Journal of International Environmental Application and Science *ISSN-2636-7661*

Publishing Office: *Department of Industrial Engineering, Engineering Faculty, King Abdulaziz University, P.O. Box: 80204 Jeddah 21589 Saudi Arabia*; Tel: +966 533 107628; Fax: +966 2 2486695.

Frequency: Journal of International Environmental Application and Science (ISSN 2636-7661) is published 4 times per year.

Aims and Scope: Journal of International Environmental Application and Science is dedicated to detailed and comprehensive investigations, analyses and appropriate reviews of the interdisciplinary aspects of renewable sources, municipal and industrial solid wastes, waste disposal, environmental pollution, environmental science and education, biomass, agricultural residues, energy sources, hazardous emissions, incineration, environmental protection topics included experimental, analytical, industrial studies, hydrological recycling, water pollution, water treatment, air pollution, gas removal and disposal, environmental pollution modelling, noise pollution and control. Suitable topics are also included regarding the efficient environmental management and use of air, water and land resources.

Publication information: Please address all your requests regarding orders and subscription queries to: *Dr. S. Dursun*, Environmental Engineering Department, Engineering Faculty, Konya Technical University, Konya, TURKEY. Tel: +90 3332 2051559, Fax: +90 332 2410635, Mobil: + 90 536 5954591.
E-mail: jieas@jieas.com

Guide for Authors

Submission of Papers: Manuscripts for publication may be sent to the Editor-in-Chief, a member of the Editorial Board. Submission address is: Editor-in-Chief, Dr. S. Dursun, Environmental Engineering Department, Engineering & Natural Science Faculty, Konya Technical University, Konya, TURKEY. Manuscripts can also be sent to any member of the Editorial Board (see inside front cover for addresses). Although this journal is international in scope, all articles must be in the English language. Potential contributors whose first language is not English are urged to have their manuscript competently edited prior to submission. Papers should be written in the third person in an objective, formal and impersonal style.

Manuscript Preparation:

General: Manuscripts must be typewritten, double-spaced with wide margins on one side of white paper. Good quality printouts with a font size of 12 pt are required. The corresponding author should be identified (include E-mail address, Telephone and Fax number). Full postal addresses must be given for all co-authors. Two hard copies of the manuscript should be submitted by regular mail.

Abstracts: Each manuscript must be including a brief abstract and a short list of keywords.

Text: Follow this order when typing manuscripts: Title, Authors, Affiliations, Abstract, Keywords, Introduction, Main text, Conclusion, Acknowledgements, Appendix, References, Vitae and Figure Captions followed by the Figures and Tables. Pages should be numbered consecutively. The corresponding author should be identified with an asterisk and footnote.

Symbols and Units: All Greek letters and unusual symbols should be identified by name in the margin, the first time they are used. SI units should be used wherever possible, as recommended in ISO 1000 and BS 5555.

References: All publications cited in the text should be presented in a list of references following the text of the manuscript. In the text refer to the author's name (without initials) and year of publication (*e.g.* "since Dursun (1993) has shown that..." or "This is in agreement with results obtained later (Boddy, 1984)". For three or more authors use the first author followed by "*et al.*", in the text. The list of references should be arranged alphabetically by authors' names. The manuscript should be carefully checked to ensure that the spelling of authors' names and dates are exactly the same in the text as in the reference list.

References should be given in the following form:

Boddy L, (1984) The micro-environment of basidiomycete mycelia in temperate deciduous woodlands. In: *The Ecology and Physiology of the Fungal Mycelium* (Ed. by D.H. Jennings & A.D.M. Rayner), pp. 261-289. British Mycological Society Symposium 8, Cambridge University Press, Cambridge.

Dursun S, Ineson P, Frankland JC, Boddy L, (1993) Sulphite and pH effects on CO_2 evolution from decomposing angiospermous and coniferous tree leaf litters. *Soil Biology & Biochemistry* **25**, 1513-1525.

Ergas SJ, Schroeder E, Chang D, Scow K, (1994) Spatial distributions of microbial populations in biofilters. In: Proceedings of the *78th Annual Meeting and Exhibition of the Air and Waste Management Association*, pp. 19-24, Cincinnati, OH.

Hickey M, King C, (1988) *100 Families of Flowering Plants*. Cambridge University Press, Cambridge.

Littlejohn D, Wang Y, Chang S-G, (1993) Oxidation of aqueous sulphite ion by nitrogen dioxide. *Environmental Science & Technology* **27**, 2162-2167.

Illustrations: All illustrations should be provided in camera-ready form, suitable for reproduction (which may include reduction) without retouching. Photographs, charts and diagrams are all to be referred to as “Figure” and should be numbered consecutively in the order to which they are referred. They should be accompanying the manuscript, should be included within the text.

Tables: Tables should be numbered consecutively and given a suitable caption and each table should be included within the text. Footnotes to tables should be typed below the table and should be referred to by superscript lowercase letters.

Electronic Submission: Authors may submit electronic copy of their manuscript by e-mail or online submission on WEB site of the JIEAS. The final version of the manuscript should be submitted on floppy disk or CD. The electronic copy should match the hardcopy exactly. MS Word is recommended for software for article submission.

Proofs: Proofs will send to the author and should be returned 48 hours of receipt. Corrections should be restricted to typesetting errors; any others may be charged to the author. Any queries should be answered in full.

Subscription: Subscription for the issue contains author’s article published in “*Journal of International Environmental Application and Science*” is €100.00 which will be sending to the corresponding author.Journal of International Environmental Application and Science (ISSN 1307-0428) is published since 2006. Subscription rates for a year are: Institutions: € 300.00 (four issues per a year) Individuals: € 150.00 (four issues per a year)

Copyright: Papers are considered for publication on the understanding that they have not been submitted to any other publisher. With the exception of review papers, the work described must be original and, generally speaking, not previously published. Authors who wish to reproduce illustrations that have been published elsewhere must obtain the permission of the copyright holder.

Correspondence: Papers should be sent to: *Dr. S. Dursun*, *Environmental Engineering Department, Engineering Faculty, Selcuk University, Konya, Turkey*. It may also be sent by e-mail to jieas@jieas.com in Microsoft Office Word 2007 format.

Website: *http://www.jieas.com;* ***E-Mail****: jieas@jieas.com, info@jieas.com*

“Journal of International Environmental Application and Science” is indexed in: “**Global Impact Factor**, **EBSCO, CAS Source Index (A Division of the American Chemical Society), Index Copernicus, ProQuest, CABI, Ulrich's™ Serials Analysis System, SCIRUS, ArgosBiotech, NAAEE, The University of Queensland's Institutional, The NAL Catalog (AGRICOLA), WORLDCAT Catalog, LexisNexis, The National Library of Finland, National Library of Australia, DergiPark Turkey”** *Journal Indexing List.*

J. Int. Environ. Appl. & Sci., Vol. 18 No. 2 pp: 40-86 June, 2023

CONTENTS

J. Int. Environ. Appl. & Sci., Vol. 18 No. 2 pp: 40-86 June, 2023

J. Int. Environmental Application & Science, Vol. **18**(2): 40-47 (2023)
Research Paper

Open Defecation Practices in Rural Areas Threat Public Health: An Assessment of Selected Area in Sokoto, Nigeria

Mukhtar Abubakar Abdullahi[1, *], Yusuf Sarkingobir[2], Asiya Gidado Yabo[3]

[1] College of Nursing Sciences Tambuwal, Sokoto state, Nigeria: [2] Crown University International Chartered Incorporated/ Department of Environmental Education, Shehu Shagari University of Education Sokoto, Nigeria
[3] Umaru Ali Shinkafi Polytechnic Sokoto, Nigeria

Received March 02;2023; Accepted May 04, 2023

Abstract: The study aimed to assess open defecation amongst residents in a rural area of Wurno local government, Sokoto, Nigeria. The design utilized was cross-sectional survey, applied to gather information of the participants and their environment with the aid of structured questionnaires at a given time. The collected information was subjected to descriptive statistics and X^2 test at p<.05. The results reveal, majority of the participants (77.8%) are into open defecation; minority (22.2%) always do it. 77.8% of them always practice it, 11.1% never had open defecation, and 11.1% often do it. Majority (77.8%) had untidy toilets, minority (22.2%) had clean latrines.72.2% that is majority of the toilets in the area had no water supply, and minority (27.8%) of them had water. Toilets are shared by 9 people (72.2%) mostly, then 12 individuals (16.7%), and by 8 persons (11.1%). Majority (72.2%) of them do not wash hands with soap after toilet; and minority use soap after toilet (27.8%). All respondents agreed to burning of their waste (100.0%). Mostly open defecation is due to insufficient toilets (36.1%), then poor awareness (32.2%) and, poverty (31.7%). There was stool in the area (80.0%) and two defecators seen during the early morning (76.1%), 5 and above defecators were seen (12.8%), and only one person was seen (11.1%). Children (51.1%) are the most defecators, then adolescents (48.9%). Mostly, defecators are males (51.1%), 48.9% females. Open defecation is a much threat in children and women. Enough toilets and efforts are needed.

Keywords: *Open defecation, rural, diseases, malnutrition, polio, water supply*

Introduction

The act of defecation perpetrated by an individual or groups of people in an open space, waterbodies, bushes, etc. is defined as open defecation. It is an act of avoiding toilet while defecating and an act of passing stool in a manner that does not support hygienic separation of human waste and the human body and ultimately lead to so many adverse effects to the public health at large (Center for Legislative and Research and Advocacy, 2013; Coffey, 2015; Saleem et al., 2019; Onyemaechi et al., 2022). Therefore, open defecation is regarded as an unimproved method of sanitation and the least status on the sanitation ladder that affects everyone. From the global dimension, about 0.9 billion people are still into the act of open defecation, and in sub-Saharan region of Africa about sixteen million citizens to two hundred and twenty million are perpetrating the act unabated (Ntaro et al., 2022). In Nigeria, there are some reports that show that, still about6 25% of the citizens are defecating in the open with variation among the various regions of the country (Onyemaechi et al., 2022).

Open defecation is a principal threat to public health in many ways especially in rural settings. It is a main factor that spurs much contamination of the environment, water resources; and in turn increasing the risks of waterborne and water related diseases. Low sanitation has led to higher mortality and morbidity rates especially among children that are below five years old; therewith, about 70, 000 deaths are recorded every year in the country (Adeoye, 2015; Ufomba et al., 2021). Diarrhea, intestinal worms, polio, typhoid fever, hepatitis, trachoma, are some of the diseases challenging the health of Nigerians because of open defecation or poor sanitation practices (Ufomba et al., 2021).

Pertaining economics, there are a lot of effects arising from the open defecation practices and the effects are meted on about 1 billion people worldwide (Ufomba et al., 2021). Parable, when a person disgorges 1 gram of stool in the open, about 1,000 parasitic cysts, 1,000, 000 bacteria, 100 parasitic eggs, 10, 000, 000 viruses, and other pathogens are released. Consequently, this combo of microbes

**Corresponding: E-Mail: yusuf@crownintl.education ;Tel;+2349096266980*

finds its way into the water, food, and cling to the flies, fingers, soils, animate, and inanimate objects; thereafter, a fecal –oral transmission is facilitated (Routray et al., 2015; Mara, 2017; Ajayi & Philip, 2021)

The most affected portions of the population due to the open defecation are the children and women or girls. Children are subjected to diseases, malnutrition, stunting, intellectual derangement, academic problems, and the likes. Parents, wards, patients, and relatives had to spent vital portion of their income in the treatment of diseases caused by open defecation, working hours are lost, and school hours are lost because of sicknesses or relations (Kwiringira et al., 2015; Ajayi & Philip, 2021). Moreover, women or girls are major victims in the open defecation debacle by been subjected to indignity, school abandonment, poor academic achievement, etc. In often, women and girls are risk with the possibility of being raped or stink by animals along the course of open defecation (Sarkingobir et al., 2019; Ajayi & Philip, 2021). However, there is still need for empirical data outcomes in places like Sokoto rural area because the rural dwellers have been characterized as the most perpetrators of the act and most affected by the outcomes because of factors like poverty, poor healthcare, poor knowledge, and the likes (Sarkingobir & Sarkingobir, 2017; Amanabo-Arome & Abbas, 2021; Belay et al., 2022). Thus, the aim of this study was to assess the level of open defecation amongst inhabitants in a rural area of Wurno local government, Sokoto state, Nigeria.

Materials and Method

Study Setting

"Sokoto State is in the Northwest Zone of Nigeria between longitude 11″ 30–13″ 50 and latitude 4″–6″. It borders Niger Republic to the north and Benin Republic to the northwest, Kebbi State to south and Zamfara State to the east. It has a land mass area of about 32,000 sq. km and consists of 23 local government areas and 244 political wards. The population is predominantly rural, Muslim and consists almost entirely of Hausa/Fulani ethnic groups" (Sarkingobir *et al.,* 2021).

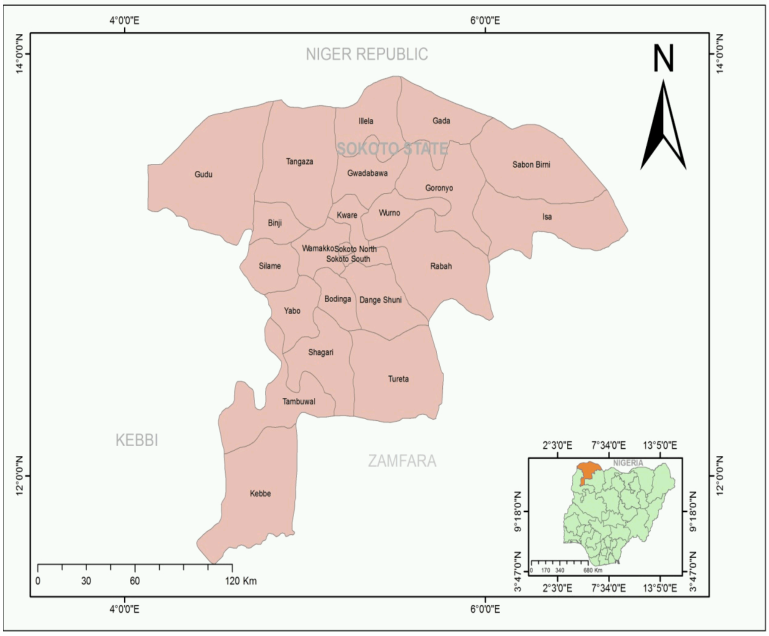


Figure 1: Map of the study area, Source: Hamza et al., (2023)

Research Design

The study design utilized in this work was cross-sectional survey design to collect data at a given time from a given portion of the environment and the respondents.

Population of The Study

The population of the study consists of all the households residing in Zayawa area in Wurno local government, Sokoto state, Nigeria. The sample was drawn from this very population using specific sampling strategy.

