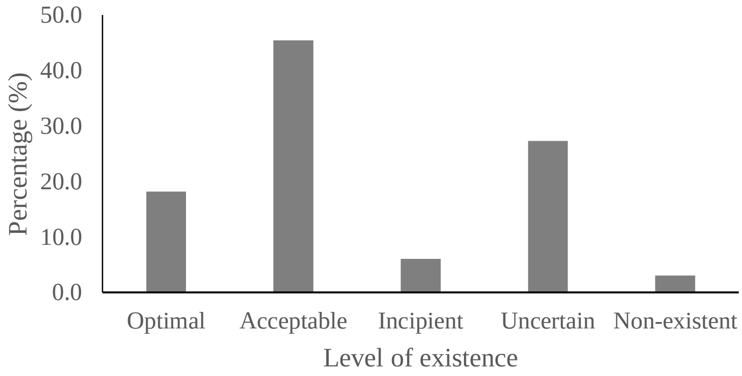

Figure 22: Existence of hydrogeological maps

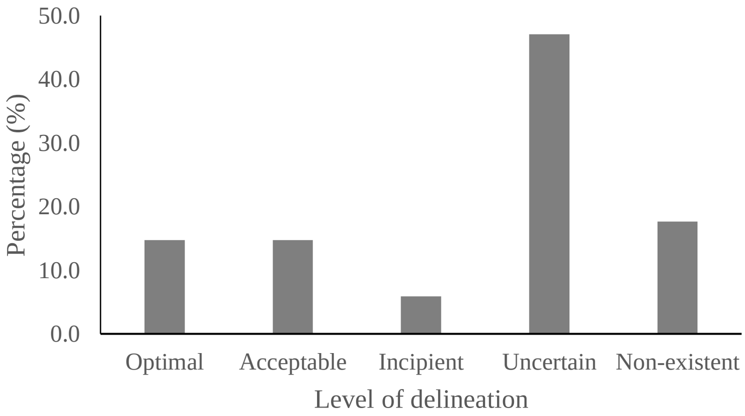

Figure 23: Delineation of aquifers

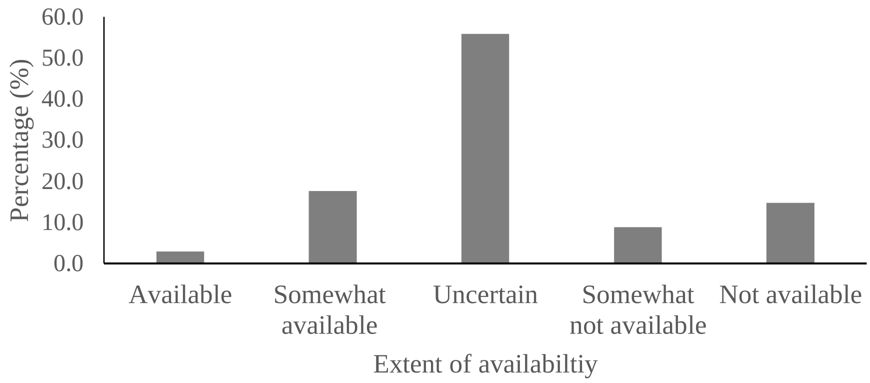

Figure 24: Availability of aquifer numerical ‘management models'

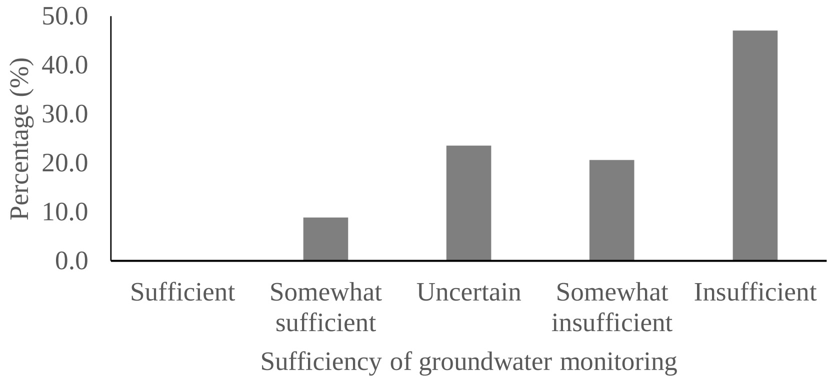

Figure 25: Sufficiency of groundwater monitoring

Majority of the experts (45.5%) indicated that the existence of hydrogeological maps is at an acceptable level (Figure 22), followed by the experts who were uncertain about the existence of hydrogeological maps (27.3%). Approximately 18.2% of the experts indicated that the existence of hydrogeological maps was optimal. About 6.1% of the experts responded that the existence of hydrogeological maps was incipient, while 3% of the experts were of the view that hydrogeological maps were not available.

The majority of the experts constituting 47.1% were uncertain about aquifer delineation compared to 14.7% of the respondents who indicated that aquifers in Ghana are not delineated (Figure 23). About 14.7% of the experts also indicated that aquifer delineation was optimal. Similarly, some other 14.7%

of the experts indicated that aquifer delineation was acceptable, while 5.9% indicated that aquifer delineation in Ghana was incipient.

Similar to the trends in aquifer delineation, majority of the experts, constituting 55.9% were uncertain about the availability of aquifer numerical management models (Figure 24). An estimated 17.6% of the experts indicated that aquifer numerical management models were somewhat available; 14.7% indicated that the models were not available; and 8.8% indicated that the models were somewhat not available. Only 2.9% of the experts indicated that aquifer numerical management models were available.

Results on the sufficiency of groundwater monitoring showed that 47.1% of the experts responded that groundwater monitoring was insufficient (Figure 25). Experts who were uncertain about the sufficiency of groundwater monitoring constituted 23.5%, while 21% of the respondents indicated that groundwater monitoring was somewhat insufficient. Interestingly, none of the respondents indicated that groundwater monitoring was sufficient.

The study revealed that groundwater quality and levels were monitored by the WRC in northern Ghana since 2007 under the Hydrological Assessment Project of the Northern Regions of Ghana. The assessment was initially undertaken by CSIR-WRI and later by GAEC, whose monitoring programs were carried out from 2012 to 2014. There are thirty-seven monitoring wells in total. Since the last monitoring drive in 2014 by GAEC, the monitoring wells have not been assessed, except for five of the wells that were adopted; the Department of Earth Science of the University of Ghana, Legon, adopted and monitors three (3) of the wells in Janga, Nalerigu, and Tuuni communities, while the Regional Water and Environmental Sanitation Centre of the Kwame

Nkrumah University of Science and Technology adopted and monitors the other two (2) wells in Bawku and Kabingo communities. Findings also showed that the monitoring exercises ceased when funds from foreign agencies ran out. The study also revealed that an initial field visit to some monitoring wells in the White Volta Basin in Ghana was done in February 2021, following the plans of the WRC to take up those monitoring wells. Findings from the field visit revealed that some monitoring wells had been converted to water-supply wells in some communities because the residents lacked knowledge of the importance of monitoring wells. In some cases, bush burning and piling of firewood around monitoring wells, which can lead to their damage, was reported. In other cases, it was reported that the residents of the communities had little or no knowledge about the presence of monitoring wells in their communities.

Legal and institutional capacity

Findings on legal and institutional capacity showed that the Water Resources Commission (WRC) Act (Act 522) enacted in 1996 and the National Water Policy (NWP) of 2007 are the key documents that provide the policy framework for water resources management in Ghana. The WRC is responsible for regulating and managing the use of all water resources as well as coordinating policies related to water resources in Ghana. The National Water Policy on the other hand provides a framework for the sustainable development of water resources in Ghana. Aside from the above policy documents, there are other legislative documents, guidelines, and regulations that are focused on specific areas related to groundwater. They include the following:

1. Water Use Regulation, 2001 (L.I. 1692): This regulation, which was promulgated in July 2001 by the Water Resources Commission, contains procedures for the issuance of permits for water abstraction for various uses. The use of water for firefighting and domestic purposes is exempted from obtaining permits.
2. Drilling License and Groundwater Development Regulations, 2006 (L.I. 1827): It outlines the procedures for obtaining a drilling permit and the steps to be taken to prevent groundwater contamination.
3. CWSA Small Community Sector Guidelines, 2010: This provides the guidelines for the operation and maintenance of water supply systems in small communities. These water sources are mostly groundwater. The document outlines steps to prevent groundwater pollution and the procedures and frequency of groundwater monitoring. It also states that two persons in each community: the caretakers of the Water and Sanitation (WATSAN) committee would be trained on how to carry out sanitary surveys.
4. Groundwater Management Strategy, 2011: The document stated the WRC's vision for groundwater for the period between 2011 and 2020. The WRC's vision included (i) collecting and exchanging data on the state of groundwater resources in Ghana to support water use in different sectors, (ii) strengthening policies for groundwater protection through the Integrated Water Resources Management (IWRM) framework, and (iii) fostering multi-level cooperation in groundwater. The expected long-term outcomes of the groundwater management strategy were increased (i) understanding of the hydrogeology of Ghana, (ii) access to

groundwater information, (iii) technical and institutional capacities in groundwater management, and (iv) stakeholder participation in groundwater management. Approaches outlined to address the needs for groundwater monitoring were (i) a short-term approach: through a shared partnership with a government agency (GAEC or CSIR-WRI) and (ii) a long-term approach: through the strengthening of the River Basin Management Board to achieve the groundwater management strategy. The document also stated that the CWSA had, for a long time, acted in an unofficial capacity as the agency that sets standards guiding the construction of groundwater facilities.