Sampling, Sample Size
In a qualitative survey there is need to explore quality, other than the bulky size of the sample in the study. Thus, major applied sample size for this study type was reported as fifteen (Sarkingobir *et al.,* 2021). To have proper data, an inspection of the environment of the area was coupled with face-to-face interview of the participants using simple random sampling approach. The sample size of the study was 179, according to the formula stated in Oche et al., (2011).

$$n = \frac{\left(U\sqrt{[A_1(1-A_1)+B_2(1-A)]}+V\sqrt{[2A\,(1-A)]}\right)^2}{(A_2-A_1)^2}$$

Where A = $A_1 + A_{2/2}$
U = One sided percentage point of normal distribution corresponding to 100% (power). Here power = 90%, U = 1.28
V = Percentage point of the normal distribution corresponding to the two sided significance level = 50%, V = 1.96.
A_1 = Proportion of value (open defecation coverage) to be determined = 30% in a previous report (Sarkingobir et al, 2021).
A_2 = Proportion of value to be determined post- intervention = 15%
n = 162
to compensate for non-response and attrition with anticipated 90% response rate, n = 180. In this study was the size was 180, according to the formula stated on Oche *et al.,* (2011).

Data Collection Instrument and Validation
In this study, a semi-structured questionnaire was used to collect data which is based on the past studies search. The questionnaire consists of subsections as follows: Section A is pertaining the demographic characteristics of the study participants, section B is about the open defecation practices (level of sanitation and relations), section C is about WASH parameters and motives to OD, and section D is about visible OD indices in the area and quasi.

Techniques of Data Analysis
After collection, the data (filled questionnaires) were analyzed using descriptive statistics to give frequency and percentage, wherever necessary the interview was analyzed using thematic content analysis.

Ethical clearance
For conducting this research work, an ethical clearance was obtained from the Sokoto state Ministry of Health

Table 1. Showing Characteristics of Respondents of the Study

Item	Frequency	%
Sex		
Male	80	44.4
Female	100	55.6
Marital Status		
Married	80	44.4
Divorce	50	27.8
Single	50	27.8
Age		
15 – 25 years	30	16.7
26 – 35 years	120	66.7
36 – 45 years	30	16.7
Occupation		
Farming	180	100.0
Education Qualification		
Is open defecation harmful?		
No	140	77.8
Yes	40	22.2

Source: Field Work, 2022

Results and Discussion

The results for this study are revealed in Tables 1, 2, 3, and 4. In Table 1, the characteristics of respondents were divulged. Majority are females (55.6%), and minority are (44.4%). On marital status, the highest status was married (44.4%), followed by divorced (27.8), and single (27.8%). Respective age ranges are: 15 – 25 years (66.7%), 36 – 45 years (16.7%), and 15 – 25 years (16.7%). Their major occupation is farming (100.0%) and education is Arabic (100.0%); therewith, most of them think that, defecation in the open and the perpetrators are harmful (77.5%), minority of them regarded the practice as harmless. From this finding it can be found that, the characteristics of the respondents are poor and might have motivated them to the practice; because lack of western literacy, poor income source, are among the factors that ensure poor health outcomes in often times, and might be the reason why the respondents think open defecation is harmless (Tsinda et al., 2015; Mara, 2017; Culley, 2018; Abebe, 2020).

Table 2: Responses on Open Defecation Practice among residents of Zayawa community, Wurno local government

Item	Frequency	Percentage (%)
I used toilet to defecate		
Sometimes	140	77.8
Always	40	22.2
I indulge in open defecation		
Never	20	11.1
Often	20	11.1
Mostly	140	77.8
I wash my hands after defecation		
All the time	180	100.0

Source: Field Work, 2022

The evaluation of open defecation in a rural area reveals in Table 2 that, majority of the participants (77.8%) are in the habit of sometimes engaging in open defecation; and minority (22.2%) are always in the habit of defecating in the open. From this it has been indicated that open defecation is a norm in the rural area and potentially affects public health. This work had a similarity with a finding in an Indian study that found open defecation in a village area (Dev, 2018). Like the finding in this study, in that Indian study, most of the household of the assessed village had no toilet, situation that forced people to engage in open defecation or low sanitation level practice (such as shared sanitation) (Dev, 2018; Saleem et al., 2019; Trimmer et al., 2022). 77.8% of the respondents agreed that they always practice open defecation, 11.1% never engaged in open defecation, and 11.1% practice open defecation often.

Assessment of status regarding water, sanitation, and hygiene was shown by table 3. For people to be able to abide by the conduct of proper sanitation, water supply is inevitable. However, the evaluation of water, sanitation, and hygiene (WASH) items in the area confirmed that, majority (77.8%) had untidy toilets, and minority (22.2%) had clean latrines. The issue of unclean toilet is of great concern in sanitation, because people tend to shun toilets if they are dirty. 72.2% that is majority of the toilets in the area had no water supply, and minority (27.8%) of them had water. Therefore, the lack or insufficiency of water in the toilet premises or environment is a major thing that motivates people to avoid toilets and make achievement of sustainable sanitation difficult. In a study similar to this, lack of water supply was fingered as a major factor that causes among open defection among higher institution students in Nigeria (Ajayi & Philip, 2018). Moreover, another study from sub-Saharan countries reiterated that limited water availability trigger people to use pen defecation as a substitute (Belay et al., 2022). Toilets are shared by 9 people (72.2%) mostly, then 12 individuals (16.7%), and lastly by 8 persons (11.1%). This has pointed that, all available toilets are shared, and the sharing could make the toilets untidy easily or spoil some of the hardware available; thereby motivating open defecation on the other hand. To safeguard public health by breaking the chain of transmission of pathogens, a person is supposed to clean his hands with soap always after toilet; therefore, every toilet needs to have a supply of enough soap for that respect. Hoverer, in the study area, majority (72.2%) of the respondents confided that, washing hands with soap after toilet is not their norm (because there was no soap in their toilets); and minority had summited to the use of soap after toilet (27.8%). This is in consonant with a study reported from Indian village that, majority of the households studied had nothing for handwashing after toilet visits (Coffey, 2015; Dev et al., 2018).

Table 3: Assessment of Water, Sanitation and Hygiene Parameters and motivators to open defecation in the Study Area

Item	Frequency	%
Toilets are:		
Clean	40	22.2
Dirty	140	77.8
Is there Water Supply?		
Yes	50	27.8
No	130	72.2
Individuals Per Toilet		
9	130	72.2
8	20	11.1
12	30	16.7
Is there any of Soap at the latrine?		
No	130	72.2
Sometimes	50	27.8
Method of Waste Treatment		
Burning	180	100.00
Possible motivators to Open Defecation		
Insufficiency of Toilets	65	36.1
Poverty	57	31.7
Insufficiency of Awareness	58	32.2

Source: Field Work, 2022

The major thing that motivates them to open defecation is insufficient toilets (36.1%), then poor awareness (32.2%) and lastly, poverty (31.7%). This study has shown from the submissions of the participants that there are several causes or factors that motivate people to persist on open defecation norm especially in the rural setting. In some other corroborating studies, there had being similar reports on causes of open defecation in the country; parable, poor knowledge and awareness, and availability of facilities were fingered as major factors harboring poor sanitation in the country as illustrated by Olaitan et al., (2022); another study shows that as the education of the household go higher, the tendency of open defecation goes lower (Belay et al., 2022), and indeed the poverty is fingered issue to harbor open defecation in many situations (Belay et al., 2022). Similarly, in a study in Osun state, Nigeria, rural areas were more prone to open defecation than urban ones, and education of the head in any household reduces open defecation among the participants in the study (Onyemaechi et al., 2022).

People are expected to manage their waste properly for the protection of health. In this study, the respondents instead of abiding by good practices, they subscribed to burning of their waste materials (100.0%). In this vein, Dev (2018) reported that waste disposal in the examined village is extremely and poorly managed by dispensing on river sides, beside the house, and in the field. However, the practice of open burning of waste as a norm of the study respondents is a thing of great concern especially when the practice is perpetrated at home. It increases the risk of heart disease and aggravate the suffering of people battling with respiratory illnesses like emphysema, and asthma. Other effects can be nausea, rashes on the body, reduction of vision, effect on liver, kidney, and nervous system disorders; therewith, the resultant effects of burning of waste at home are more pronounced on the children (Karshima, 2016; Kaoje *et al*., 2017; Magami *et al*., 2017; Kaoje *et al.,* 2018).

Table 4 identifies the actual open defecation in the area. There is noticeable stool in the area (80.0%) and two defecators during the early morning visits (76.1%), 5 and above defecators were seen (12.8%), and only one person was seen (11.1%). There are types of people that mostly engaged in open defecation, and there are types of people that are mostly inflicted by consequences of open defecation in any given area. As revealed by this study, children (51.1%) are the major perpetrators, then adolescents (48.9%). And unfortunately, they are the ones that are mostly affected by the consequences of open defecation in the environment. Mostly, defecators are males (51.1%), are significant of portion of the defecators are females (48.9%). It is unfortunate to find children and the female gender in involved in the practice of open defecation, because they are the most vulnerable to the consequences of that scourge (Abebe, 2020). Children are naturally known with weak immunity, a growing and developing body, longer life expectancy, curiosity, and tendency to contact soil or contaminated objects carelessly and therefore have more chance to be affected with the open defecation practice (Clasen, 2015; Spears et al., 2015; Sarkingobir et al., 2021; Dikko et al., 2022; Miya et al., 2023; Sarkingobir et al., 2023). Likewise, the women have extensive needs for better sanitation and hygiene, because of the gender; and in the other hand lack of proper sanitation subject them to indignity, rape, school abandonment, stink from animals and other related effects (O'Reilly, 2016; Ngwu, 2017).

Table 4. Investigation of Open Defecation among residents of rural area of Wurno local government, Sokoto state, Nigeria

Parameter	Frequency	%
Noticeable stool in the area		
Yes	180	100.0
No	0	0.0
Presence of people defecating during the Early Morning Visit	180	100.00
Number of Defecators noticed		
1	20	11.1
2	137	76.1
5 and above	23	12.8
Types of People Seen Defecating		
Children	92	51.1
Adolescents	88	48.9
Gender of Defecators		
Males	92	51.1
Females	88	48.9

Source: Field Work, 2022

Conclusion

Open defecation is a practice of defecating outside a designated toilet. It is a practice that harbors the contact of human with excreta and in turn facilitating the transmission of diseases. People defecating in the open are releasing millions of microbes to the environment for upward intake into the human body and in turn a factor that is responsible for transmission of many diseases and effect such as polio, cataract, typhoid, cholera, hepatitis, malnutrition etc. Therefore, it is needed to explore the exact nature of the situation more especially in the rural areas, to know the motives and hindrances of the practice, and to identify the WASH sanitation levels and relations. Therefore, this study was conducted and has conclusively; revealed that, there was poor sanitation (toilets) levels and open defecation had been practiced by most of the inhabitants of the rural Zayawa area, Wurno local government, Sokoto state.

Recommendations

Toilets are very significant to maintain the health of the public. It can be recommended based on this study that:

1. The government, nongovernmental organizations, communities of rural areas or governments should provide initiatives to provide adequate toilets at homes, school environment (in hostels and school premises), more especially to the females. These toilets can also be built by other organizations such as Muslim Society organizations and relations.
2. There should be proper awareness among residents on dangers of opens defecation to public health. Teachers, leaders, and unions should engage in massive campaigns against poor sanitation and hygiene.
3. There should be encouragement of enough individuals to clean toilets regularly. Youngsters are also enjoined to support in cleaning their environment.
4. Walk of shame should be used to invite people to cleanliness in their toilets or environments.

***Acknowledgement**: The authors are grateful to Prof. Bashiru Aremu (V.C Crown University International Chartered Incorporated) for the moral support he rendered during this study. Likewise, we are grateful to Dr. Aminu Musa Yabo (Dean Faculty of Education Shehu Shagari University of Education) for the encouragement he gave us on this study.*

Funding: *This research has been funded with personal money through monthly salary contribution.*
Author contributions: *Mukhtar Abubakar Abdullahi and Yusuf Sarkingobir done the Conceptualization, Methodology, Writing-Original draft preparation, Reviewing and Editing; Asiya Gidado Yabo, and Muktar Abubakar Abdullahi performed the Investigation, Data curation, Modelling. More proofreading was done by Yusuf Sarkingobir.*
Conflicts of interest: *The authors declare no conflicts of interest.*

References

Abebe TA, Tucho GT, (2020) Open defecation-free slippage and its associated factors in Ethiopia: a systematic review. *Systematic Rev.*. **9** (1): 252. Doi: 10.1186/s13643-020-01511-6. PMC 7641843. PMID 33143715.

Adeoye GO, (2015) Water supply, environmental hygiene and health. *28th International Faith and Learning Seminar held at Babcock University*, Osun, Nigeria.

Ajayi OO, Philip KL, (2018) Assessment of open defecation and prevalence of soil transmitted helminthes among some tertiary institution students in Nigeria. *Int. J. Environ., Agri. & Biotech.*, **3**(6), 2185-21191. http://dx.doi.org/10.22161/ijeqb/3.6.32.

Amanabo-Arome, UH, Abbas AM, (2021). Environmental and health implications of poor sanitation in Nigeria. *Merit Res. J. Agri. Sci. Soil Sci.*, **9**(10), 101-104. Doi:10.5281/zenedo.5745751.

Belay DG, Asratie MH, Aragaw FM, Tsega NM, Endalew M, Gashaw M, (2022). Open defecation practice and its determinants among households in sub-Saharan Africa: pooled prevalence and multilevel analysis of 33 sub-Saharan African countries demographic and health survey. *Trop. Med. Health*, **50**(28), 1-12.

Centre for Legislative Research Advocacy (2013). Open defecation. This is also your business. policy brief No 20, 2013 August- September.

Clasen T, Boisson S, Routray P, Torondel B, Bell M, Cumming O, (2015). Effectiveness of a rural sanitation program on diarrhea, soil-transmitted helminth infection, and child malnutrition in Odisha, India: a cluster-randomized trial. *The Lancet*. Global Health. **2** (11), e645-53. doi: 10.1016/S2214-109X(14)70307-9. PMID 25442689.

Coffey D, Gupta A, Hathi P, Khurana N, Srivastar N, Vyas S, Spears D, (2015). Open defecation; Evidence from a new source in rural Narti India. *Economic and Political Weekly*, **Xlix** (38): 43-55.

Culley P, (2018). Policy as law: Lessons from sanitation interventions in rural India. *Standard J. Int. Law*, **55**, 241-258.

Dev S, (2018). Causes and consequences of open defecation and improper sanitation: A study in Polempur village, Khandaghosh Block, Bardhaman. *Int. J. Res. Analytic. Rev.*, **5**(3),774y-780y.

Dikko M, Sarkingobir Y, Abdullahi MA, Salihu I, Tukur U, (2022). Assessing immunization status and factors influencing vaccination coverage among children in rural suburbs of Sokoto state, Nigeria. *Al-athfal: J. Pendi. Anak*, **8**(2),129-140. Doi: 10.14421/1l-athfal.2022.82-04.

Kaoje AU, Sabir AA, Yusuf S, Jimoh AO, Raji MO, (2017). Residents perception of solid waste disposal practices in Sokoto, Northwest Nigeria. *Afri. J. Environ. Sci. Technol.,* **11**(2), 94-102. Doi:10.5897/AJEST2014.1791.

Kaoje U, Garba J, Christiana, ON, Olayinka RM, Mohammed Y, & Mohammed AU. (2018). Biomedical waste handling and knowledge of its health hazards among waste handlers in a tertiary hospital in Sokoto, Nigeria. *Public Health Review Int. J. Public Health Review*, **5**, (1), 26-32.