5. National Integrated Water Resources Management (IWRM) Plan (2012): The National IWRM Plan provides the cross-sector legal and institutional framework for the implementation of the water resources management aspect of the National Water Policy.

   Some groundwater-related actions prescribed to be taken include (i) the implementation of the Groundwater Management Strategy, (ii) the promotion of more national hydrogeological studies, (iii) revision of the existing drilling license and groundwater development regulations to include drilling for non-water related purposes such as mineral exploration that can affect groundwater, (iv) the development of a wastewater/effluent discharge regulation and mechanisms for its enforcement, (v) implementation of water monitoring and evaluation, (vi) strengthening the capacities of institutions for data analysis, and (vii) the development of decision support models for water quality and quantity management.

6. Water Sector Strategic Development Plan (2014): This plan was published by Ghana's Ministry of Water Resources, Works and Housing. It provides the framework for the implementation of all the components of the National Water Policy. Specifically, one of the strategic plans is to implement the Groundwater Management Strategy of 2011.
7. National Building Regulations 1996 (L.I. 1630): Established in 1996 by the Ministry of Works and Housing, Ghana, the National Building Regulations contain regulations that are to be applied when erecting or extending a building. Some groundwater-related regulations in L.I 1630 includes regulations on the construction of (i) wells and boreholes, septic tanks, and cesspools, and (ii) wastewater and refuse disposal, among others which help prevent groundwater pollution.

Figure 26 presents the results of experts' views on the establishment of groundwater policy.

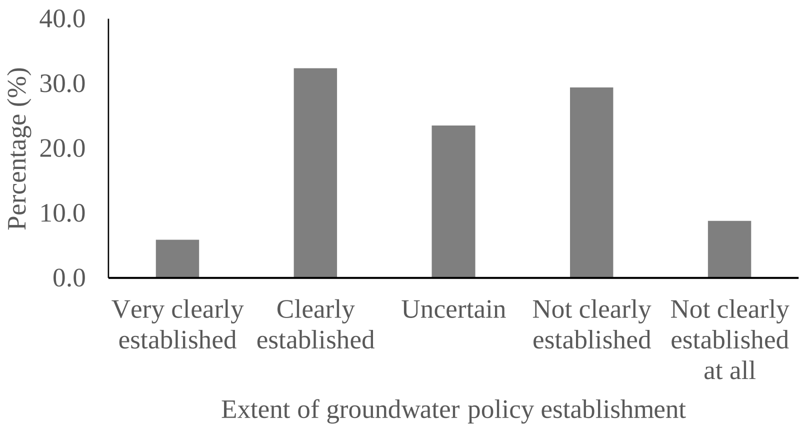

Figure 26: Establishment of groundwater policies

The results revealed that whereas 5.9% of the experts indicated groundwater policies are very clearly established, 32.4% indicated groundwater policies are clearly established. Also, 29.4% of the experts indicated groundwater policies are not clearly established compared to 8.8% of the experts who indicated that groundwater policies are not clearly established at all while 23.5% are uncertain. As a follow-up on the establishment of groundwater policy, experts were asked to identify which government institution is in charge of groundwater management in Ghana. Interestingly, most of the experts stated the Water Resources Commission, hence this criterion was deemed to be at the optimum level.

Cross-sector policy coordination

Results on cross-sector policy coordination are presented in Figure 27-30.

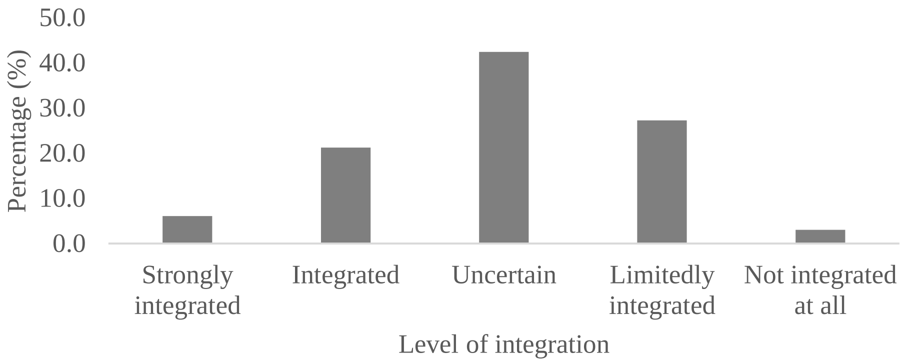

Figure 27: Integration with land use policies

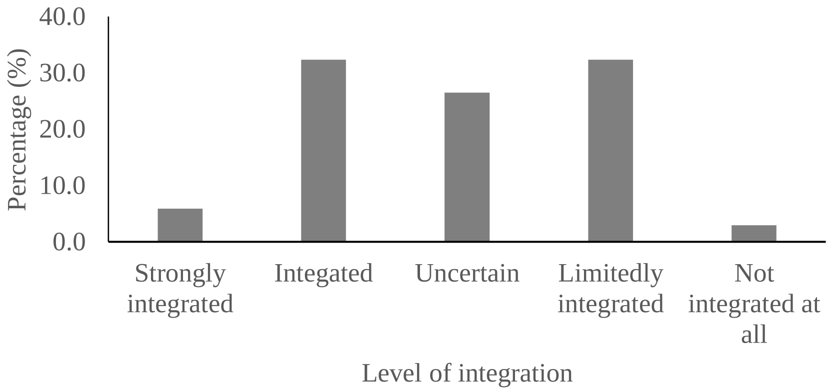

Figure 28: Integration with waste management policies

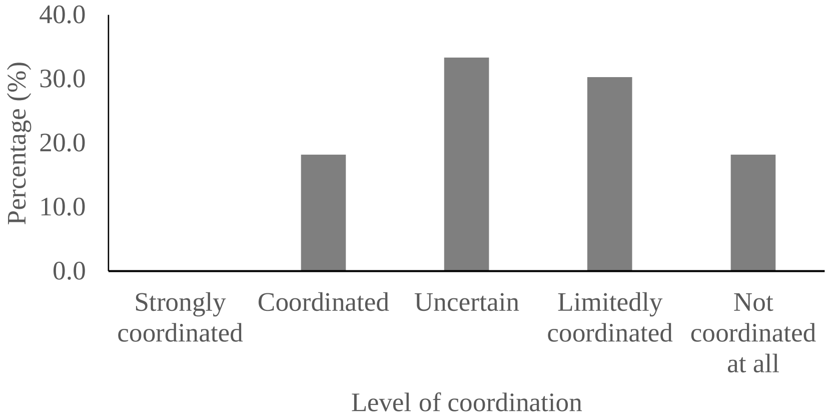

Figure 29: Coordination with agricultural development

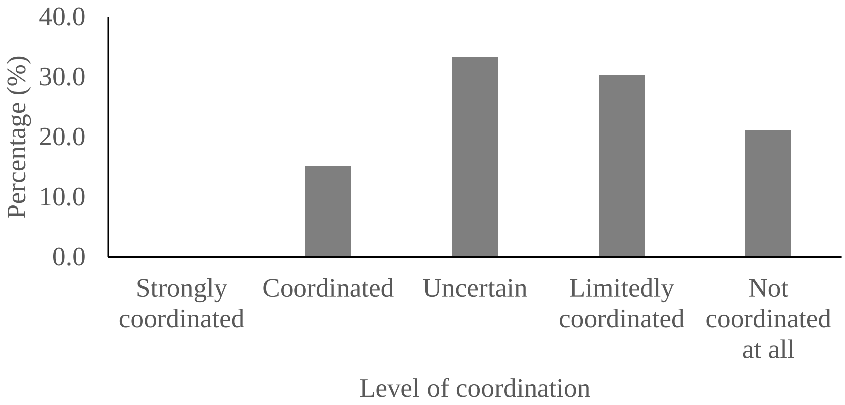

Figure 30: Coordination with Urban and industrial planning

Results on the integration of groundwater policies with land use policies show that 42.4% of the experts of the study were uncertain about the level of integration (Figure 27). Also, 27.3% of the experts indicated that land use policies were limitedly integrated with groundwater policies, while an overwhelming 3.0% indicated that the policies were not integrated at all. Some of the respondents that constituted 21.2% were of the view that land use policies were integrated with groundwater policies; 6.1% indicated that the level of integration was strong.

Interestingly, the same number of experts each made of 32.4% of the respondent, indicated that waste management policies with groundwater policies was integrated, and limitedly integrated, while 26.5% were uncertain (Figure 28). Only 5.9% of the experts responded that there was a strong integration of waste management policies with groundwater policies.

Findings on the coordination of groundwater policies/development with agricultural development showed that the most frequent response (33.3%) was uncertainty about the level of coordination (Figure 29). About 30% of the experts indicated limited coordination. Interestingly, there was a tie in the number of experts who indicated that groundwater policies/development was coordinated with agricultural development (18.2%) and those who indicated that groundwater policies/development was not coordinated with agricultural development at all (18.2%). None of the respondents indicated that groundwater policies/development was strongly coordinated with agricultural development.

Findings on the level of coordination of groundwater policies/development with Urban and industrial planning were very similar to the trends observed in groundwater coordination with agricultural development (Figure 30). About 33.3% of the experts were uncertain about the level of coordination; 30.3% indicated limited coordination, 21.2% indicated that there was no coordination at all; 15.2% indicated that there was coordination; and none of the experts indicated that there was strong coordination. In general, results show that cross-sector policies are not well integrated with groundwater policies, and a large percentage of experts are uncertain about cross-sector policy coordination.

Operational capacity

Figure 31-36 presents the results on operational capacity.

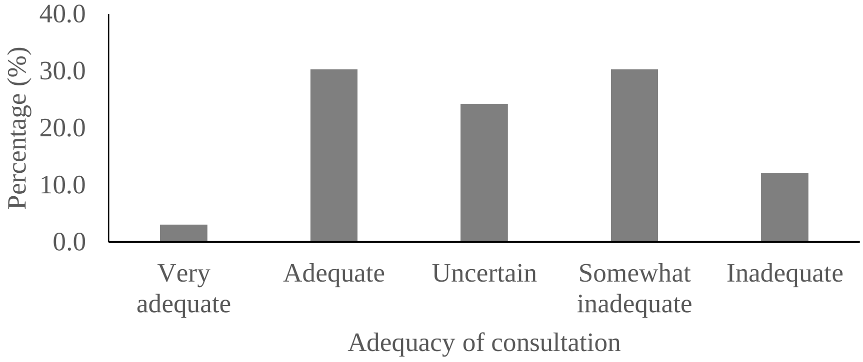

Figure 31: Consultation with stakeholders before groundwater policies are made

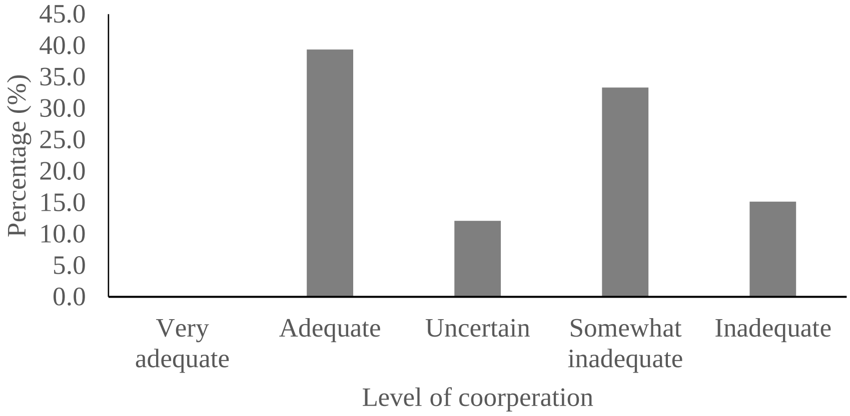

Figure 32: Cooperation between institutions responsible for groundwater management

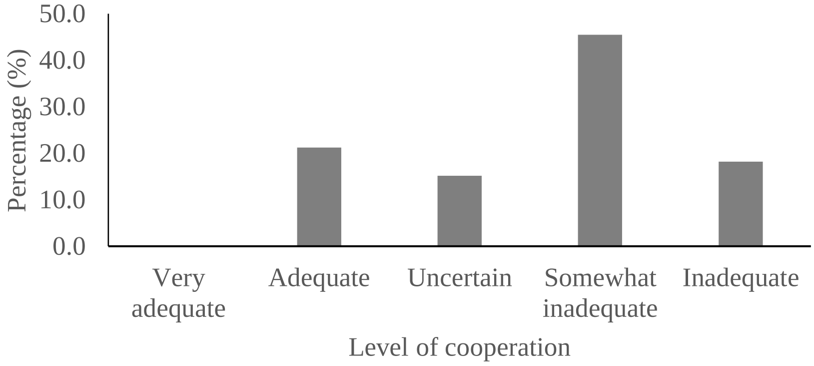

Figure 33: Cooperation between water administrators and water users

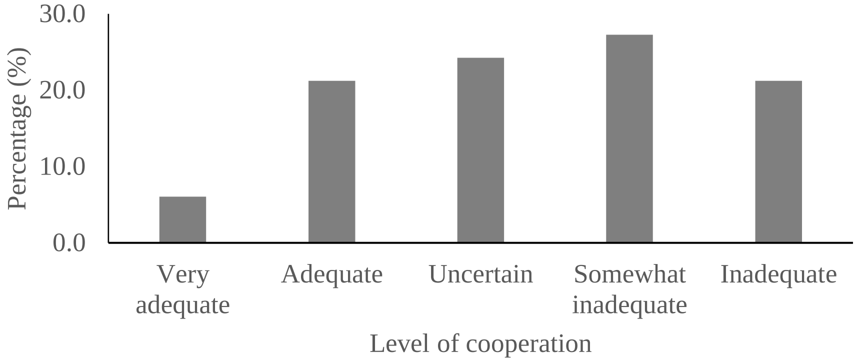

Figure 34: Cooperation between water administrators and scientific bodies

Figure 35: Existence of groundwater management plan

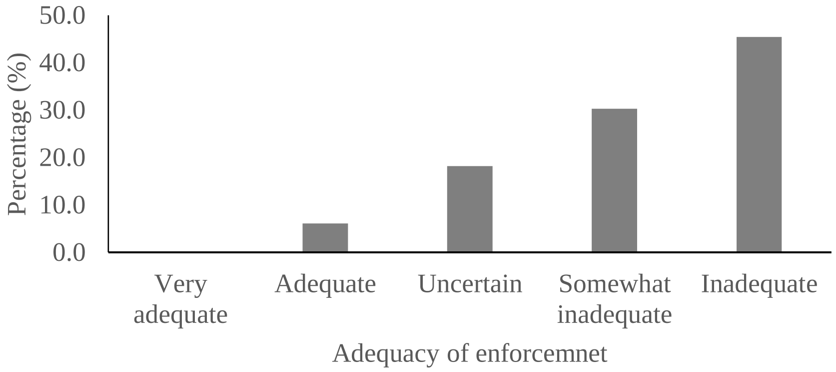

Figure 36: Enforcement of existing groundwater policies

Results showed that 30.3% of the experts think consultations made with stakeholders before groundwater policies are made were adequate (Figure 31). Another 30.3% think consultations were somewhat inadequate. About 24.2% of the experts were uncertain about the adequacy of consultations, while 12.1%

thought consultations made with stakeholders before groundwater policies are made were inadequate. Only 3% of the experts think that these consultations were very adequate.

About 39.4% of the experts think that the level of cooperation between institutions responsible for groundwater management was adequate while 33.3% think it is somewhat inadequate (Figure 32). An estimated 15.2% think the cooperation between institutions responsible for groundwater management was inadequate, while 12.1% were uncertain about the level of cooperation. None of the experts think the level of cooperation between institutions responsible for groundwater management was very adequate

On the cooperation between water administrators and water users (Figure 33), the most frequent response obtained was that cooperation was somewhat inadequate (45.5%). This was followed by adequate (21.2%), and inadequate (18.2%). About 15.2% were uncertain about the level of cooperation and none of the experts indicated that the cooperation between water administrators and water users was very adequate.

The highest percentage of experts (27.3%) think the cooperation between water administrators and scientific bodies was somewhat inadequate (Figure 34). About 24.2% of the experts were uncertain about the level of cooperation between water administrators and scientific bodies. Curiously, about 21.2% opined that the level of cooperation was adequate while another 21.2% opined that the level of cooperation was inadequate. Only 6.1% indicated that the level of cooperation between water administrators and scientific bodies was very adequate.