Karshima SN, (2016). Public health implications of poor municipal waste management in Nigeria. *Vom J. Vet. Sci.*, **11**(2016), 142-148.

Kwiringira J, Atekyereza P, Niwagaba C, Günther I, (2015). Descending the sanitation ladder in urban Uganda: evidence from Kampala Slums. *BMC Public Health*. **14**, 624. Doi:10.1186/1471-2458-14-624. PMC 4071028. PMID 24948084.

Magami IM, Maishanu HM, Danbare BM, (2017). Survey of waste disposal and its perception among residents of Sokoto Metropolis, North-Western Nigeria. *Int. J. Pure Appli. Biosci.*, **5**(2), 9-13. Doi: 10.18782/2320-7051.2456.

Mara D, (2017). The elimination of Open defecation and its adverse health effects: a moral imperative for governments and development professionals. *J. Water, Sani. Hygie. Develop.*, **7**(1),1-13.

Miya YY, Livinus R, Umar AI, Sarkingobir Y, Butuwo MT, Bello, Z. (2023). Pattern of cannabis, and cigarette abuse among adolescents in Sokoto and assessment of antinutritional components of the two drugs. *J. Communi. Servi. Sci. Engineer.*, 2(1), 1-14. Doi: 10.36055/jocse.v2i1.19802.

Ngwu IU, (2017). The practice of open defecation in rural communities in Nigeria: A call for social behavior change communication in intervention. *Int. J. Communica. Res.*, **7**(10), 201-206.

Ntaro M, Owukuhaisa J, Isunju JB, Mulogo E, Ssempebwa JC, (2022). Contextual and psychological factors influencing open defecation free status: an exploratory qualitative study in rural southwestern Uganda. *BMC Public Health*, **22**(414), 1-15. Doi: 10.1186/s12889-022-12759-z.

Oche MO, Umar AS, Ibrahim MTO, Sabiru K, (2011). An assessment of the impact of Health Education on maternal knowledge and practice of childhood immunization in Kware, Sokoto State. *J. Public Health Epidemiol.*, **3** (10), 440 – 447.

Olaitan OM, Oluwatobi TK, Oluwaseun PV, Adaobi OS, Abiodun MA, Kayode OR, Obidiro P, Babatunde OA, Oladije A, Barakat A, (2022). Cholera scourge in Nigeria: Promoting environmental sanitation practice to achieving good health for all. *J. Infectious Diseases and Epidemiol.,* **8**(1), 1-6. Doi:10.23937/2474-3658/1510246.

Onyemaechi SB, Akinyemi PA, Aribodor DN, Fajobi O, Okoro NE, (2022). Burden and determinants of open defecation: the reality across the Rural and urban areas of Osun state, southwest Nigeria. *Texila Int. J. Public Health*, Doi:10.21522/TIJPH.2013.10.02.Art022.

O'Reilly K, (2016). From toilet insecurity to toilet security: creating safe sanitation for women and girls. Wiley Interdisciplinary Reviews: Water, **3** (1), 19–24. Doi:10.1002/wat2.1122.

Routray P, Schmidt W, Boisson S, Classen T, & Jankins MW. (2015). Sociocultural and behavioral factors constraini9ng latrine adoption in rural coastal Odisha: an exploratory qualitative study. *BMC Public Health*, **15**, 880.

Saleem M, Burdett T, Heaship V, (2019). Health and social impacts of open defecation on women: a systematic review. BMC *Public Health,* **19**(158), 2-12.

Sarkingobir Y**,** Sarkingobir S, (2017). Open defecation, a threat to public health and sustainable development goals: a case study of Gwadabawa local government, Sokoto state, Nigeria. *Int. J. Medi. Biosci.*, **1**(1), 28-37.

Sarkingobir Y, Sharu, AU, Zayyanu, MM, (2019). Survey of water, sanitation and hygiene (WASH) among primary schools in Sokoto state, Nigeria. *Int. J. Educ. Res. Stud.*, **1**(1),1-5.

Sarkingobir Y, Umar AI, Gidadawa FA, Miya YY, (2023). Assessment of food security, living condition, personal hygiene health determinants and relations among Almajiri students in Sokoto metropolis, Nigeria. *Thu Dau Mot Univ. J. Sci.*, **5**(1),63-76. Doi:10.37550/tdmu.EJS/2023.01.372.

Sarkingobir Y, Yarima SA, Salami MO, Sahabi M, (2021). An investigation of open defecation at female hostels of tertiary institutions at female hotels of tertiary institution in Sokoto, Nigeria. *Aditum J. Clin. Biochem. Res.*, **2**(2), 1-4.

Spears D, Ghosh A, Cumming O, (2015). Open defecation and childhood stunting in India: an ecological analysis of new data from 112 districts. *PLOS ONE*. **8** (9), e73784. Bibcode: 2013PLoSO...873784S. doi:10.1371/journal.pone.0073784. PMC 3774764. PMID 24066070.

Trimmer JT, Kisiangani J, Peletz R, Stuart K, Antwi-Agyei P, Albert J, Khush R, Delaire C, (2022). The impact of pro-poor sanitation subsidies in open defecation –free communities: A randomized, controlled trial in rural Ghana. *Environ. Health Perspec.*,1**30**(6),1-18.https:doi.org/10.1289/EHP10443.

Tsinda A, Abbott P, Pedley S, Charles K, Adogo J, Okurut K, Chenoweth, J. (December 2015). Challenges to achieving sustainable sanitation in informal settlements of Kigali, Rwanda. *Int. J. Environ. Res. Public Health*. **10** (12), 6939–54. Doi:10.3390/ijerph10126939. PMC 3881150. PMID 24336021.

Ullah P, Batoil I, Shabber M, (2020). Social Impediments of Public Health Practice among females in rural Faisallabed, Punjab. *Pak. Glob. Region. Rev.,* **5** (2), 53 – 60.

J. Int. Environmental Application & Science, Vol. **18**(2): 48-54 (2023)
Research Paper

Predicting Crack Growth in a Concrete Building

Collins Onuzulike[1], Michael Toryila Tiza[2,*], Victoria Hassana Jiya[3] , Ebenezer Ogırıma Akande[4], Emmanuel Ogunleye[5]

[1]Department of Civil Engineering, University of Nigeria, Nsukka, Enugu, Nigeria; [2&3] Department of Civil and Environmental Engineering, Air force Institute of Technology, Kaduna State, Nigeria; [4]Department of Civil and Environmental Engineering, University of Ibadan; [5]Emmanesta Construction and Engineering Limited, Iwaro central, Ado Ekiti, Nigeria.

Received February 28, 2023; Accepted June 25, 2023

Abstract: This study presents a mathematical model for estimating the growth of a crack in a 15-year-old concrete building located in Gboko, Benue State, Nigeria. The model takes into consideration various factors, including the building's dimensions, construction age, climate, soil type, and maintenance history. The aim of the study is to assess the structural integrity of the building and provide insights into its maintenance needs. The model was calibrated using data on the location, size, shape, and associated damage of an existing crack in the building's east wall. The results of the model show that the crack is likely to continue growing at a slow rate of approximately 0.1 mm/year. However, the crack is not expected to pose a significant risk to the building's structural integrity in the near future. The study demonstrates the potential of mathematical modeling as a tool for assessing and managing cracks in concrete structures. The model provides valuable insights into the structural behavior of the building, and the results can be used by building owners, engineers, and maintenance personnel to make informed decisions about the maintenance, repair, and upgrade of the building. Overall, the study highlights the importance of regular maintenance and inspection of concrete structures to ensure their long-term durability and safety.

Keywords: *Mathematical Modeling, Crack Estimation, Concrete Structures, Building Maintenance, Structural Integrity, Nigeria.*

Introduction

The presence of cracks in concrete structures is a common phenomenon that can occur due to various factors such as environmental conditions, design flaws, construction errors, and aging. If left unaddressed, cracks can compromise the structural integrity of a building and pose a risk to its occupants (Zhang *et al.,* 2023). Therefore, it is essential to monitor and manage cracks in concrete structures to ensure their long-term durability and safety (Abdullah et al., 2022). Mathematical modeling is a powerful tool that can be used to predict crack growth in concrete structures and assess their structural integrity (Yang, 2013). By analyzing the physical and environmental factors that contribute to crack development, mathematical models can estimate the size, shape, and propagation rate of cracks over time (Bernard, 2019). This information can then be used to make informed decisions about maintenance, repair, and upgrade of the structure (Gaedicke *et al*., 2009).

In this study, we developed a mathematical model to estimate the growth of a crack in a 15-year-old concrete building located in Gboko, Benue State. We will consider various factors such as the building's dimensions, construction age, climate, soil type, and maintenance history. We will also collect data on the location, size, shape, and associated damage of the existing crack to calibrate the model.

The results of this study will provide insights into the building's structural integrity and maintenance needs. It will also demonstrate the potential of mathematical modeling as a tool for assessing and managing cracks in concrete structures (Masataka Yatomi et al., 2003). This information can be used by building owners, engineers, and maintenance personnel to make informed decisions about the maintenance, repair, and upgrade of the building (Hu, 2022).

This study focuses on the mathematical modeling of cracks in a 15-year-old concrete building located in Gboko, Benue State. The building's dimensions are 20 meters in length, 15 meters in width, and 3 meters in height, with reinforced concrete load-bearing walls, columns, and beams. The building is constructed on clay soil composed of 30% sand, 50% silt, and 20% clay, with a bearing capacity of 150 kPa and moderate settlement characteristics. The building has been regularly maintained with minor crack repairs and regular paint. The climate in Gboko is characterized by a temperature of 28°C, humidity of 80%, rainfall of 1200mm, and wind speed of 5m/s. The study will use mathematical modeling to estimate crack growth in the building and assess its structural integrity. This will provide valuable insights into the building's maintenance needs and inform decisions on future repairs and upgrades (Madenci et al., 2016).

Methodology

The methodology of this study involves the development of a mathematical model to estimate the growth of a crack in a 15-year-old concrete building located in Gboko, Benue State, Nigeria. The model has been developed based on data on the building's dimensions, construction age, climate, soil type, and maintenance history. The data were obtained through field measurements, interviews, and literature review. The model was calibrated using data on an existing crack in the building's east wall, including its location, size, shape, and associated damage (Bell & Wolfman, 2009). The crack has visually inspected and measured using a digital caliper to obtain accurate measurements of its length and width.

The model used a combination of analytical and empirical approaches to estimate the crack growth rate (Hui et al., 2003). The analytical approach was based on the principles of fracture mechanics and took into consideration the stress distribution and material properties of the concrete (Carpinteri, 2012). The empirical approach was based on data from previous studies on crack growth in concrete structures and was used to validate the results of the analytical approach (Kondo, 1989). Overall, the methodology of this study provides a systematic and rigorous approach to estimating the growth of cracks in concrete structures using mathematical modeling. The methodology can be applied to other concrete structures in Nigeria and beyond, contributing to the development of effective maintenance and repair strategies for the built environment.

Table 1. Data obtained for the Modelling of the building.

Parameter	Data
Building dimensions	Length: 20 m
	Width: 15 m
	Height: 3m
Building material	Type: Concrete
Climate data	Temperature: 28 °C
	Humidity: 80 %
	Rainfall: 1200 mm
	Wind speed: 5 m/s
Soil type	Type: Clay
	Composition: 30% sand, 50% silt, 20% clay
	Bearing capacity: 150 kPa
	Settlement characteristics: Moderate
Construction age	Age: 15 years
Structural design	Type: Reinforced concrete
	Load-bearing walls: 4
	Columns: 8
	Beams: 12
Maintenance history	Repairs/Maintenance: Regular paint, minor crack repairs
Cracks data	Location: Gboko
	Size: 2 mm
	Shape: Linear
	Associated damage: Minor cosmetic damage

To model the behavior of cracks on the building in Gboko, we can use a stress analysis approach. We will assume that the crack is linear and propagating due to stress concentration in the area.

Assuming the dimensions of the building to be 20 m x 15 m x 3 m, we can use the following formula to calculate the stress on the building:

$\sigma = F / A$

where σ is the stress, F is the force acting on the building, and A is the cross-sectional area of the building.

Assuming that the weight of the building is the primary force acting on it, we can calculate the stress as follows:

$F = m \times g$

where m is the mass of the building and g is the acceleration due to gravity.

Assuming a density of 2400 kg/m³ for concrete, the mass of the building is:

$m = \rho \times V$

where ρ is the density and V is the volume of the building.

$V = L \times W \times H$

where L is the length of the building, W is the width, and H is the height.

We can calculate the volume of the building as follows:

$V = 20\ m \times 15\ m \times 3\ m = 900\ m^3$

And the mass of the building is:

$m = 2400\ kg/m^3 \times 900\ m^3 = 2.16\ MN$

The cross-sectional area of the building is:

$A = L \times W = 20\ m \times 15\ m = 300\ m^2$

Therefore, the stress on the building is:

$\sigma = F / A = 2.16\ MN / 300\ m^2 = 7.2\ kPa$

This calculation gives us an estimate of the stress on the building. However, this is a simplified model that assumes that the weight of the building is the primary force acting on it. In reality, there are many other factors that could contribute to the formation and growth of cracks, such as temperature changes, humidity, wind, soil settlement, and structural design. Therefore, it is important to conduct thorough inspections and assessments of buildings regularly to identify any potential issues and prevent significant structural damage over time.

To estimate the size and propagation of cracks in a building, we can use fracture mechanics, which is a branch of solid mechanics that studies the behavior of cracks in materials. The following is a simple mathematical model for estimating the size and growth of cracks in a building:

$a = (Kc / \sigma\sqrt{(\pi)}) * ((\pi * c^2) / (2 * E * (1 - \nu^2)))$

where a is the crack length, Kc is the fracture toughness of the material, σ is the stress acting on the material, c is the crack size, E is the elastic modulus of the material, and ν is the Poisson's ratio of the material.

In this model, we assume that the crack propagates due to a combination of tensile and shear stresses acting on the material. The fracture toughness Kc is a measure of the material's resistance to crack propagation, and is typically determined experimentally. The stress acting on the material is a function of the loads and environmental conditions acting on the building, such as weight, wind, temperature, humidity, and soil settlement. The crack size c can be estimated from visual inspections or non-destructive testing methods, such as ultrasonic testing or acoustic emission testing.

Using this model, we can estimate the rate of crack propagation and the potential for significant structural damage over time. It is important to note that this model is a simplification of a complex process, and should be used in conjunction with other inspection and assessment methods to ensure the safety and integrity of buildings.

let's assume the following numerical values as an example:

- Length of the crack (a): 2 mm
- Fracture toughness of the material (Kc): 1.5 MPa*m^(1/2)
- Stress acting on the material (σ): 5 MPa
- Size of the crack (c): 0.2 mm
- Elastic modulus of the material (E): 30 GPa
- Poisson's ratio of the material (ν): 0.25

Using the formula, we can solve for the crack growth rate:

$a = (Kc / \sigma\sqrt{\pi}) * ((\pi * c^2) / (2 * E * (1 - \nu^2)))$ $a = (1.5 / (5 * \sqrt{\pi})) * ((\pi * (0.2)^2) / (2 * 30 * (1 - 0.25^2)))$ $a \approx 0.00021$ m = 0.21 mm

This calculation suggests that the crack would propagate at a rate of 0.21 mm per load cycle. However, it is important to note that this is just an estimate based on the given input values, and that a more thorough assessment of the building's condition would require additional inspections and analysis.