Findings on the level of existence of a groundwater management plan (Figure 35) showed that 45.5% of the experts think it is incipient. About 21.2% of the experts indicated that a groundwater management plan is existing but is not fully implemented while 15.2% indicated that a groundwater management plan is existing and is fully implemented. About 9.1% of the experts were uncertain about the existence of a groundwater management plan while another 9.1% opined that a groundwater management plan was non-existent.

Results on the adequacy of enforcement of existing groundwater policies (Figure 36) showed that most experts (45.5%) think it is inadequate. About 30.3% of the experts think the enforcement of existing groundwater policies was somewhat inadequate and 18.2% were uncertain. Only 6.1% of the experts indicated that the enforcement of existing groundwater policies was adequate. None of the experts opined that the enforcement of existing groundwater policies was very adequate.

Table 12 presents a summary of the groundwater governance capacity in Ghana. The results showed that while legal and institutional capacity was at an acceptable level, technical capacity, cross-policy coordination, and operational capacity were incipient. Also, only the existence of a government agency as a 'groundwater resource guardian' and of basic hydrogeological maps were at optimal and acceptable levels, respectively. All other criteria were incipient.

Table 12: Summary of Groundwater Governance Capacity in Ghana

Type of Capacity	Criteria	Mean	Level of governance capacity
Technical	Existence of basic hydrogeological maps	3.48	Acceptable
	Groundwater body/aquifer delineation	2.62	Incipient
	Sufficiency of groundwater quality monitoring	1.94	Incipient
	Availability of aquifer numerical ‘management models'	2.85	Incipient
		2.72	**Incipient**
Legal and institutional	Groundwater policies are clearly established	2.97	Incipient
	Government agency as 'groundwater resource guardian'	5.00	Optimum
		3.99	**Acceptable**
Cross-sector policy coordination	Integration with land-use policy	3.00	Incipient
	Groundwater policies integrated with waste management policies	3.06	Incipient
	Coordination with agricultural development	2.52	Incipient
	Groundwater-based urban/industrial planning	2.42	Incipient
		2.75	**Incipient**
Operational	Consultation of stakeholders before groundwater policies are made	2.82	Incipient
	Cooperation between institutions with responsibilities in water management	2.76	Incipient
	Cooperation between water administrators and water users	2.39	Incipient
	Cooperation between water administrators and scientific bodies	2.64	Incipient
	Existence of a groundwater management action plan	3.24	Incipient
	Enforcement of groundwater policies	1.85	Incipient
		2.62	**Incipient**
	Overall capacity	**3.02**	**Incipient**

Reasons given for the low enforcement of groundwater policies included the WRC not emphasizing attention on groundwater management, the absence of long-term groundwater monitoring across the country, limited research in the area, inadequate groundwater experts in water management institutions, inadequate funding by the central government, lack of institutional cooperation, and corruption.

When asked about other concerns the experts expressed concerns about inadequate monitoring and the negative effects it would have on the sustainability of the resource. Other concerns raised were the lack of hydraulic data on groundwater, the absence of legislation or regulation that protect groundwater recharge systems, the presence of uncapped and abandoned boreholes that serve as a direct conduit for pollutants to aquifers, and the low conjunctive use of groundwater particularly in the agricultural sector despite its huge potential for economic development.

Responses from experts showed that areas that need urgent attention concerning groundwater governance include the enforcement of existing policies and regulations, the revision of existing policies that are difficult to comprehend and enforce, the establishment of an agency whose sole responsibility will be the management of groundwater, robust groundwater education to ensure that it is in the public's mind, the need to strengthen collaboration between stakeholders, the need to adequately equip the current institution in charge of monitoring, the need to specify the drilling depth in each aquifer and the need to ensure that drillers submit their drill logs and borehole logs to WRC (either in hard or soft copy) before the renewal of their licenses.

Lastly, to establish the importance of groundwater in the coastal areas of Ghana, the experts were asked about the importance of the resource. Figure 37 presents their responses. Majority of the experts (55.9%) think groundwater is very important in the coastal areas and 26.5% think it is extremely important. There was no response for the option 'not at all important'.

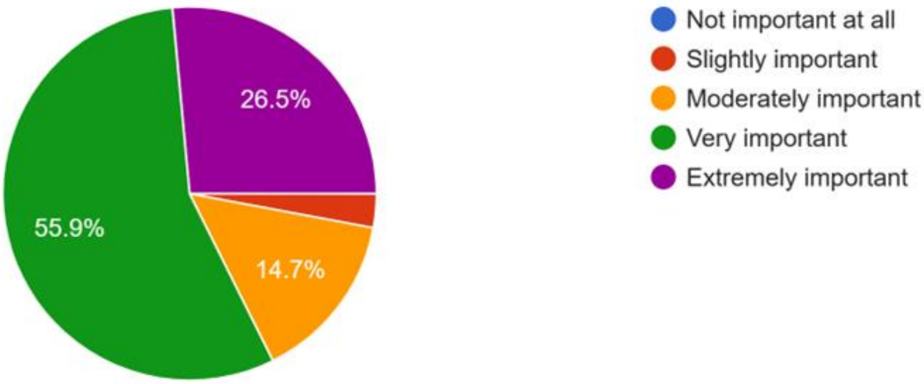

Figure 37: Importance of groundwater in the coastal areas of Ghana

Snapshot of issues surrounding groundwater at the community level in the coastal area of Ghana

Table 13 presents the results of the field observations and focused group discussions with community leaders in the study communities.

The results show that groundwater sources such as wells and boreholes are major sources of water in the four study locations. Thus, groundwater is a very important source of water in the study locations as expressed by a community leader in Essiama "*Very important…because of the high percentage of the population using it*".

Results also show that in Essiama, the people also depend directly on rivers and streams for domestic water supply.

Table 13: Summary of findings from field observations and FGD on local conditions and issues surrounding groundwater in the coastal areas of Ghana

Issues and local conditions	Essiama	Winneba	Accra	Keta
Water supply	Wells, boreholes, CWSA, and streams	GWCL, wells, and boreholes	GWCL, wells, and boreholes.	GWCL and wells
Main source	Wells	GWCL and wells	GWCL	Wells
Importance of groundwater to the community	"*Very important…because of the high percentage of the population using it*"	Very important	Important	Very important
Challenges in accessing clean water	Serious water shortage during the dry season "*…people have to queue in the night, wake up at dawn, 4 am, to get water…. it is a very challenging and a very disturbing problem and by that time too, streams might have dried up*" Saline water during the dry season	None	Water is potable but not readily available "*…sometimes too, 4,5 months at some places we don't get water, ... So, we have to travel to some places before we get water*"	Water shortage Saltwater intrusion
Groundwater policies in the community	Simple hygiene rules	Simple hygiene rules	None	Simple hygiene rules
Awareness of groundwater policies at the regional and national level	Aware of professional laws only	Not aware -Only surface water	Not aware	Not aware -Only surface water
Groundwater monitoring network	None-only environmental officer	None-only sanitary inspectors	None	None

CWSA- Community Water and Sanitation Agency,
GWCL- Ghana Water Company Limited

The rivers and streams mentioned were the Amanzule River, the Bonrenle River, Norbaya Stream, and the Nwanwagya Stream.

Results indicated that the studied communities (except Winneba) face some challenges in accessing clean water. Water shortage during the dry season, as well as saltwater intrusion, were notable challenges. Additionally, in Essiama most of the streams that serve as alternative sources of water dry up during the dry season. This makes it difficult for the residents of Essiama to access clean water during the dry season. In the Korle Lagoon catchment area of Accra and Keta, water shortages are mainly due to interruptions of the flow from the GWCL water supply.

Findings from this study also showed that groundwater policies at the community level were mainly general hygiene rules on environmental cleanliness and the location of burial sites. These simple hygiene rules were absent in the Korle Lagoon catchment area of Accra. Moreover, while the rules on environmental cleanliness were in existence in Essiama, Winneba, and Keta, adherence is very poor (except in Keta). Figure 38 shows some wells in the studied communities. It is also important to note that issues such as the proximity of wells to wastewater drains and, in some cases, latrines are not captured in these rules. Furthermore, groundwater monitoring networks were absent in the studied communities. This notwithstanding, the work of environmental officers/sanitary inspectors in enforcing existing hygiene rules in Essiama and Winneba was mentioned. Also, the community leaders were not aware of any groundwater policy at the national and regional level except in Essiama where the leaders were aware of some professional laws that guide well and borehole construction.

Figure 38: Some wells in the studied communities (the red arrows in the Figures indicate the position of the wells)

Results on the risk-priority matrix and Nemerow's pollution index for microbial and chemical water quality are shown in Tables 14, 15, and 16. Risk-priority matrix for microbial water quality shows that 9.40% of the groundwater sources in the studied communities were at very high risk and need urgent action while 58.12% were at high risk and need higher action priority. Furthermore, 29.06% of groundwater sources were at intermediate risk and need low action priority. Only 3.42% of groundwater sources in the studied communities were at low risk and do not require any action. Results on Nemerow's pollution index also showed the presence of chemical pollutants in some of the studied communities. Specifically, nitrate pollution was observed in Winneba and Accra where NPI values were 2.86 and 1.53, respectively. The results also showed that NPI values for lead in the coastal communities were less than 1. For arsenic and iron, NPI values below 1 were observed in Essiama, Winneba, and Keta while in Accra NPI values of 1.27 and 6.17 were observed for arsenic and iron, respectively.

Table 14: Risk-priority matrix for microbial water quality in the coastal communities of Ghana

E. coli (CFU/100 ml)	**Percentage sanitary risk score**															
	Essiama				**Winneba**				**Accra**				**Keta**			
	0-25%	26-50%	51-75%	76-100%	0-25%	26-50%	51-75%	76-100%	0-25%	26-50%	51-75%	76-100%	0-25%	26-50%	51-75%	76-100%
<1	1	4	0	0	0	1	1	0	2	6	2	0	1	4	0	0
1-10	4	1	0	0	0	4	0	0	1	5	1	0	1	3	0	0
11-100	3	14	1	0	2	11	9	0	0	5	1	0	0	17	1	0
>100	0	2	0	0	0	0	2	0	0	3	0	1	0	3	0	0

Legend

Risk level	Low risk	Intermediate risk	High risk	Very high risk
Priority action level	No action required	Low action priority	Higher action priority	Urgent action required

Data source: Ayeta et al., 2023

Table 15: Proportion of wells in action need categories based on risk-priority matrix

Action needs	Percentage of wells
No action required	3.42
Low action priority	29.06
Higher action priority	58.12
Urgent action required	9.40%

Table 16: Nemerow's Pollution Index for chemical contaminants in the coastal communities of Ghana

Groundwater pollutants	Locations				WHO 2017 Standards
	Essiama	Winneba	Accra	Keta	
Nitrate (mg/L)	41.92±4.90 (0.84)	142.95±8.63 (2.86)	76.30±11.70 (1.53)	41.32±6.75 (0.83)	50
Pb (μg/L)	0.62±0.21 (0.06)	0.20±0.20 (0.02)	0.10±0.10 (0.01)	0.10±0.10 (0.01)	10
As (μg/L)	1.82±1.19 (0.18)	1.67±0.91 (0.17)	12.70±10.1 (1.27)	5.87±2.32 (0.59)	10
Fe (μg/L)	150.00±76.40 (0.50)	167.00±167.00 (0.06)	1850.00±821.00 (6.17)	200.00±68.30 (0.67)	300

NPI values are shown in brackets.

Discussion

Groundwater governance in Ghana

Technical capacity in groundwater governance in Ghana was generally incipient (Table 1 and Figure 22-25). All criteria within the technical capacity sub-group were incipient, except for the existence of basic hydrogeological maps. Pietersen et al. (2012), in their study of groundwater governance in South Africa, reported that groundwater governance capacity under technical capacity sub-group were incipient, except for the availability of aquifer numerical management models which were non-existent. Mumma et al. (2011) also reported a generally low technical capacity in groundwater governance in Kenya, although, in their study, the availability of aquifer maps was at an acceptable level. It is revealed in this present study that efforts have been expended in developing hydrogeological maps in Ghana. There is a need to replicate such efforts in other areas such as the delineation of aquifers, the development of aquifer numerical management models, amongst others. A crucial aspect of technical capacity is monitoring. Although groundwater monitoring provides the basis for making sound policy decisions, the findings of this study further revealed that groundwater monitoring in Ghana is incipient and has been almost absent in the last 9 years (Table 12 and Figure 25). According to experts who were participants in this study, some major set-backs to the development of technical capacity in groundwater governance include low financing of groundwater research and monitoring programmes as well as lack of qualified personnel in the field.

There are existing policies set to manage and protect groundwater in Ghana. While majority of these policies stem from the water sector, a few others emanate from the housing sector. However, the experts-based assessment showed that the establishment of groundwater policies was incipient (Table 12 and Figure 26). Consequently, Ghana is at the initial stage of groundwater management, where groundwater policies are mainly tailored towards water supply and sanitation, and to specific groundwater problems facing the country (de Chaisemartin et al., 2017a; García et al., 2017). In their studies in Kenya and South Africa, Mumma et al. (2011) and Pietersen et al. (2012) reported that the presence of a government agency that acts as a groundwater resource guardian was incipient. In general, results on legal and institutional capacity showed that it was acceptable. In Ghana, the WRC acts as a government agency that oversees all water resources in Ghana including groundwater.

Cross-sector policy coordination was incipient per findings of the present study (Table 12 and Figure 27-30). This finding is in agreement with the findings from Garduño et al. (2011) who report that cross-sector policy coordination in groundwater governance for three states in India was incipient. The findings in our study are, however, different from the findings of Mumma et al. (2011) who reported that cross-sector policy coordination was non-existent. Cross-sector policy coordination plays a key role in solving systemic problems as policies across various sectors work synergistically (Peters, 2018). Cross-sector policy coordination can also help in resource mobilization and in preventing wasteful duplication of actions (Arbeiter & Bucar, 2021; Peters, 2018). Thus, cross-sector policy coordination is particularly important for the resource-scarce water sector in Ghana as lack of resources and funding are major problems in groundwater governance in the country. One factor that stifles cross-sector policy coordination globally is lack of information sharing

(Peters, 2018). Currently, the *modus operandi* for obtaining data on available monitoring wells, hydrogeological maps, as well as other valuable information is to make an official request to the WRC. To this end, there is a need to develop an open-access database for the water sector to promote data accessibility and exchange within and outside the sector.

This present study again showed that all the criteria related to operational capacity were incipient (Table 12 and Figure 31-36). Public participation in groundwater governance was incipient (Table 12, Figure 31, Figure 33, and Figure 34). Pietersen et al. (2012) reported that public participation in groundwater governance in South Africa was incipient, while the UNDP (2013) reported that public participation is well established in some Arab states. Interestingly, Mumma et al. (2011) reported that public participation in groundwater governance was non-existent in Kenya. Low public participation in resource governance makes the implementation of policies and plans difficult. There is a need to promote public participation in groundwater governance in Ghana through public education and effective consultations. The findings of this study also showed that cooperation amongst institutions involved in water management was incipient (Table 1 and Figure 32) . Ott (2014) reported that cooperation among institutions involved in drinking water governance in Cameroon was non-existent. Cooperation among stakeholders in the water sector amongst institutions in the water sector, between water administrators and scientific institutions, and between water administrators and water users is key to the effective implementation of water policies and regulations. For example, while there is an obvious lack of human capacity in groundwater governance institutions, there is an increasing trend in human capacity in academic institutions in Ghana. Strategic collaborations between stakeholders and the scientific institutions will help the water sector harness the human capacity in academic institutions. Enhancing cooperation amongst stakeholders requires adequate engagement. Little wonder stakeholder engagement is considered a key principle of good water governance (Akhmouch & Clavreul, 2017). Stakeholder engagements such as meetings, expert panels, surveys, workshops, town hall meetings, traditional media, capacity development etc., hold the promise of (i) bringing to bare the needs, interests, and concerns of various groups, (ii) enhancing ownership of decisions, and (iii) increasing acceptance and trust in the groundwater governance process (Akhmouch & Clavreul, 2017).

The enforcement of groundwater policies was also shown to be incipient in this study (Table 12 and Figure 36). Low enforcement of groundwater policies is a common situation in most developing countries and, sometimes, in developed countries. Ott (2014) observed that in Cameroon, drinking water policies are existent but are not actively implemented. Similarly, most Arab nations have groundwater governance frameworks and strategies in place but their implementation is often difficult (UNDP, 2013). Petersen-Perlman et al. (2018) also reported increasing difficulty in implementing groundwater policies in the United States as a result of budget and staffing-related constraints. Low enforcement of groundwater policies in Ghana is mainly due to poor attention to groundwater resources, low funding, and inadequate personnel.

Findings from the experts' survey showed that groundwater is a very important resource in the coastal areas of Ghana (Figure 37). That freshwater is relatively scarce in coastal areas due to saltwater intrusion, groundwater remains an important resource in coastal areas around the world (Behera et al., 2019; Wang et al., 2021).