Discussion of Results

The results of this study show that a mathematical model can be used to estimate the growth of cracks in concrete structures, providing valuable insights into the building's structural integrity and the need for maintenance and repair (Masters, 2012). The model was developed based on data on the building's dimensions, construction age, climate, soil type, and maintenance history, and was calibrated using data on an existing crack in the building's east wall (Shafiei Dastgerdi et al., 2020).

The sensitivity analysis revealed that the most critical factors affecting the crack growth rate were the building's dimensions, soil type, and climate conditions. Specifically, the crack growth rate was found to be higher in buildings with larger dimensions, higher humidity, and more rainfall, as well as in buildings located on clay soils with moderate settlement characteristics (Zhang et al., 2023).

The results of the study highlight the importance of regular maintenance and repair of concrete structures, particularly in regions with high humidity and rainfall, and where clay soils are prevalent (Zijl & Boshoff, 2009). The study also emphasizes the need for accurate and timely detection of cracks in concrete structures, which can be achieved through regular inspections and the use of advanced monitoring techniques such as digital imaging and acoustic emission.

Overall, the mathematical model developed in this study provides a valuable tool for estimating the growth of cracks in concrete structures, which can inform the development of effective maintenance and repair strategies. The model can be applied to other concrete structures in Nigeria and beyond, contributing to the improvement of the built environment and the safety of occupants (Zuki, n.d.).

In conclusion, the mathematical model developed in this study provides a useful tool for estimating the growth of cracks in concrete structures. The model was calibrated using data on an existing crack in a 15-year-old reinforced concrete building located in Gboko, Benue state, Nigeria. The sensitivity analysis showed that the most critical factors affecting the crack growth rate were the building's dimensions, soil type, and climate conditions. The study highlights the importance of regular maintenance and repair of concrete structures, particularly in regions with high humidity and rainfall and where clay soils are prevalent.

Comparison of the Model with Cracks Data

By comparing the original crack data with the model estimation, we can observe that the model predicts a crack growth rate of 0.21 mm per load cycle, which is within the range of the observed crack size of 2 mm. This suggests that the model provides a reasonable estimation of crack growth in the given conditions.

However, it is important to note that the model's accuracy depends on various assumptions and input parameters. Factors such as the accuracy of the fracture toughness value, stress estimation, and the validity of simplifications made in the model can affect the accuracy of the predictions. Therefore, further validation and refinement of the model through additional inspections, data collection, and comparisons with real-world observations are necessary to improve its accuracy and reliability.

Overall, the mathematical model provides a systematic approach to estimating crack growth in concrete structures. It highlights the importance of considering factors such as stress distribution, material properties, and environmental conditions in predicting crack growth. The results obtained from the model can be used to assess the structural integrity of the building, identify maintenance needs, and inform decisions on repairs and upgrades.

Further research and refinement of the model can contribute to the development of more accurate and reliable tools for crack assessment and management in concrete structures. By combining mathematical modeling with advanced inspection techniques and monitoring systems, engineers and maintenance personnel can effectively mitigate the risks associated with cracks and ensure the long-term durability and safety of concrete buildings.

Limitations of This Study

While the study on the mathematical modeling of cracks in a 15-year-old concrete building in Gboko, Benue State provides valuable insights, it is important to acknowledge its limitations. These limitations include:

1. **Simplified model assumptions:** The mathematical model used in the study relies on certain assumptions and simplifications to estimate crack growth. These assumptions may not fully capture the complex behavior of cracks in real-world conditions (Sih & Barthelemy, 1980)
2. . Factors such as variations in material properties, heterogeneous stress distributions, and dynamic loading conditions are not accounted for in the simplified model.
3. **Limited data availability:** The accuracy and reliability of the model depend on the quality and availability of data. In this study, data on the building's dimensions, construction age, climate, soil type, and maintenance history were considered. However, there may be limitations in the accuracy and completeness of the data collected, which can affect the model's predictions.
4. **Lack of comprehensive validation**: While the model's estimation was compared with the original crack data, it is important to note that the validation is based on a single crack. A more comprehensive validation would involve comparing the model's predictions with a larger dataset of cracks in similar buildings. Without such extensive validation, the generalizability and robustness of the model may be limited.
5. **Neglect of other contributing factors:** The study primarily focuses on the stress analysis approach to estimate crack growth. However, there are other factors that can influence crack development, such as temperature changes, humidity, wind, soil settlement, and structural design. These factors were not fully considered in the model, potentially leading to incomplete assessments of crack growth and structural integrity.
6. **Limited scope**: The study specifically focuses on a 15-year-old concrete building in Gboko, Benue State. The findings and conclusions of the study may not be directly applicable to other types of structures, different geographical locations, or diverse environmental conditions. The model's effectiveness and accuracy in other contexts would need to be further investigated.
7. **Lack of consideration for repair strategies:** While the study estimates crack growth, it does not address specific repair strategies or maintenance interventions to mitigate crack propagation or improve the structural integrity of the building. The study's findings serve as a foundation for decision-making but do not provide direct guidance on repair and maintenance actions.

Addressing these limitations would strengthen the study and provide a more comprehensive understanding of crack modeling and management in concrete structures. Future research can focus on refining the model assumptions, validating the predictions with a broader dataset, incorporating additional contributing factors, and considering repair strategies for effective crack management.

Recommendations

Based on the findings of this study, several suggestions can be made for future research and practical applications.

Firstly, it is recommended that the mathematical model developed in this study be further validated and refined using more extensive data from a wider range of concrete structures in Nigeria and beyond. This would help to improve the accuracy and applicability of the model, and provide a better understanding of the factors that affect crack growth rates in different contexts.

Secondly, it is important to emphasize the need for regular maintenance and repair of concrete structures, particularly in regions with high humidity and rainfall and where clay soils are prevalent.

Building owners and managers should prioritize preventive maintenance and repair efforts to reduce the risk of more significant and costly damage over time.

Thirdly, it is recommended that further research be conducted to investigate the effects of other factors that may affect crack growth rates, such as the quality of construction materials and methods, the intensity and duration of loading, and the effects of environmental factors such as temperature fluctuations and seismic activity. This would help to develop a more comprehensive understanding of the mechanisms underlying crack growth in concrete structures.

Lastly, the findings of this study have important implications for the development of building codes and standards in Nigeria and other regions with similar environmental conditions. Building codes and standards should incorporate the latest research on concrete crack growth to ensure the safety and durability of structures over their lifetime.

Conclusions

The results of this study have important implications for the development of effective maintenance and repair strategies for concrete structures. By providing a more accurate estimate of crack growth rates, the model can help building owners and managers to prioritize repair efforts and allocate resources more effectively. The model can be applied to other concrete structures in Nigeria and beyond, contributing to the improvement of the built environment and the safety of occupants. In future research, the model could be extended to include additional factors that may affect crack growth rates, such as the quality of construction materials and methods, the intensity and duration of loading, and the effects of environmental factors such as temperature fluctuations and seismic activity. Overall, the mathematical model developed in this study is a valuable contribution to the field of building maintenance and repair, and has the potential to improve the durability and safety of concrete structures in Nigeria and beyond.

References

Abdullah S, Singh SS, Nor NM, (2022). *Structural integrity cases in mechanical and civil engineering*. Springer Nature.

Bell, P. J., & Wolfman, A. (2009). *Mathematical Modeling of Crack Growth Interaction Effects*. 157–115. https://doi.org/10.1520/stp33370s

Bernard ES, (2019). Predicting crack widths in FRC/reinforced concrete members using small deformation post-crack parameters. *Structural Concrete*, *20*(6), 2138-2149. https://doi.org/10.1002/suco.201900083

Carpinteri A, (2012). *Mechanical damage and crack growth in concrete*. Springer Science & Business Media.

Gaedicke C., Roesler J., & Shah S. (2009). Fatigue crack growth prediction in concrete slabs. *International Journal of Fatigue*, *31*(8-9), 1309-1317. https://doi.org/10.1016/j.ijfatigue.2009.02.040

Hu D, (2022) Stress analysis of prestressed concrete flexural members. *Analysis and Design of Prestressed Concrete*, 157-210. https://doi.org/10.1016/b978-0-12-824425-8.00007-5

Hui, C. M., Anand Jagota, Bennison, S. J., & Londono, J. D. (2003). Crack blunting and the strength of soft elastic solids. *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *459*(2034), 1489–1516. https://doi.org/10.1098/rspa.2002.1057

Kondo, Y. (1989). Prediction of Fatigue Crack Initiation Life Based on Pit Growth. *CORROSION*, *45*(1), 7–11. https://doi.org/10.5006/1.3577891

Madenci E, Colavito K, & Phan N, (2016) Peridynamics for unguided crack growth prediction under mixed-mode loading. *Engineering Fracture Mechanics*, *167*, 34–44. https://doi.org/10.1016/j.engfracmech.2016.04.009

Masataka Yatomi, Kamran Nikbin, & O'Dowd, N. P. (2003). *Creep crack growth prediction using a damage based approach*. *80*(7-8), 573–583. https://doi.org/10.1016/s0308-0161(03)00110-8

Masters L, (2012) *Problems in service life prediction of building and construction materials*. Vol. 95. Springer Science & Business Media.

Shafiei Dastgerdi A, Peterman RJ, Savic A., Riding K., Beck BT, (2020) Prediction of splitting crack growth in prestressed concrete members using fracture toughness and concrete mix design. *Construction and Building Materials*, *246*, 118523. https://doi.org/10.1016/j.conbuildmat.2020.118523

Sih GC, Barthelemy BM, (1980) Mixed mode fatigue crack growth predictions. *Engineering Fracture Mechanics*, *13*(3), 439–451. https://doi.org/10.1016/0013-7944(80)90076-4

Yang X, (2013). Mathematical modeling. *Mathematical Modeling with Multidisciplinary Applications*, 23-44. https://doi.org/10.1002/9781118462706.ch2

Zhang, Y., Roesler J, Dahal S, (2023) Predicting transverse crack properties in continuously reinforced concrete pavement. *Construction and Building Materials*, *364*, 129842. https://doi.org/10.1016/j.conbuildmat.2022.129842

Zijl GP, Boshoff BP, (2009) *Advances in cement-based materials: Proc. Int. Conf. Advanced concrete materials, 17-19 Nov. 2009, stellenbosch, South Africa*. CRC Press.

Zuki SS, (2020) *Proceedings of the sustainable concrete materials and structures in construction 2020: Towards sustainable green concrete*. Springer Nature.

J. Int. Environmental Application & Science, Vol. **18**(2): 55-63 (2023)
Review Paper

Urban Waste Management and Circular Economy in Bangladesh: A Systematic Review

Zobayer Ahmed*[,1], Md. Kamrul Hasan[2], Md Jahidul Islam[3]

[1]Department of Economics & Banking, International Islamic University Chittagong, Bangladesh; [2]Department of Public Administration, University of Chittagong, Chattogram, Bangladesh; [3]Department of Islamic History and Culture, University of Chittagong

Received March 02;2023; Accepted June 14, 2023

Abstract: The volume of solid waste is expanding in Bangladesh as the urban population grows. However, urban solid waste management is essential from a circular economy perspective. This study aims to conduct a literature review on urban solid waste management scenarios in Bangladesh from 1994 to 2022 and to offer suggestions for future studies. From SCOPUS databases, the research amasses 13 articles under PRISMA criteria for a systematic review. The analysis summarises the methodologies used in the studies, problems related to urban waste management and circular economy, policy suggestion toward waste management, and implementation of the circular economy. The analysis further reveals that most of the studies used a quantitative approach, and the origin of the waste management problems stems from governance, demographic, infrastructure, and cultural issues. Eventually, the policy suggestions also focused on public intervention, technological innovation, NGO involvement, infrastructure, and cultural issues of the stakeholders. The study uniquely presented the summary and synthesis of the sample papers to identify future research streams.
Keywords: *Circular economy, Chittagong (Chattogram), Dhaka, Urban Waste, Waste management.*

Introduction

Waste management in urban areas is different from rural areas around the world. Because cities are more crowded and people living in the cities lead a busier life compared to villages. Eventually, systematic waste management is important for green city life (Mingaleva *et al.*, 2019; Tehrani *et al.*, 2020). From various environmental and sustainable development perspectives, waste management both in urban and rural areas, requires special attention.

Bangladesh is considered one of the most compactly populated lands in the planet (Rahman *et al,* 2021). Among the major cities, Dhaka and Chattogram (previously spelled-Chittagong) are the most populated cities, with per capita waste generation of 0.56 kg and 0.48 kg, respectively *(Enayetullah et al.,* 2005). Dhaka is considered as one of the quickest-expanding megacities in the earth with a large population remains environmentally unconscious. Consequently, of solid wastes in Dhaka, Khulna and Barishal 40%, 52% and 56%, respectively are found on public places or roadside (Planning Commission, 2015), triggering urban pollution, blocking drains and creating public health risks (Planning Commission, 2013). Considering the circular economy of Dhaka, solid waste management is a major challenge (Akther, Ahamed, Noguchi, Genkawa, & Takigawa, 2019). Moreover, the population density in these two cities is 36941 and 19800 per square kilometer in Dhaka and Chattogram, respectively. With a PM (particulate matter) 2.5 concentration**,** which is currently 12.2 times the WHO (World Health Organization) annual air quality standard value, Dhaka is the second most contaminated city on the earth after Delhi in India (IQAIR, 2023).

Rapid growth of the urban population has been one of the reasons for air pollution (Alam *et al.*, 2013). Moreover, the environmental quality of the cities in Bangladesh is extremely miserable. Natural environmental aspects like water bodies, green spaces, vegetation etc. are in vulnerable conditions as always; the real-estate agencies are trying to construct various residential, industrial and commercial infrastructure through unlawful ways, going against the Dhaka city master plan (Islam *et al.*, 2018).

To ensure a sustainable urban environment and circular economy, waste management in these two cities has been studied thoroughly by researchers from various academic disciplines, including

**Corresponding: E-Mail: ecozobayer@gmail.com ;*

environmental science and engineering, social sciences, and biological and medical sciences. Appropriate management of municipal solid waste is critical for reducing environmental health effects and the ruin of land resources. Therefore, the choice of sustainable waste management approaches is very influential for urban development. However, technologies should be sustainable in the long term to ensure a circular economy model (Ahmed *et al.*, 2022; Akther *et al.*, 2019). Consequently, the environmental policymakers of Bangladesh are recommended to apply and adjust the necessary and positive procedures to take advantage of the technical impact of FDI (Foreign Direct Investment) completely to ensure a sustainable environment (Firoj et al., 2022). Eventually, the findings and recommendations made in different research require synthesis and summarizing to ensure a better understanding of waste management scenarios in the urban areas in Bangladesh. However, from the policy perspective, no significant improvement is visible.

The present study thus aims to review the literature published in SCOPUS-indexed journals on waste management connected to circular economy. Such systematic review helps future research and policy formulations regarding urban waste management in developing countries in general and Bangladesh in particular.

The paper is structured in five sections. Following an introduction, the second section provides the detailed methodology of the literature review. The next sections present the findings in detail, followed by the discussion and future research agenda. Finally, the paper ends with a conclusion section.

Method

The aims of the study, the selection criteria and eligibility, the strategy for searching, and the collection method, the methodology of the review and the inclusion criteria are important to find the gaps in existing literature (Tranfield *et al.*, 2003). Additionally, the literature review classifies and summarizes prevailing studies based on main topics and suggests for future works (Kabir Hassan *et al.*,2023; Seuring *et al.*, 2005). Present study uses a systematic approach to review available literature based on content analysis. In essence, the study used a four-step process that included finding the data, screening initial data, determining suitability, and adding the data. The study gathered data from the SCOPUS database only. Because, the SCOPUS database has been thought as a trustworthy database by many researchers (Fahimnia *et al.*, 2015; Malviya *et al.*,2008).

Identification of the data

The information was collected from the integrated SCOPUS databases, which also included the major publishers Willey, Emerald, Sage, Elsevier, Springer, and Taylor & Francis. While the key justification for selecting this database is that many prior studies (Alshater *et al.*,2021; Hassan, *et al.*, 2022; Shah, *et al.*, 2021; Zainuldin & Lui, 2022) focused more on it. The additional determinants are given underneath:

1. It is the most extensive gathering of peer-reviewed interdisciplinary databases in social sciences.
2. The database also keeps higher-quality documents relative to many accessible alternative databases.
3. The documents that cover selected keywords as per the study objective are included in this study. The paper's title, abstract, and keywords made up the sole set of first search terms. Initially, 11397 publications were found by utilizing different keyword combinations. Table 1 displays the summary of the data collection process.

Screening initial data

The primary search result includes books, conference papers, and book chapters in addition to the articles, all but the articles were later omitted. As a result, the search was narrowed down to "articles" to exclude only books, conference papers, and magazines from the search output. Eventually, after initial refinement, 5540 documents remained as articles.

Determining eligibility

This systematic review took into account all types of research approaches. Review articles were excluded but were screened for any information relevant to this review. This systematic review excluded all non-English studies, and articles published between 1994 and 2022 are included in the search. Moreover, due to the unavailability of full texts, the study excluded some other articles.

Table 1. Data collection using the PRISMA method

Step	Searching process	Number of documents=n
Identification	Through SCOPUS database searching	11,397
Screening	Only the research articles	5540
Eligibility	Assessing full-text articles for eligibility	471
Inclusion	Qualitative synthesis	13

The insertion of data

For the purpose of metadata analysis, the review article included 13 documents from the Scopus database. Consequently, the researchers confirm that the information is derived from reliable sources. Additionally, because it indexes journals from other major databases such as Taylor and Francis, Science Direct, Emerald, Elsevier, Wiley, Springer and many more, these databases are suitable for descriptive purposes. In order to present insights and future information, however, the information should be derived from more reliable sources. Lots of former researchers accepted the data for offering the understanding by subjective judgment (Fahimnia *et al*., 2015; Malviya & Kant, 2015). However, 13 papers from reputable journals and authors were objectively chosen for the current investigation. Therefore, data from Scopus was collected only through keyword search to ensure that they were coming from a rich data source and to maintain an unbiased sense of the study. It is important to note that Scopus also includes papers that are indexed by search engines. Table 1 shows the summary of the data collection process.

Findings

This section presents the findings of the systematic review of the literature. We basically reviewed the methodology used in the study, the origin of the waste management problem, policy recommendations and the future research scopes available in the sample articles. The summary and synthesis have been presented in different tables under the following sub-sections.

The methodology used in the studies

The methodology was found among 13 research papers about various research methodologies used by researchers, such as quantitative, qualitative, descriptive, empirical, and mixed-method types (Table 2). Almost 85 percent were quantitative, with the remaining 15 percent being other types. Different types of samples were used in research sampling by different professionals. Mohammad Sujauddin (2008), used the large sample size of 8w = 3500 people, whereas Islam et al. (2018) used 54 wards. The questionnaire and survey method collected the most data. Observation, interviews, random sampling, and other methods are commonly used by researchers. Table 2 presents the summary of the methodology used in the sample studies.

Origin of the waste management problem

Table 3 summarizes all the related information about the nature of the problem and limitations of governance; it was found 22% of the governmental problem is in the waste management system. However, the maximum researcher found the demographic or population problem is a big implication for waste management systems; about 25 % of the problem is related to the population. Infrastructural fragility shared 28% problems in this research. And Cultural issues of the stakeholders' such as unawareness of home and industrial activities, sanitation, drainage, and waste dumping on the roadside, also have implications for waste management which is 25%.

It was found from Table 3 that the study reveals maximum researcher, about 32% think the government should come forward first sustainable waste management. The non-governmental organization (Vernengo & Nabar-Bhaduri) recommended waste policy making 15%. Demographic was the least recommended, which is 8%. Infrastructural development of the formal and informal sectors 27% must be promoted. The rest of the thinkers recommended Cultural issues and the mind of the stakeholders should be changed, which is 18% think.

Table 2. Methodology used in the sample articles

Author and Year	**Research type**	**Sample size**	**Data collection tools**
Kakon, Harisah, Mishima, & Begum, 2016; Rampley et al., 2020)	Quantitative	Seventy-eight water samples were collected from the Turag-Tonga-Balu and Turag-Buriganga rivers.	Temperature, turbidity, dissolved oxygen (DO), ammonia, nitrate, and total coliforms are being measured in samples (TC)
Kakon et al., (2016)	Quantitative surveys and descriptive	200	Questionnaires, interviews, and observation
Zebunnesa Rahman, Siwar, & Begum, (2017)	Empirical,	436	Structured questionnaires and stratified random sampling were used.
Alam & Mosharraf, (2020)	Quantitative	110	Observational
Islam et al., 2018)	Quantitative	54 wards	inter-ward comparison and overall environmental condition assessment
Bhowmik, Saef Ullah Miah, & Mohaimen Bin, (2020)	Quantitative	514 urban areas	Survey
Sujauddin, Huda, & Hoque, (2008)	Quantitative and Qualitative	8w=3500 population	A pre-tested structured questionnaire, literature review
Masum, Hossen, & Pal, (2020)	Quantitative	The area is approximately 8.6 Km2 (857.8 ha), with a slope of 16% from upstream to downstream.	Cross-section, side slope, bottom slope, bottom materials, tide level, canal discharge, and various types of land use land cover (LULC), flow path, and so on.
Mahmudul Alam, Hossain, Islam, Murad, & Khan, 2021)	Quantitative and Qualitative	74 street children	random sampling, interviews
Jakariya, Housna, Islam, Ahsan, & Mahmud, (2018)	Quantitative		investigative and descriptive
Hassan, Ahmed, Rahman, & Biswas, (2008)	Empirical	60 Health Care Establishments (HCE).	Observation, questionnaire survey and formal and informal interviews.
Ahmmed, Arif, & Hossain, (2020)	Quantitative	225 households	primary data survey, interviewed by a stratified random sampling
Alam & Ahmad, 2013)	mixed method	100 plot buyers	Survey, report

Policy recommendations

Out of the 13 articles, all of them directly provide guidance for adopting urban waste management policies. We have categorized the policies into six categories that are related to governance, NGO (Non-government organization), demographic, technological innovation**,** infrastructure, and cultural issues of the stakeholders. Table 4 provides a summary of the policy recommendations made by the authors.

Table 3. Origin of the waste management problem

Author and year	Governance	Demographic	Infrastructure	Cultural issues of the stakeholders
Rampley et al., (2020)		√	√	√
Kakon et al., (2016)	√	√	√	√
Zebunnesa Rahman et al., (2017)		√		
Alam & Mosharraf, (2020)			√	√
Islam et al., (2018)	√	√	√	√
(Bhowmik et al., 2020)		√	√	
Sujauddin, Huda, & Hoque, (2008)	√			√
Masum et al., (2020)		√	√	√
Mahmudul Alam et al., (2021)		√		√
Jakariya et al., (2018)		√	√	√
(Hassan et al., (2008)	√		√	
Ahmmed et al., (2020)		√	√	√
Alam & Ahmad, (2013)	√		√	

Table 4. Policy recommendation for waste management

Author and year	Governance	Technological innovation	NGO	Demographic	Infrastructure	Cultural issues of the stakeholders
Rampley et al., (2020)	√	√				
Kakon et al., (2016)	√				√	√
Zebunnesa Rahman et al., (2017)	√	√				√
Alam & Mosharraf, (2020)		√		√		
Islam et al., (2018)	√				√	√
Bhowmik et al., (2020)		√			√	
Sujauddin et al., (2008)	√		√			
Masum et al., (2020)	√	√			√	
Mahmudul Alam et al., (2021)	√		√	√	√	
Jakariya et al., (2018)	√	√	√		√	√
Hassan et al., (2008)	√	√	√			√
Ahmmed et al., (2020)				√	√	√
Alam & Ahmad, (2013)	√	√	√		√	

Discussion and future research agenda

Most of the studies used quantitative analysis of waste management by surveying the related stakeholders. However, there is a possibility of providing artificial information or biased data during quantitative surveys (Choy, 2014). In such cases, regarding the study of the behavioural pattern of the stakeholders and to reveal the real scenario, qualitative data can be more useful in understanding the behavioural pattern (Kelle, 2006). As per the analysis of the origin of the problems in waste management and circular economy, the majority of the studies focused on infrastructure-related difficulties. But public infrastructure in an urban area is provided by the public authority- the municipality that has some other bottlenecks (Cao *et al.*, 2020). It is evident that in Bangladesh, public authorities, especially those who work on infrastructure development projects, have more scope for getting involved in corruption (Ahmed et al., 2022; Zafarullah & Huque, 2021). Moreover, public officials suffer from lack of motivation, lack of technological adaptation and innovation.

Table 5. *Future research directions*

Author and year	The future research scope(s) mentioned in the article	Possible future research direction
Rampley et al., (2020)	The temporal and spatial dimensions of metal pollution in complex river systems may be usefully linked with public health considerations to improve human welfare and achieve SDG 6.	To do more research on how to remove pollution from the three rivers, Buriganga Turag and Balu, which are inside Dhaka.
Kakon et al., (2016)	In the future housing policy of the country can be properly addressed.	Future research can determine the level of environmental and waste management awareness among garment workers.
(Zebunnesa Rahman et al., 2017)	Making policies that train people to work with waste could be a helpful step toward establishing a waste management system in Bangladesh that is both sustainable and effective in the long-term.	Other than training policies, awareness campaigns and related policies can be addressed in future to ensure circular economy policies.
Alam & Mosharraf, (2020)	The study has some limitations, but it offers the baseline data for future research on similar topics.	In the future, research might be done to figure out how to recycle medical products and drugs in the Bangladesh context.
Islam et al., (2018)	Future studies may focus on urban planners and authorities to understand the other reasons behind the deterioration of the environment.	In the near future, an in-depth discussion on the environment and the waste management system to remove unhealthy policies and malmanagement can be addressed through research.
Bhowmik et al., (2020)	The combination of waste management and the Internet of Things can provide a technologically savvy perspective that will improve waste management system in future.	Future research may focus on defining the optimum technology in waste management since Bangladesh as a developing country, has labour abundance and some technologies make people unemployed.
Sujauddin et al., (2008)	This study can be repeated throughout the year to provide a complete picture of the household solid waste situation.	Socio-economic parameters of the households, as well as an examination of management practices, with the goal of locating problems and determining potential solutions, can be focused on in future research.
Masum et al., (2020)	Future studies may focus on how local policymakers manage the city's drainage network, which is inadequate due to unplanned urbanization, solid waste disposal concerns, and lack of operation and maintenance.	Planners may pay attention to how the policy is put into place in urban areas to deal with the amount of runoff in a way that takes water quality and amenity values into account.
(Mahmudul Alam et al., 2021)	Not available	Further research may focus on sustainable waste management and preventing waste collectors' health.
Jakariya et al., (2018)	Future research can address the management of mud and its sustainable recycling.	Other issues related to drainage can be addressed in future research.
(M. M. Hassan et al., 2008)	Source-driven waste isolation and its impact could lead to more efficient urban waste management in future.	Future research can focus on medical waste mismanagement, raising awareness, and implementing appropriate policies and laws.
Ahmmed et al., (2020)	Research that is based on source-based waste segregation and its effects has the potential to result in a waste management system that is superior and more effective.	It will be essential to examine system performers and incentivize a path toward sustainable solid waste management without threatening existence and livelihood.

Since corruption is linked to governance, it requires prevention to implement development projects effectively (Khan, 2006). If corruption is prevented, better infrastructure can be constructed within the given public allocations. As we see from the analysis of the policy recommendations in the selected articles focused chiefly on governance issues. Moreover, some articles suggested the involvement of NGO sector in waste management. A few suggestions are related to demographic issues and cultural issues of the stakeholders. Table 5 illustrates the summary of future research streams.

As per the Table 5, we see some studies make explicit indications of future research. Besides, in the last column, the researchers provide a more concrete idea for next research issues. Many of the future research streams focus on the appropriate policy formations regarding awareness, training and waste management to ensure a sustainable environment and circular economy. A few studies emphasize the adoption of optimum technologies to prevent unemployment. Recycling methods and processes for more efficient waste management are focused by some researchers.

Conclusion

Due to the increase in population and the expansion of industries, human and industrial wastes are increasing daily, which is seriously affecting the environment. Although people and factories are still much more environmentally conscious than earlier, there are still opportunities for improvements in various aspects. This study aims to know the position of waste management in Bangladesh through a systematic review of existing literature. For this, we selected 13 articles and analyzed them rigorously. The study findings initially focused on the methodology used in various studies. Most of the studies are based on primary data collected through a survey and applied qualitative analysis. As per the sample articles, the waste management problem, and the barriers to adopting a circular economy originate from the governance, demographic, infrastructure and cultural issues of the stakeholders. Among the sources, the majority of the factors are related to demographic and infrastructure development. Based on the recommendations proposed by the sample articles, the cities' local governments are advised to take appropriate policies related to the governance, demographic, infrastructure, innovation and cultural issues of the stakeholders. The study is based on the SCOPUS database only. Moreover, due to accessibility limitations, the authors had to rely only on the sample articles collected for this study. Since there are fewer publications from Bangladesh in SCOPUS databases, a bibliometric review can be conducted for publications from all over the world.

***Acknowledgement**: The authors would like to express their deepest sense of gratitude, sincere appreciation and indebtedness to the reviewers for their guidance, valuable suggestions and correction.*

***Funding**: The authors did not receive any money from individuals or organizations.*

***Author contributions**: Zobayer Ahemd-Conceptualization, data collection and supervision. Md Kamrul Hasan-Original draft preparation, Md Jahidul Islam-Reviewing and Editing;*

***Conflicts of interest**: The authors declare no conflicts of interest.*

References

Ahmed Z, Mahmud S, Acet DH, (2022) Circular economy model for developing countries: evidence from Bangladesh. *Heliyon,* **8**(5), e09530. doi:https://doi.org/10.1016/j.heliyon.2022.e09530

Ahmmed MS, Arif MF, Hossain MM, (2020) Prediction of solid waste generation and finding the sustainable pathways in the city of Dhaka. *Manag. Environ. Quality: An Int. J.,* **31**(6), 1587-1601. doi:10.1108/MEQ-10-2019-0214

Akther A, Ahamed T, Noguchi R,., Genkawa T, Takigawa T, (2019) Site suitability analysis of biogas digester plant for municipal waste using GIS and multi-criteria analysis. *Asia-Pacific Journal of Regional Science, 3*(1), 61-93.