Snapshot of issues and local conditions surrounding groundwater at the community level in the coastal areas of Ghana

Findings from this study showed that groundwater is important to the well-being of the residents of the studied communities (Table 13). This resonates well with the findings from the expert survey. Indeed, groundwater is a major source of water in many parts of the world. High dependence on groundwater has been reported in Kenya, Nepal, South Africa, Ontario, Saudi Arabia, and Turkey (Davraz & Varol, 2012; Latchmore et al., 2022; Marko et al., 2014; Olonga et al., 2014; Pathak et al., 2011; Potgieter et al., 2020). The findings reported in this present study are contrary to the general notion that high groundwater usage is limited to the rural areas of Ghana, as all the studied communities were urban communities. An unexpected finding from the study was that residents of Essiama still depend directly on water from streams and rivers for domestic water. Surface water is easily contaminated and often requires treatment to become potable (CDC, 2022; Walker et al., 2019). The use of water from streams and rivers without treatments exposes the residents of Essiama to a wide range of contaminants.

The challenges faced by the inhabitants of the communities in accessing clean water raise serious concerns as access to clean water is a basic human right (Masindi & Foteinis, 2021; United Nations General Assembly, 2010). For many residents of these communities, this basic human right is violated due to the failure of the State in fulfilling its obligation of providing adequate water facilities and protecting alternative water sources such as groundwater. Implications of this are health-related consequences for the residents of the communities. Furthermore, reduced access to clean water can negatively affect a wider range of human rights such as the right to life, a healthy environment, a good standard of living, and the rights of the child (Boyd, 2021).

The general lack of knowledge on groundwater policies and regulations shows that there is low level of public education on the issue. While the CWSA Small Community sector guidelines (Government of Ghana, 2010) state that communities that benefit from the Small Communities Water Supply (which are mainly groundwater sources) will be educated on the needed hygiene and sanitation practices, such education is either not done at all, or not done properly. Similarly, the fact that no mention of the WATSAN Committee was made in all the communities is an indication that their role in sanitary surveys around water points is only written on paper; the performance of their duties at the community level is absent. Although groundwater monitoring networks were absent in the communities, the work of the environmental officers and sanitary inspectors in enforcing existing hygiene rules in Essiama and Winneba is worth noting (Table 13). This notwithstanding, there is a need to widen the scope of their monitoring to include more issues that affect groundwater, for example, siting of wells near septic tanks, pit latrines, and wastewater drains. Additionally, it would be worthwhile to have the caretakers of the WATSAN Committee carry out their duties concerning sanitary surveys at the community level, as currently, the environmental officers and sanitary inspectors are at the district level: one sanitary inspector is assigned to a district, which makes their work enormous and inspection quite irregular. Gudaga et al. (2018b) in their study of the effectiveness of groundwater governance structures reported that local governance structures are very effective in influencing the actions of water users. Hence, limitations facing the caretakers of the WATSAN Committee in each community should be addressed to ensure that they carry out their duties.

Findings from the risk-priority matrix suggest that groundwater in the coastal communities of Ghana is generally in a poor state in terms of microbiological quality as only 3.42% of the groundwater sources were at low risk and required no action (Table 15). Most of the groundwater sources (58.12%) were at high risk and required higher priority action, and 9.40% of the groundwater sources were at very high risk and required urgent action. These findings are slightly different from the findings of Alemayehu et al. (2020) in the Southern Nations, Nationalities, and Peoples' Region of Ethiopia who reported that 21.5% of water resources required no action, 27.9% required higher priority action, and 15.9% required urgent action. The findings are also slightly different from the findings of Jovanović et al. (2017) who reported that 23.1% of individual supply water sources (mainly groundwater sources) in Serbia were at low risk and required no action, while 33.5 and 7.1% required high action priority and urgent action, respectively.

Results from Nemerow's pollution index show that chemical pollution of groundwater is occurring in some of the studied coastal communities (Table 16). Chemical pollution of groundwater is a common problem faced by aquifers, particularly in countries located in the eastern hemisphere (Li et al., 2021). This is mainly due to industrialization, urbanization, and population growth that is fast occurring in these regions (Li et al., 2021). This resonates with our findings as Nemerow's pollution index showed that chemical pollution was most prominent in Accra, which is the most industrialized, most urbanized, and most populated of the studied communities. The microbiological and chemical status of groundwater obtained in this study may be attributed to weak groundwater governance in Ghana, as achieving good groundwater status often requires good groundwater governance. The protection of groundwater quality can be achieved by setting groundwater quality protection zones (Foster & Cherlet, 2014). This involves controlling land use and effluent discharge, particularly in aquifer recharge and water-supply capture zones, as well as aquifer monitoring (Foster & Cherlet, 2014). In the coastal communities of Ghana, the control of activities such as the disposal of household waste, domestic wastewater, and industrial effluents is needed to protect the bacteriological and chemical integrity of groundwater.

Improving groundwater governance in Ghana

We recommend the following based on the responses of experts on key areas of urgent attention in groundwater management in Ghana and also on the findings from the snapshot of local conditions at the community level. Actions should be taken to (i) delineate and characterize aquifers in Ghana, (ii) enforce existing groundwater policies, and revise unenforceable and incomprehensible policies (iii) actively and consistently monitor groundwater quality and quantity nationwide, and (iv) increase public awareness and local participation in groundwater management. These recommendations require funding from the central government and private partners through the WRC, and establishing an agency that will be solely responsible for groundwater monitoring. If the above role will be assigned to the River Basin Management Board as stipulated in the

Groundwater Management Strategy of 2011, then a specific unit or division for groundwater should be set up within the Board. Personnel in this groundwater division will require training to efficiently discharge their duties. To achieve these, existing human technical capacity in the local academic institutions should be harnessed. Local governance structures at the community level should be actively engaged in groundwater governance processes.

Conclusion

This study assessed the status of groundwater governance in Ghana and provided a snapshot of local conditions that affect groundwater quality in selected coastal communities. The results revealed that groundwater governance capacity, i.e., technical, cross-sector policy coordination and operational capacity were incipient in Ghana, while legal and institutional capacity is at an acceptable level. Results further revealed that groundwater is very relevant to the well-being of the communities and that most of the studied communities have problems accessing clean water. Low public participation and low awareness of groundwater policies at the community level were observed. Poor microbiological and chemical status of groundwater was also observed. These findings suggest a need to boost groundwater governance in Ghana, particularly concerning understanding the resource, enforcement of existing policies, monitoring, human technical capacity, and public participation. Failure to do this will result in the continued deterioration of groundwater in Ghana.

CHAPTER SIX

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

Summary

This study presented findings on the assessment of groundwater quality and governance in the coastal communities of Ghana. The study aimed to fill some gaps in groundwater research in Ghana which included the scarcity of; (i) research on the long-term assessment of bacteriological groundwater quality that captured seasonal variations in the coastal communities of Ghana; (ii) research on the potential health risk associated with bacterial and metal pollution of groundwater along the coast of Ghana; (iii) studies on groundwater microbiome in Ghana; (iv) studies assessing the status of groundwater governance in Ghana. Therefore, the specific objectives of the study were to; (i) assess groundwater pollution along the coast of Ghana using physicochemical parameters, metals, nutrients, and indicator bacteria; (ii) assess the seasonal variations in groundwater quality; (iii) assess bacterial diversity in the groundwater along the coast of Ghana; (iv) determine the potential health risks associated with groundwater pollution; (v) assess the status of groundwater governance in Ghana.

The significance of the study, the importance of groundwater, its role in water supply, and in achieving global goals were elucidated in Chapters One and Two.

Some of the findings from the study were compiled in three articles. The titles of the articles and a summary of the findings in each article are presented below. The fourth manuscript on bacterial diversity (microbiome) is still under preparation, hence, it was not included in this report.

a. Seasonal variations and health risk assessment of microbial contaminations of groundwater in selected coastal communities of Ghana.

The study presented the findings on seasonal variations in microbial contaminations of groundwater and associated health risks in four coastal communities (Essiama, Winneba, Accra, and Keta) in Ghana. It also showed the results of sanitary risk inspection which was used to identify the risk of contamination and the probable risk factors.

Results showed 70.00%, 53.33%, 70.37% and 90.00% of groundwater sources in Essiama, Winneba, Accra, and Keta, respectively, were at intermediate risk, whereas 3.33%, 40.00%, 14.81%, and 3.33%, respectively, were at high risk. Very high-risk levels of contamination were recorded only in Accra. Common risks factors recorded were the presence of animal wastes within a 10 m radius of the groundwater collection point, bad drainage systems, collection of spilt water in the apron area, the use of ropes and buckets when fetching water from wells, and the absence of aprons and well covers.