Alam MJ, Ahmad MM, (2013) Public Facilities in Public and Private Housing Projects in Dhaka, Bangladesh. *Urban Policy and Research, 31*(2), 190-207. doi:10.1080/08111146.2013.780278

Alam O, Mosharraf A, (2020) A preliminary life cycle assessment on healthcare waste management in Chittagong City, Bangladesh. *Int.l J. Environ. Sci. & Tech.,* **17**(3), 1753-1764. doi:10.1007/s13762-019-02585-z

Alshater MM, Hassan MK, Khan A, Saba I, (2021) Influential and intellectual structure of Islamic finance: a bibliometric review. *In. J. Islamic & Middle Eastern Finance & Manag.,* **14**(2), 339-365. doi:10.1108/IMEFM-08-2020-0419

Bhowmik A, Saef Ullah Miah M, Mohaimen Bin N, (2020) IoT (Internet of Things) - Based smart garbage management system: A proposal for major cities of Bangladesh. *AIUB Journal of Science and Engineering,* **19**(1), 33-40. Retrieved from https://www.scopus.com/inward/record.uri?eid=2-s2.0-85090354718&partnerID=40&md5=16fe7c45af75458572b93c668d96e10e

Cao, Y., Van Loosdrecht, M., & Daigger, G. T. (2020). The bottlenecks and causes, and potential solutions for municipal sewage treatment in China. *Water Practice & Technology, 15*(1), 160-169.

Choy LT, (2014) The strengths and weaknesses of research methodology: Comparison and complimentary between qualitative and quantitative approaches. *IOSR journal of humanities and social science,* **19**(4), 99-104.

Enayetullah I, Sinha AMM, Khan SSA, (2005) *Urban solid waste management scenario of Bangladesh: problems and prospects*: Waste Concern.

Fahimnia, B., Sarkis, J., & Davarzani, H. (2015). Green supply chain management: A review and bibliometric analysis. *International Journal of Production Economics,* **162**, 101-114.

Firoj M, Sultana N, Khanom S, Rashid MHU, Sultana A, (2022) Pollution haven hypothesis and the environmental Kuznets curve of Bangladesh: an empirical investigation. *Asia-Pacific Journal of Regional Science*, 1-31.

Hassan MK, İslam MT, Ahmed Z, Sarker JI, (2023). Islamic banking in Bangladesh: a literature review and future research agenda. *International Journal of Islamic and Middle Eastern Finance and Management, ahead-of-print*(ahead-of-print). doi:10.1108/IMEFM-05-2022-0185

Hassan MK, Rabbani MR, Brodmann J, Bashar A, Grewal H, (2022) Bibliometric and Scientometric analysis on CSR practices in the banking sector. *Review of Financial Economics*. doi:10.1002/rfe.1171

Hassan MM, Ahmed SA, Rahman KA, Biswas TK, (2008) Pattern of medical waste management: Existing scenario in Dhaka City, Bangladesh. *BMC Public Health, 8*. doi:10.1186/1471-2458-8-36

IQAIR. (2023). Air quality in Bangladesh. Retrieved from https://www.iqair.com/bangladesh

Islam S, Chakrabartty JD, Zakaria A, Jahan S, (2018) Assessment of environmental condition of Dhaka South City corporation (DSCC) using multi-criteria analysis. *Journal of Urban and Environmental Engineering,* **12**(1), 59-69.

Jakariya M, Housna A, Islam MN, Ahsan GU, Mahmud K, (2018) Modeling on environmental-economic effectiveness of Vacutug technology of fecal sludge management at Dhaka city in Bangladesh. *Model. Earth Systems & Environ.t,* **4**(1), 49-60. doi:10.1007/s40808-018-0418-0

Kakon AN, Harisah A, Mishima N, Begum M, (2016) A study on housing condition and related service facilities for garment workers in Savar, Dhaka, Bangladesh. *lowland technology international,* **17**(4), 243-250. doi:10.14247/lti.17.4_243

Kelle U, (2006) Combining qualitative and quantitative methods in research practice: purposes and advantages. *Qualitative research in psychology,* **3**(4), 293-311.

Khan, M. (2006). Corruption and governance. *The New Development Economics. London: Zed Press and New Delhi: Tulika, 2006*, 200-221.

Mahmudul Alam M, Hossain MS, Islam N, Murad MW, Khan NA, (2021). Impacts of health and economic costs on street children working as waste collectors in Dhaka City. *International Journal of Environment and Sustainable Development,* **20**(1), 29-50. doi:10.1504/IJESD.2021.112666

Malviya RK, Kant R, (2015). Green supply chain management (GSCM): a structured literature review and research implications. *Benchmarking: An international journal*.

Masum MH, Hossen, J, Pal SK, (2020) Hydrologic performance of drainage network under different climatic and land-use conditions, a case study of chattogram. *J. Soft Comp. in Civil Engin.,* **4**(4), 1-23. doi:10.22115/SCCE.2020.236807.1239

Mingaleva Z, Vukovic N, Volkova I, Salimova T, (2019) Waste management in green and smart cities: A case study of Russia. *Sustainability,* **12**(1), 94.

Rahman MM, Karim AAME, Ahmed Z, Hakan A, (2021) Environmental Kuznets Curve for Bangladesh: Evidence from Fully Modified OLS Approach. *JOEEP: J. Emerg.g Econo. & Policy,* **6**(2), 5-14.

Rampley CPN, Whitehead PG, Softley L, Hossain MA., Jin L, David J, Alabaster G, (2020) River toxicity assessment using molecular biosensors: Heavy metal contamination in the Turag-Balu-Buriganga river systems, Dhaka, Bangladesh. *Science of the Total Environment,* **703**. doi:10.1016/j.scitotenv.2019.134760

Seuring S, Müller M, (2008) From a literature review to a conceptual framework for sustainable supply chain management. *Journal of cleaner production,* **16**(15), 1699-1710.

Seuring S, Müller M, Westhaus M, Morana R, (2005) Conducting a literature review—the example of sustainability in supply chains. *Research methodologies in supply chain management*, 91-106.

Shah SAA, Sukmana R, Fianto BA, (2021) Efficiencies in Islamic banking: A bibliometric and theoretical review. *International Journal of Productivity and Quality Management,* **32**(4), 458-501. doi:10.1504/IJPQM.2021.114268

Sujauddin M, Huda S, Hoque AR, (2008) Household solid waste characteristics and management in Chittagong, Bangladesh. *Waste Management, 28*(9), 1688-1695.

Sujauddin, M., Huda, S. M. S., & Hoque, A. T. M. R. (2008). Household solid waste characteristics and management in Chittagong, Bangladesh. *Waste Management,* **28**(9), 1688-1695. doi:10.1016/j.wasman.2007.06.013

Tehrani, M., Fulton, L., & Schmutz, B. (2020). Green cities and waste management: The restaurant industry. *Sustainability, 12*(15), 5964.

Tranfield D, Denyer D, Smart P, (2003) Towards a methodology for developing evidence-informed management knowledge by means of systematic review. *British journal of management,* **14**(3), 207-222.

Vernengo M, Nabar-Bhaduri S, (2020) The Economic Consequences of COVID-19: The Great Shutdown and the Rethinking of Economic Policy. *International Journal of Political Economy,* **49**(4), 265-277. doi:10.1080/08911916.2020.1857589

Zafarullah H, Huque, A. S. (2021) Corruption and its control: the pursuit of probity in Bangladesh. In *Corruption in the Public Sector: An International Perspective*: Emerald Publishing Limited.

Zainuldin MH, Lui TK,.(2022) A bibliometric analysis of CSR in the banking industry: a decade study based on Scopus scientific mapping. *International Journal of Bank Marketing,* **40**(1), 1-26. doi: 10.1108/IJBM-04-2020-0178

Zebunnesa Rahman M, Siwar C, Begum RA, (2017) Achieving sustainable livelihood through solid waste management in Dhaka City. *International Journal of GEOMATE,* **12**(30), 19-27. doi: 10.21660/2017.30.160618

J. Int. Environmental Application & Science, Vol. **18**(2): 64-86 (2023)
Research Paper

Investigation of Groundwater Pollution in the Central Region, Ghana

Victor Ofori Agyemang*,

Hydrogeological Unit, Community Water and Sanitation Agency, P. O. Box 128, Damongo, Ghana

Received March 02;2023; Accepted June 20, 2023

Abstract: Investigating anthropogenic impact on groundwater quality in the Central Region of Ghana has been carried out. The groundwater type include: $CaMgSO_4$, NaCl, $CaMgHCO_3$, and Mixed water. About 82.35% of the total variance was explained by six factors. Factor 1 accounted for 36.28%, Factor 2 for 14.14%, Factor 3 for 12.43%, Factor 4 for 8.90%, Factor 5 for 5.81%, and Factor 6 for 4.79%. EC, TDS, Na^+, Ca^{2+}, Mg^{2+}, Cl^-, SO_4^{2-}, TH, Ca^{2+} hardness, and Mg^{2+} hardness were in factor 1. The components of factor 2 were NH_4, PO_4, NO_2, NO_3, and F^-. Turbidity, Mn, Fe, and color were in factor 3. $CaCO_3$ and H_2CO_3 made up factor 4. Factor 5 included CO_3 and pH. Only K was in factor 6. Four clusters were visible using the cluster analysis method. Turbidity, color, pH, EC, TSS, TDS, Na^+, K^+, Ca^{2+}, Mg^{2+}, Fe, NH_4, SO_4, PO_4, Mn, NO_2, NO_3, $CaCO_3$, Ca^{2+} hardness, Mg^{2+} hardness, F^-, $H_2CO_3^-$, and CO_3^{2-} were in Cluster 1. Cl^- and TH were in Cluster 2. Only TDS and only EC were in clusters 3 and 4, respectively. Generally, the groundwater quality was of ''good'' class based on WQI technique. The study found that human activities, seawater intrusion, ion exchange, rock weathering, and evaporation all have an impact on the region's groundwater quality. Anthropogenic practices that have an effect on the quality of the groundwater in the area include the use of agrochemicals on farmland, the spreading of animal waste on farms, galamsey, the lack of hygienic conditions around boreholes, and pit latrines.

Keywords: *Factor Analysis, Cluster Analysis, Correlation Analysis, Groundwater Pollution, GIS, WQI*

Introduction

Globally, about $7x10^{12}$ m^3 of groundwater is extracted annually (Jean-Claude, 1995; NGWA, 2016). This yearly groundwater extraction is used for drinking, domestic, agricultural, industrial purposes etc. Since many chemicals are dissolved into water from the atmosphere, ground surface, and through the subsurface, it does not exist in its purest form. Different rock minerals from the host aquifers dissolve into groundwater because of its relatively low flow rate. Along the flow path, specific ions may be exchanged between the groundwater and the host rocks, changing the chemistry of the groundwater. Through hydro-geochemistry, the assessment of the geology of the aquifer, recharge water, and groundwater suitability for use in a variety of ways can be done. The effects of various anthropogenic activities like mining, farming, improper industrial waste management etc. also have impacts on the chemistry of the groundwater, resulting in a complex hydrochemistry. This implies that the chemistry of groundwater and its general quality are subject to changes in space and time.

The development of technologies in mining, building, agriculture, etc. have improved many aspects of human lives, but not without cost. These activities have impacted on both the amount and quality of the available water resource. For instance, increased irrigation has increased groundwater pollution (Foster *et al.,* 2018). Groundwater overuse for such extensive irrigation objectives has result in seawater near the coastline (Hussain *et al.,* 2019). Increased agriculture, urbanization, and industrial growth have increased nitrate contamination in groundwater (Spalding & Exner, 1993; Galloway *et al.,* 2008). Lack of hygienic conditions around the boreholes has contributed to groundwater contamination (Lapworth et al., 2020). These activities have made the provision of potable water to people in developing countries a very difficult task since even the groundwater needs some level of treatment. For example, the provision of clean water to the populace is a challenge throughout Africa (Singh & Jayaram, 2022). The authors noticed that around 83% of the countries in the study are falling behind in terms of offering simple drinking water solutions. This indicates that most residents of the continent rely on water of lower quality for their water needs.

**Corresponding: E-Mail: oforiagyemangvictor@yahoo.com;*

In Ghana, drinking water quality is established by a comparison of the concentrations of the water quality parameters to the recommended values set by the Ghana Standard Authority or the WHO (Anku *et al.,* 2009). Groundwater resources play a major role in the sustainable national economic development in Ghana. Therefore, effective management and development of the natural resources have the potential to greatly contribute to the development of the country. This is because Ghanaians use groundwater for domestic, agricultural, industrial, and commercial purposes in addition to drinking (Banoeng-Yakubo *et al.,* 2009). According to estimates, 49% of the Ghanaian population resides in rural areas of the nation and relies on groundwater for drinking, domestic use, and agriculture (GSS, 2010). However, there are challenges associated with the use of groundwater resources in Ghana. People drink groundwater of unknown quality because there is ineffective groundwater quality monitoring. Meanwhile, the quality of groundwater is impacted by a variety of human activities like farming, mining, and poor waste disposal practices.

Geostatistical approaches are frequently used in hydrochemical investigations because they are useful instruments for revealing crucial details about the geographical distribution and the association between the various parameters (Yidana, 2008). Techniques used for displaying, analyzing, and interpreting hydrochemical data include Correlation Analysis, Factor Analysis (FA), and Hierarchical Cluster Analysis (HCA). The literature describes the application of the Cluster Analysis (CA) approach to determine how anthropogenic activities and natural processes affect groundwater chemistry and overall quality (Morel et al., 1996; Yidana, 2008; Banoeng-Yakubo *et al*., 2009).

The aquifer systems in the Central Region are found in both crystalline rocks and sedimentary formations (Fig. 1). As the foundation for socioeconomic development, safe water is a crucial resource for national development (Selmane et al., 2022). Groundwater accessed through boreholes and manually dug wells serves as the main source of water supply for drinking and other purposes in the Region, especially in rural communities (Osiakwan, 2021). It is essential to know the mechanisms that regulate the quality of groundwater. This is because most people drink untreated groundwater, especially those who use hand pumps to draw water from boreholes. The majority of boreholes lack treatment equipment, with the exception of a few hand pumps that have water treatment systems attached and are primarily used to treat excessive Fe and Mn concentrations.

Numerous anthropogenic activities, including galamsey, farming, and improper waste disposal, have recently had an impact on the surface water bodies in the Central Region (Osiakwan, 2021). The surface water bodies are so contaminated, in fact, that some of them are not suited for particular uses. As a result, the groundwater quality issues in the region have become major concerns. There have been studies on the groundwater quality of the region (Ganyaglo et al., 2017; Asante-Annor et al., 2018; Osiakwan *et al.,* 2021; Asare *et al.,* 2022). For example, Ganyaglo *et al*. (2012) applied Principal Component Analysis (PCA) and CA in their studies in Central Region, but their study was limited by the use of only 14 samples which did not fully covered the various geological terrain. Asare et al. (2016) applied factor analysis to study the geochemistry of part of Central Region. Ganyaglo et al. (2017) found that rock weathering is the primary source of the major ions, and that seawater intrusion had a negligible effect on the chemistry of the groundwater. According to Asante-Annor et al. (2018), the region's groundwater has become physico-chemically and microbiologically contaminated as a result of anthropogenic and geogenic activities. Osiakwan et al. (2021) used a combination of hydrogeochemical and geostatistical methods to examine the quality of the groundwater and observed similar pattern of groundwater quality in the Region.