Results on bacteriological quality of groundwater showed that mean total coliforms and *E. coli* ranged, respectively, between 123.40-501.30 and 30.98–141.90 CFU/100 ml for the four communities; the highest microbial counts for dry and wet seasons occurred in Winneba and Keta, respectively. Seasonal variations in *E. coli* counts in Winneba and Accra were significantly higher in the dry season than in the wet season while Essiama and Keta showed no significant seasonal variations.

Quantitative microbial risk assessment showed that exposure to *E. coli* O157:H7 through drinking groundwater ranged from 5 to 23 cells per day. While exposure to *E. coli* O157:H7 through bathing was less than 1 cell per day in all the communities, exposure to at least one *E. coli* O157:H7 cell would occur every 62, 141, 237, and 282 days in Winneba, Accra, Keta, and Essiama, respectively. The annual risk of infection and illness for all the studied communities was 1 for drinking, whereas that for bathing ranged between 0.65 and 0.99. The Disability-Adjusted Life Years (DALY) obtained for the study was higher than the WHO-acceptable DALY. Also, the findings revealed that groundwater resources in the studied communities were vulnerable to microbial contamination.

b. Groundwater in the coastal areas of Ghana: Quality and associated health risks.

The study applied the Canadian Council of Ministers of the Environment Water Quality Index (CCME-WQI) and Nemerow's Pollution Index (NPI) to assess groundwater quality along the coast of Ghana. Incremental life cancer risk and hazard quotient were also employed to assess the health risks associated with metal pollution in the area.

Results showed that groundwater was acidic during the rainy season in all the studied communities (Essiama, Winneba, Accra, and Keta). Electrical conductivity ranged from 0.44 to 2.61 mS/cm during the rainy season and from 0.43 to 2.45 mS/cm during the dry season. Results of EC showed that groundwater in Essiama was fresh while that of the other Winneba, Accra and Keta is brackish and mineralized. Whereas arsenic exceeded the WHO standard in Accra and Keta during the dry season, while iron was higher than the acceptable levels in Accra in both seasons. Lead concentrations were at acceptable levels in all the studied communities for both seasons.

In addition, principal component analysis revealed that metals (Pb, As, and Fe) had the highest loadings in the first component in Essiama. While EC, TDS, and salinity had the highest loadings in the first component in Winneba, Accra, and Keta. Furthermore, phosphate and lead had the highest loadings in the second component in Accra. The high loadings of the metals and phosphate in these coastal communities show their contributions to the pollution of the groundwater sources in the area.

CCME-WQI showed that groundwater quality in the studied communities ranged from marginal to poor water quality. Marginal groundwater quality indicates that groundwater in the studied locations often depart from desirable levels while poor water quality indicates that groundwater in the studied locations usually depart from desirable levels. Likewise, NPI showed that the physicochemical parameters that contributed to the deterioration of groundwater in the studied communities were nitrate, arsenic, and iron.

Additionally, hazard quotient showed non-cancer health risks for arsenic in Accra and Keta. Therefore, these findings revealed a need to take urgent steps to improve groundwater quality in the coastal areas of Ghana.

c. Groundwater governance and a snapshot of associated issues in selected coastal communities in Ghana.

This study assessed the groundwater governance status in Ghana and identified existing gaps. The study also presents findings on a snapshot of issues and local conditions surrounding groundwater in the coastal communities of Ghana.

Results on the status of groundwater governance showed that technical capacity, cross-sector policy coordination, and operational capacity were incipient while legal and institutional capacity was at acceptable level. Overall groundwater governance status was incipient. The low enforcement of groundwater policies, inadequate monitoring, poor technical and operational capacity, low cooperation within the water sector and across other sectors, and low public participation in water governance were the major gaps in groundwater governance.

The snapshot of issues and local conditions surrounding groundwater at the community level showed that groundwater is an important water source in the coastal communities of Ghana. Findings also revealed that some of the studied communities face challenges accessing clean water, particularly during the dry season. Furthermore, there is low awareness of groundwater policies, presence of some simple hygiene rules within some of the studied communities that protect groundwater sources, and the absence of groundwater monitoring networks in the communities. In addition, assessment of water quality using Nemerow's pollution index showed that the chemical status of groundwater in the studied communities was poor. Risk-priority matrix also showed poor microbiological status as 58.12% of the groundwater sources were at high risk and needed higher action priority.

Conclusions

The following conclusions were drawn based on the findings of this study for each objective:

Objective 1: Assess groundwater pollution along the coast of Ghana using physicochemical parameters, metals, nutrients, and indicator bacteria.

1. Groundwater in the coastal communities of Ghana is vulnerable to microbial contamination and is not potable.
2. Major risk factors predisposing groundwater to contamination in Essiama, Winneba, Accra, and Keta are the presence of animal wastes within a 10 m radius of the groundwater collection point, bad drainage systems, collection of spilt water in the apron area, the use of ropes and buckets when fetching groundwater, and the absence of aprons and well covers. Some of these risk factors are related to poor sanitation practices while others are related to poor design and construction of wells and boreholes.
3. Canadian Council of Ministers of the Environment water quality index (CCME-WQI) showed that groundwater quality ranged from marginal to poor.
4. Nemerow's pollution index showed that nitrate, arsenic, and iron contributed to the deterioration of groundwater in the studied communities.
5. Metals (Pb, As, and Fe) had the highest loadings in the first PCA component in Essiama, suggesting the influence of gold mining activities on groundwater sources in and around the community.

However, in Winneba, Accra, and Keta where EC, TDS, and salinity had the highest loadings in the first component of the PCA which is expected for coastal areas.

6. PCA also showed that phosphate and lead had the highest loadings in the second component in Accra. This suggests the influence of the high population, high sewage disposal, and the electronic waste hub in the area.

Objective 2: Assess the seasonal variations in groundwater quality

1. Temporal variation in microbial groundwater quality in the studied communities is influenced by both seasonal changes and site-specific conditions.
2. Average pH values indicate groundwater is acidic in the rainy season and less acidic in the dry season with more basic groundwater conditions in the Keta area.
3. EC/TDS/Salinity values are higher in the rainy season than the dry season for Winneba and Accra, invariable over the seasons for Essiama, and high in the dry season for Keta.
4. Nitrate content is comparatively high in the rainy season with average values above the WHO standards for Keta and Accra.

Objective 3: Assess bacterial diversity in groundwater along the coast of Ghana. The manuscript containing the findings on groundwater microbiome is yet to be completed and was not included in this report.

Objective 4: Determine the potential health risks associated with groundwater pollution.

1. Quantitative microbial risk assessment revealed that exposures to *E. coli* O157:H7 through drinking groundwater, and the risk of infection and illness is high. The annual probability of having an infection and falling ill from drinking groundwater in the studied location is 1.
2. Arsenic poses non-cancer health risks in some of the studied locations.

Objective 5: Assess the status of groundwater governance in Ghana.

1. Groundwater is an important water source in all the studied communities.
2. Some of the studied communities face challenges accessing clean water, particularly during the dry season.
3. There is low awareness of groundwater policies in the studied communities and there are no groundwater monitoring networks in the communities.
4. The overall status of groundwater governance in Ghana is incipient. Specifically, technical capacity, cross-sector policy coordination, and operational capacity were incipient while only legal and institutional capacity was at an acceptable level.
5. The major gaps in groundwater governance were low enforcement of groundwater policies, inadequate monitoring, low technical and operational capacity, poor cooperation within the water sector and across other sectors, and low public participation in water governance.

Recommendations

The following recommendations are made based on the findings of this study.

1. The Water Resources Commission and the Ministry of Health should carry out public education on the current state of groundwater (in terms of quality) in the studied communities, as well as on the importance of environmental sanitation. Such education should highlight the roles of environmental sanitation in groundwater protection. Residents of these communities should also be taught and encouraged to carry out some simple water treatment steps before using groundwater for domestic purposes. Furthermore, the public should be educated on the adverse effects of free range (the practice of allowing animals to roam freely outdoors) as it was a common practice that pre-disposed groundwater to contamination.
2. Artisanal masons should be trained by the Water Resources Commission and the Community Water and Sanitation Agency in wells construction standards. Additionally, major public wells (particularly community wells) should be fitted with rope pumps to reduce microbial contamination caused by the use of ropes and buckets. Owners of individual wells should be encouraged to do the same.
3. More public toilet facilities should be built in densely populated communities like the Korle-Lagoon Catchment Area and Old Winneba.
4. The Water Resources Commission and the Community Water and Sanitation Agency should set up local groundwater monitoring teams in the studied communities to monitor activities such as sanitary conditions

around wells, and compliance with well construction standards for new wells amongst others. In communities where the WATSAN committee already exists, they can be reinvigorated and made to perform this duty as stated in the CWSA Small Community Sector Guidelines of 2010. Also, the local governance structures at the community level should be actively engaged in groundwater management processes

5. Efforts should be made by the Water Resources Commission to delineate and characterize the aquifers in Ghana. Existing human technical capacity in local academic institutions should be harnessed for this. Likewise, efforts should be made to consistently monitor groundwater quality and quantity in areas where monitoring wells already exist. Groundwater monitoring efforts should also be expanded to every part of the nation to protect the health of groundwater users. In addition to this, existing groundwater policies should be enforced and those that are unenforceable and incomprehensible should be revised.