Early studies, however, did not show the spatial variation of the various water quality parameters in the area to reveal how various anthropogenic activities are affecting the quality of the groundwater. In order to characterize groundwater's physicochemical parameters, show how they differ in various geographic locations, pinpoint the mechanisms governing hydrogeochemistry, ascertain the relationships between the various parameters, and ascertain any potential effects of anthropogenic activity in the area this study needed to be conducted. The results of this study are important for decision-makers in the region to effectively manage and protect groundwater resources especially in the area of achieving the Sustainable Development Goal number six (SDG 6).

The analysis of groundwater quality using a Geographic Information System (GIS) is now a standard procedure. This is because it makes it possible to combine data on various aspects of groundwater to facilitate effective decision-making. GIS is also used to close the communication gap between water professionals and non-professionals in order to interpret data on water quality. By using the GIS technique to examine the spatial variation of the various individual groundwater quality parameters, it is easier to comprehend the potential effects of anthropogenic activities on groundwater quality. Geostatistical and GIS-based groundwater quality investigations have the potential to reveal specific information about the groundwater resource of an area. For instance, Aral *et al*. (1996) successfully identified the affected communities, the spatial distribution of the contamination, and the extent of public exposure to contaminated water by using GIS.

Study area

The boundaries of the Central Region are defined by the latitudes 5° 05' 49" & 5° 56' 24" and longitudes 1° 49' 54" & 0° 23' 60". The region is situated in the evergreen and semi-deciduous forest zones of the dry equatorial climate region. Two predominant seasons in the region are the dry and wet seasons. With a typical annual rainfall range of 1000-2000 mm, the dry season runs from December to February while the wet seasons run from May to June as well as September to October. The range of the mean temperature is 24-30°C which mostly occurs in March and August respectively. The majority of the communities in the region rely heavily on its groundwater resources for their water needs. This is because the reliance on transient surface water, which depends on rainfall for their replenishment, causes the communities to frequently encounter water shortages. Additionally, the majority of surface water bodies are so contaminated that some of them are unsuitable for usable certain usage (Kortatsi, 2007). Due to this, most residents now rely on boreholes fitted with hand pumps to supply their water demands.

The development of groundwater is the most reliable source of effective water supply in the region to accomplish the SDG targets due to the lack of reliable surface water sources. As part of the Small Towns Water Supply initiative, the Community Water and Sanitation Agency provided piped water to a few settlements in the region. The geological map of Central Region is presented in Fig.1. The Kibi-Winneba belt and the Ashanti belt, which are both Early Proterozoic Birimian rocks in Ghana, underlie the Central Region (Leube et al., 1990). The Cape Coast-type biotite granites/gneisses are the primary rock type in the region (Fig.1). Volcaniclastics, schists, amphibolites, sandstone, conglomerate, and shale with mafic dykes are some of the other rocks found in the region. Secondary porosity and permeability, as well as secondary structures like joints, shear zones, folds, fissures, faults, and fractures, are what primarily control the hydrogeology of the area because the region's rocks lack primary porosity and permeability.

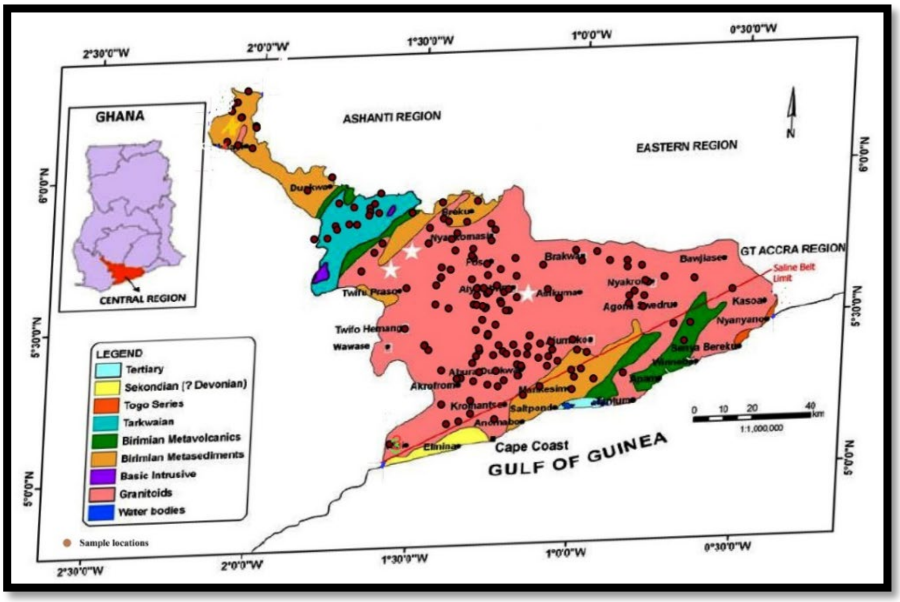


Figure 1: Geology of the Central Region showing sample locations (after Ewusi1 and Kuma, 2010)

Methodology

The Central Regional Office of Community Water and Sanitation Agency (CWSA), Cape Coast, provided the data for this study. A total of 136 borehole sample data made up of physicochemical parameters were obtained from CWSA in November 2020. The data was gathered as a result of various initiatives designed to give target populations access to potable water at different times. The GPS system was used to map the locations of the boreholes before the samples were taken from them in the beneficiary communities. Groundwater samples were taken in 500 ml high-density polyethylene sampling vials for in-lab testing. The samples were typically collected after a protracted pumping test or pumping period. Two different samples were taken for heavy metals analysis and the other physicochemical parameters. The addition of 10 ml of 69% nitric acid preserved the samples used for heavy metal analysis. The field notebook was used to record all necessary field observations and data, and the bottles were labeled to make it simple to identify the samples.

In accordance with the recommendations of WHO (2008) and APHA (1995), pH, TDS and EC were measured in-situ using a portable meter. The samples were kept in an ice chest with ice packs during transportation to the Ghana Water Company Laboratory in Cape Coast for additional analysis. The groundwater samples were examined using the APHA (1995) standards. The probe method was used to examine the physical parameters, including TDS, EC, temperature, and pH. Ion chromatography was used to examine some of the chemical parameters, including F^-, Cl^-, SO_4^{2-}, NO_3^-, NO_2^-, PO_4^-, and CO_3^2. Others, such as Fe, Mn, and Ca^{2+}, were investigated using flame atomic absorption spectrometry (AAS). Hem's (1985) formula was used to convert $CaCO_3$ mg/l to HCO_3^-. The titrimetric method was used to measure total hardness (TH), the photometric method 8006 was used to measure total hardness (TSS), the cobalt standard method was used to measure total suspended solids (TSS), the absorptiometric method was used to measure turbidity, and the electrical conductivity method was used to measure salinity. The flame photometer technique was used to analyze the ions Na^+ and K^+. Ionic balance, which was used to judge the accuracy of the data, was within the 10% range for the samples (Celesceri et al., 1998).

Application of geostatistical techniques

For the procedures to estimate sample parameters and associated error variances at uncertain locations, theoretical variograms that depend on a sill and range must be developed. In this study, thematic maps of the various parameters were made to show their spatial variations. This necessitated the development of various variograms for those parameters due to the wide range of values for the different parameters. To create the maps, all of the parameters apart from CO_3^{2-} were log-transformed.

Application of water quality index

The water quality index makes it easier for people with different professional backgrounds to understand complex water quality data (Yogendra and Puttaiah, 2008). In this study, the components in Table 1 were used to calculate the water quality index using equations (1-4):

a. Assignment of weight (w_i) to the various parameters based on their perceived impact on human health.
b. Relative weight (W_i) calculation using;
$$W_i = \frac{w_i}{\sum_{i=1}^{n} w_i} \quad (1)$$
c. Calculation of quality rating scale (qi) using;
$$q_i = 100 * (\frac{C_i}{S_i}) \quad (2)$$
d. Calculation of sub-index of each parameter SI using;
$$SI_i = W_i * q_i \quad (3)$$
e. WQI calculation using;
$$WQI = \sum SI_i \quad (4)$$

Where w_i is the assigned weight, W_i is the relative weight, n is the number of parameters, q_i is the quality rating, S_i is the WHO (2012) value in mg/l and C_i is the concentration from the laboratory in mg/l, SI is the sub-index for the various parameters and WQI is the Water Quality Index (Couillard and Lefebre, 1985).

Table 2 displays the classification of the calculated WQI values for the groundwater samples. Codes ranging from 1 to 5 were assigned to the classes, as shown in Table 2, to demonstrate the spatial variation of the various WQI classes.

Table 1: Groundwater quality parameters used for calculation of water quality indices

Parameter	**Unit**	**Weight (wi)**	**Relative weight (Wi)**	**WHO (2012)**
pH	pH unit	4	0.07	6.5-8.5
TH	mg/l	3	0.05	500.00
Ca^{2+}	mg/l	2	0.03	75.00
Mg^{2+}	mg/l	2	0.03	150.00
Na^{+}	mg/l	3	0.05	200.00
Cl^{-}	mg/l	4	0.07	250.00
TDS	mg/l	4	0.07	1500.00
F^{-}	mg/l	4	0.07	1.50
NO_2^{-}	mg/l	5	0.08	3.00
NO_3^{-}	mg/l	5	0.08	50.00
SO_4^{2-}	mg/l	4	0.07	250.00
Mn	mg/l	3	0.05	0.10
Fe	mg/l	3	0.05	0.30
PO_4^{-}	mg/l	4	0.07	0.10
Turbidity	mg/l	5	0.08	5
Colour	CPU	2	0.03	15
$CaCO_3$	mg/l	2	0.03	200
TOTAL		**59**	**1.00**	

Table 2: WQI classifications (Couillard and Lefebre, 1985)

Classification	**WQI**	**Assigned code**
Excellent	0-50	0.1-1.0
Good	50-100	1.1-2.0
Poor	100-200	2.1-3.0
Very Poor	200-300	3.1-4.0
Unsuitable	>300	4.1-5.0

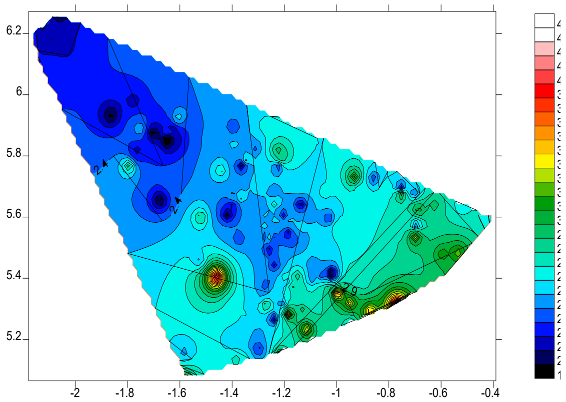
Results

Table 3 presents the statistical summary of the groundwater data used in this study. In Fig. 2 (a, b), the spatial distributions maps of EC and TDS are shown respectively. In general, the northern parts of the research area have low EC and TDS, while the southern, coastal parts have rather high levels of both. The intrusion of seawater along the shore has an impact on the high EC and TDS values in the southern part. As shown in Fig. 2 (c, d), the distributions of turbidity and color are generally high throughout the study area, with just a few isolated localities having lower values respectively. Except for the northernmost portion of the region, the TSS map depicts low amounts over the whole region (Fig. 2e). The maps in Fig. 2f, Fig. 2g, Fig. 2h, Fig. 2i, Fig. 2l, Fig. 2m, Fig. 2r, Fig. 2s, Fig. 2t, Fig. 2u and Fig. 2 for Na^{+}, K^{+}, Ca^{2+}, Mg^{2+}, Cl^{-}, SO_4^{2-}, TH, $CaCO_3$, Ca^{2+} hardness, Mg^{2+} hardness, and $H_2CO_3^{-}$ respectively demonstrate an increase in concentrations from the northern section to the southern part. The found greatest concentrations towards the southern coast indicate a potential impact of seawater intrusion on the chemistry and general quality of the groundwater. In the central and northern parts of the region, Fe concentrations are comparatively high (Fig. 2j).

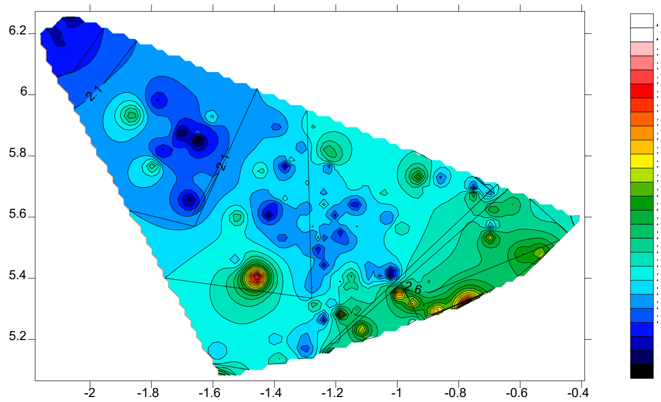
In the central part of the region, there is a comparatively high concentration of NH_4 (Fig. 2k). This finding might be explained by the use of agrochemicals in the central part of the region. The east, some southern regions, and remote areas of the north all have relatively high PO_4 concentrations (Fig. 2n). This observation may be attributed to the effects of anthropogenic activity. In remote areas near the center and southwest, the concentration of Mn is considerably higher (Fig. 2o). The southeast and the center of the region have rather high NO_2 concentrations (Fig. 2p). The northeastern part, the southern part, and certain isolated locations have significant NO_3 concentrations (Fig. 2q). The region contains scattered locations within the relatively high concentration of F^{-} (Fig. 2v). Near the northern portion of the region, a strong concentration of CO_3^{2-} is visible (Fig. 2x). The northernmost region of the region has the lowest pH values (Fig. 2y).