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APPENDICES

Appendix A

Instrument for data collection: Interview guide for focused group discussion

1. What are the various sources of water in your community?
2. Do you have any challenges accessing clean water in your community? If yes, what are the challenges?
3. How important is groundwater as a source of water to your community?
4. In your opinion, what factors contribute to problems mentioned above? (Poor waste management, siting of septic tanks, etc.)
5. Do you have groundwater policies in your community?
6. Are groundwater policies clearly established? Please describe the current ground water regulations and any changes made to them in the past.
7. Are you aware of the process behind putting your ground water (water resource) regulations into place? If yes, briefly describe the process.
8. Are you consulted when water laws/ regulations are made?
9. Are you aware of any permit system for well drilling? Is a permit needed to drill a well in your community?
10. How does the ground water regulation system work? What is the difference between what is on paper and what actually happens?
11. Is there a groundwater monitoring network in your community/district?
12. Are there community aquifer (groundwater) management organizations in your community? If yes, please tell me about them and their activities.

Appendix B

Instrument for data collection: Questionnaire for expert assessment

This questionnaire is meant to solicit information on groundwater governance in Ghana. The information being solicited for is purely for a PhD thesis and not for any financial gains. The researcher is a student of the University of Cape Coast, Ghana. Information provided by respondents will be treated confidentially by not revealing the identity of respondents. You are therefore, urged to feel free and provide the information being asked for. Thank you in anticipation of your cooperation.

SECTION I: PARTICIPANT'S INFORMATION

1. Gender
   Male [ ]
   Female [ ]

2. Specialization
   ………………………………………………………………………
3. Position at work ……….………………………………………………
4. Years of experience

a. 0-4 [ ]
b. 5-9 [ ]
c. 10-14 [ ]
d. 15-20 [ ]
e. 20 and above [ ]

SECTION II: TECHNICAL CAPACITY IN GROUNDWATER GOVERNANCE

5. How important is groundwater in the coastal areas of Ghana?

a. Not at all important [ ]
b. b. Slightly important [ ]
c. c. Moderately important [ ]
   d. Very important [ ]
   e. Extremely important [ ]

6. Are hydrogeological maps available in Ghana? (If no, move to question 10)

a. Yes- Optimal [ ]
b. Yes- Acceptable [ ]
c. Incipient [ ]
d. Uncertain [ ]
e. No [ ]

7. If yes, are they available to the public and other institutions? (If no, move to question 9
a. Yes [ ]
b. No [ ]
8. If yes to Q7, kindly provide the links to the website or database where this information can be found.

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………………………………………………………………………………

9. If no to Q7, why are they not available to the public and other institutions?

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10. Are the aquifers in Ghana clearly delineated? (If no, move to question 14)
a. Yes- Optimally delineated [ ]
b. Yes- Acceptably delineated [ ]
c. Delineation ongoing [ ]
d. Uncertain [ ]
e. No [ ]
11. If yes, are information on aquifer delineation available to the public and other institutions? (If no, move to question 13)
a. Yes [ ]
b. No [ ]
12. If yes, kindly provide the links to the website or database where this information can be found.

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13. If no to Q11, why are they not available to the public and other institutions?

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14. Are aquifer numerical 'management models' available in Ghana?
a. Not available [ ]
b. Somewhat not available [ ]
c. Uncertain [ ]
d. Somewhat available [ ]

e. e. Available [ ]

15. Which organization is responsible for groundwater monitoring in Ghana?

………………………………………………………………………………………………

16. Is there a groundwater [piezometric (water pressure, level and flow pattern) and quality] monitoring network in Ghana?

a. Yes [ ]

b. No [ ]

17. If yes to Q16, kindly provide some details about the network and their activities (e.g. name, what is monitored, how often monitoring is done etc.).

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18. How sufficient is the groundwater monitoring?

a. Not sufficient [ ]
b. Somewhat insufficient [ ]
c. Uncertain [ ]
d. Somewhat sufficient [ ]
e. Sufficient [ ]

19. What are the key threats to maintaining groundwater quality?

a. ……………………………………………………………………………………

b. ……………………………………………………………………………………

c. ……………………………………………………………………………………

d. ……………………………………………………………………………………

……………………………………………………………………………………

SECTION III: LEGAL AND INSTITUTIONAL CAPACITY IN GROUNDWATER GOVERNANCE

20. Groundwater policies clearly established.

a. Strongly disagree [ ]
b. Disagree [ ]
c. Undecided [ ]
d. Agree [ ]
e. Strongly agree [ ]

21. Please describe the current ground water regulations and any changes made to them in the past.

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…………………………………………………………………………………

22. Are there community aquifer management organizations?

a. Yes [ ]
b. No

23. If yes, kindly provide some details about the organization and their activities (e.g. name of the community, name of the group, what is monitored, how they operate etc.).

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24. What legal instruments are available in Ghana to prevent well construction in polluted areas?

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25. What sanctions are available for illegal well operators and those who evade the drilling permits?

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SECTION IV: CROSS-SECTOR POLICY COORDINATION

26. Are water policies integrated with land use policies?

a. Not integrated at all [ ]
b. Limitedly integrated [ ]
c. Uncertain [ ]
d. Integrated [ ]
e. Strongly integrated

27. Are water policies integrated with waste management policies?

a. Totally not integrated [ ]
b. Limitedly integrated [ ]
c. Uncertain [ ]
d. Integrated [ ]
e. Strongly integrated

28. What regulations exist on the construction and maintenance of septic systems that safeguard against groundwater contamination?

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…………………………………………………………………………………

29. To what extent does groundwater policies consider ecosystems that have hydrological connection to groundwater? Is protection of the environment specified or otherwise addressed as part of the groundwater policies?

a. Totally not considered [ ]
b. Limitedly considered [ ]
c. Uncertain [ ]
d. Considered [ ]
e. Strongly considered [ ]

30. Are there special “protected areas” where groundwater regulations are stricter than others? (e.g. wetlands, lagoons).

a. Yes [ ]
b. No [ ]

31. How well are all stakeholders involved in groundwater use and management ((including citizens, NGOs and other private entities) consulted before groundwater policies are made?

a. Inadequate [ ]
b. Somewhat inadequate [ ]
c. Uncertain [ ]
d. Adequate [ ]
e. Very adequate [ ]

32. How effective is the cooperation between institutions (including public and private bodies) with responsibilities in water management?

a. Ineffective [ ]
b. Somewhat ineffective [ ]
c. Uncertain [ ]
d. Effective [ ]
e. Very effective [ ]

33. Is there coordination of groundwater planning/development with agricultural development?

a. No coordination at all [ ]
b. Slightly coordination [ ]
c. Uncertain [ ]
d. Coordinated [ ]
e. Strongly coordinated

34. Is there coordination of groundwater planning/development with urban and industrial planning?

a. No coordination at all [ ]
b. Slightly coordination [ ]
c. Uncertain [ ]
d. Coordinated [ ]
e. Strongly coordinated [ ]

35. How adequate is the cooperation between water administrators and scientific bodies?

a. Inadequate [ ]
b. Somewhat inadequate [ ]
c. Uncertain [ ]
d. Adequate [ ]
e. Very adequate [ ]

SECTION V: OPERATIONAL CAPACITY

36. How adequate is the enforcement of groundwater policies?

a. Inadequate [ ]
b. Somewhat inadequate [ ]
c. Uncertain [ ]
d. Adequate [ ]
e. Very adequate [ ]

37. How adequate is the cooperation between water administrators and water users?

a. Inadequate [ ]
b. Somewhat inadequate [ ]
c. Uncertain [ ]
d. Adequate [ ]
e. Very adequate [ ]

38. Is there an existing groundwater management plan?

a. Non-existent [ ]
b. Uncertain
c. Incipient [ ]
d. Existing but not yet implemented [ ]
e. Existing and fully implemented [ ]

39. If non-existent or existing but not yet implemented, what are some of the reasons for this?

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OTHERS

40. What are the key threats to maintaining groundwater quality?

a. …………………………………………………………………………………
b. …………………………………………………………………………………
c. …………………………………………………………………………………
d. …………………………………………………………………………………
e. …………………………………………………………………………………

41. If you could change one thing about groundwater governance what would that be?

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42. What else should I know about your experiences with groundwater?

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