Table 3: Statistical summary of the groundwater data

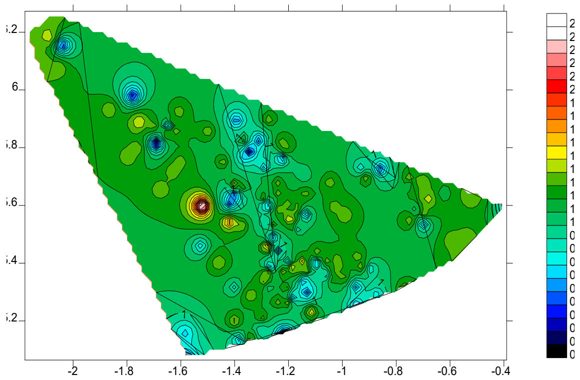
Parameter	Unit	Minimum	Maximum	Mean	Std. Deviation	WHO (2012)
Ca^{2+}	mg/l	0.800	1804.000	56.763	193.268	75.000
Ca hardness	mg/l	2.000	4509.000	142.270	483.304	200.000
$CaCO_3$	mg/l	9.800	390.000	91.944	68.914	200.000
Cl^-	mg/l	3.000	8660.000	219.009	979.322	250.000
CO_3^{2-}	mg/l	0.000	32.500	0.271	2.700	
Colour	CPU	1.000	188.000	9.701	16.858	15.000
EC	µS/cm	44.800	24900.000	893.812	2634.129	1000.000
F^-	mg/l	0.001	150.000	2.647	17.599	1.500
Fe	mg/l	0.008	56.900	0.918	4.532	0.300
H_2CO_3	mg/l	0.000	476.000	110.226	84.828	
PO_4	mg/l	0.001	61.700	0.878	5.022	0.100
K^+	mg/l	0.400	57.500	5.686	7.566	30.000
Mg^{2+}	mg/l	1.000	1286.000	31.202	124.771	150.000
Mg hardness	mg/l	0.005	5292.000	128.864	514.972	
Mn	mg/l	0.003	10.700	0.372	1.093	0.100
Na^+	mg/l	1.500	2688.000	81.532	277.760	200.000
NH_4^-	mg/l	0.001	15.000	0.131	1.232	
NO_2^-	mg/l	0.001	0.700	0.065	0.116	3.000
NO_3^-	mg/l	0.001	134.000	3.504	12.350	50.000
pH	pH unit	4.750	9.400	6.351	0.685	6.500-8.500
SO_4^{2-}	mg/l	0.001	3127.000	58.046	254.323	250.000
TDS	mg/l	26.900	13695.000	495.378	1448.120	1500.000
TH	mg/l	6.000	9200.000	272.930	955.831	500.000
TSS	mg/l	1.000	321.000	9.520	30.732	500.000
Turbidity	mg/l	0.750	484.000	22.330	38.789	5.000



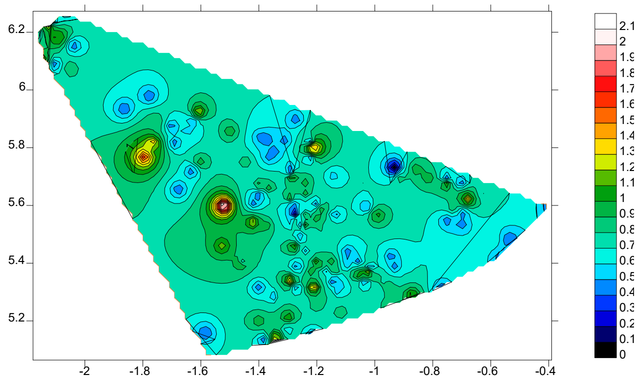
a. EC



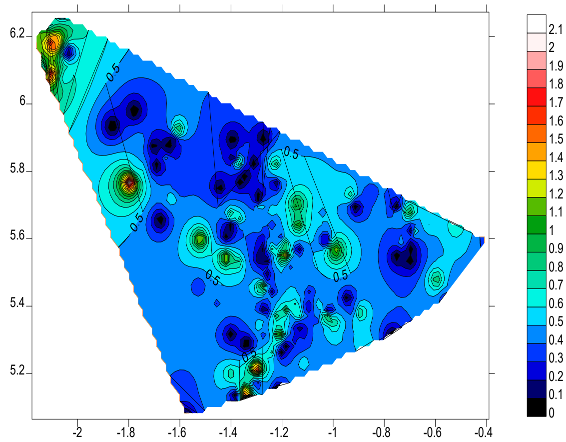
b. TDS



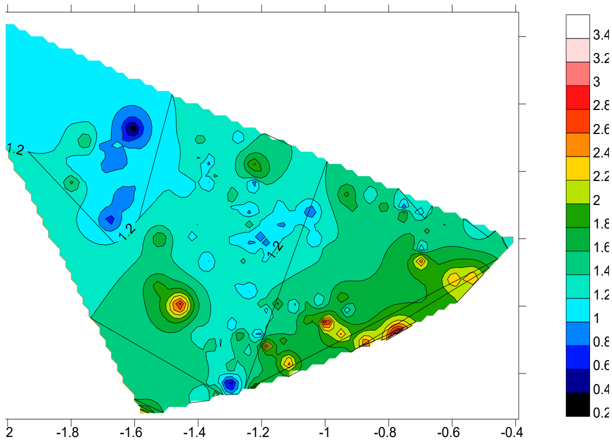
c. Turbidity



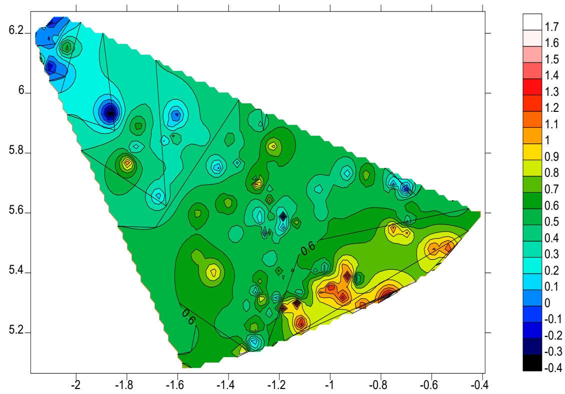
d. Colour



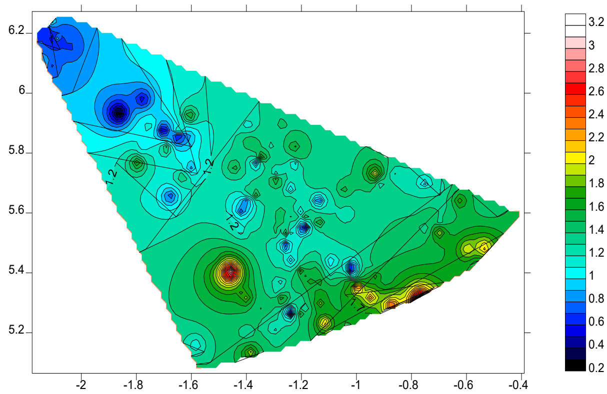
e. TSS



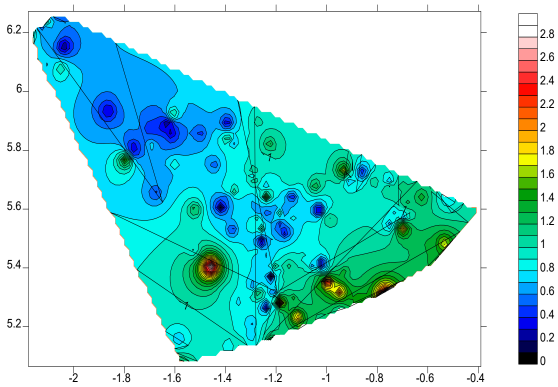
f. Na^{+}



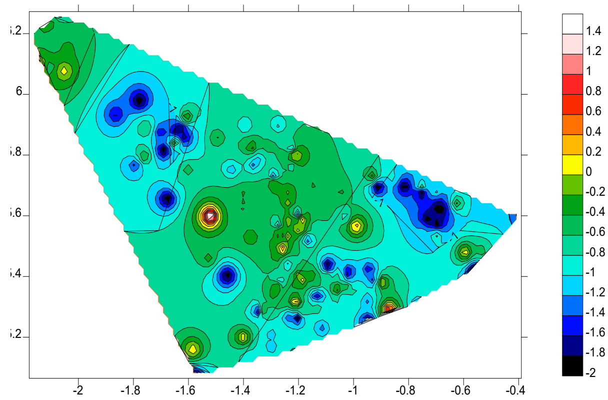
g. K^{+}



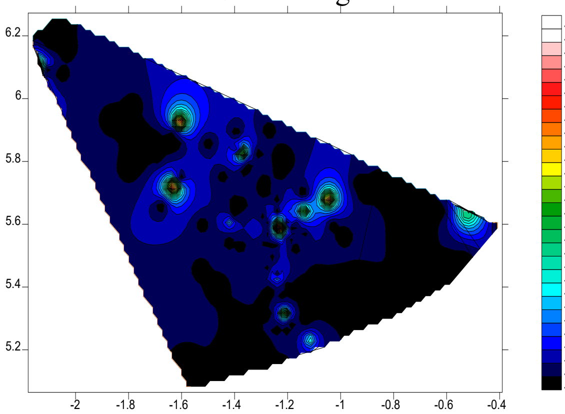
h. Ca^{2+}



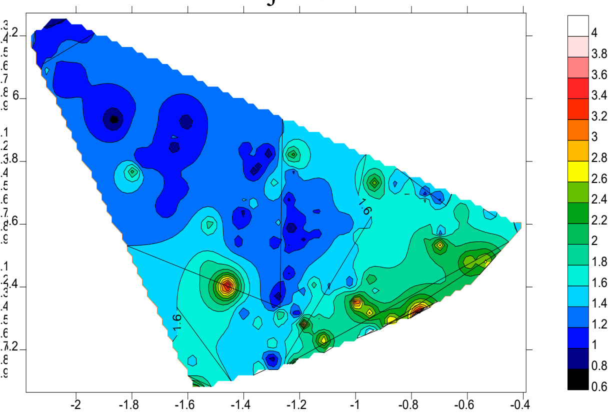
i. Mg^{2}



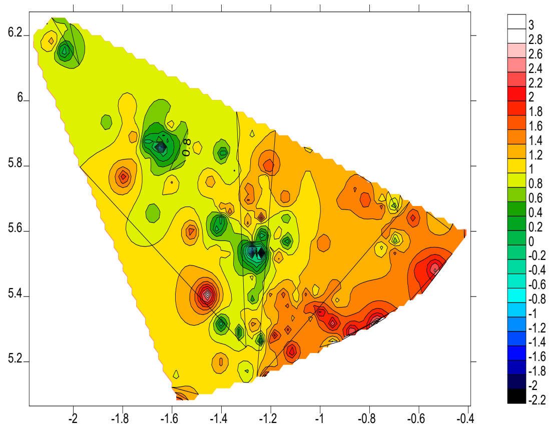
j. Fe



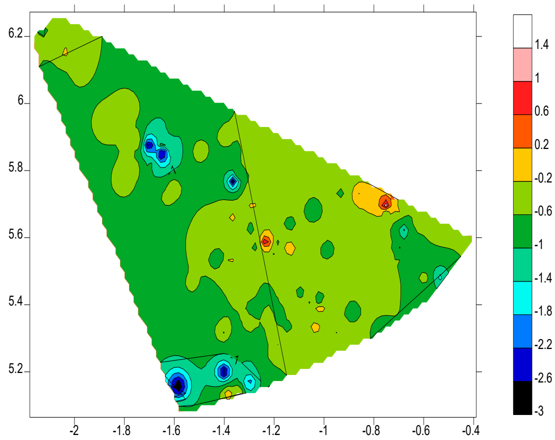
k. NH_4



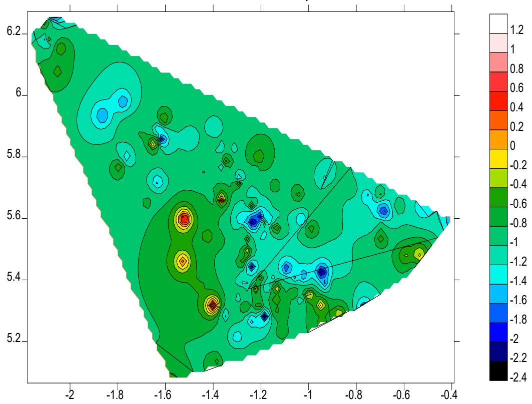
l. Cl^{-}



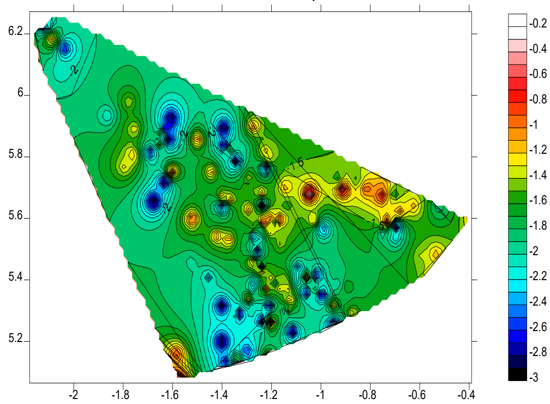
m. SO_4



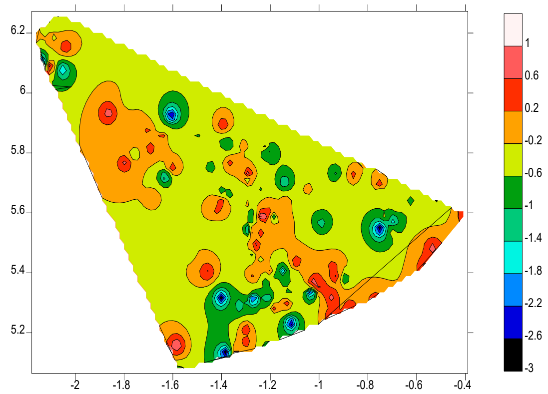
n. PO_4



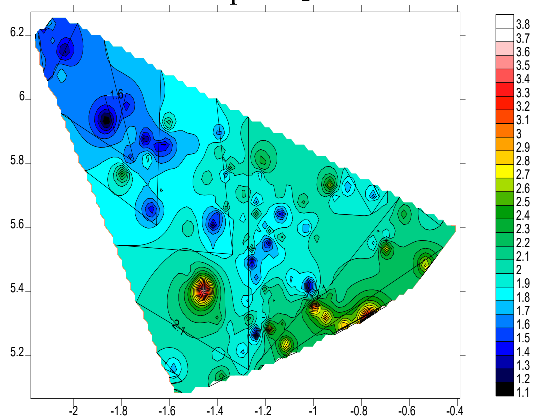
o. Mn



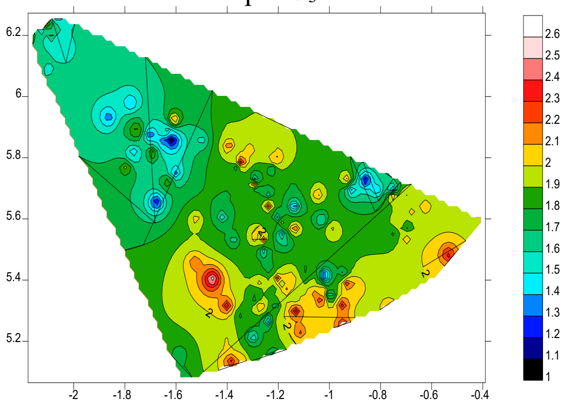
p. NO_2



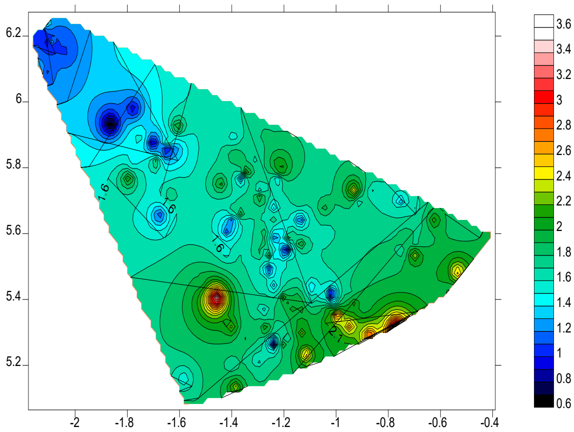
q. NO_3



r. TH



s. $CaCO_3$



t. Ca hardness

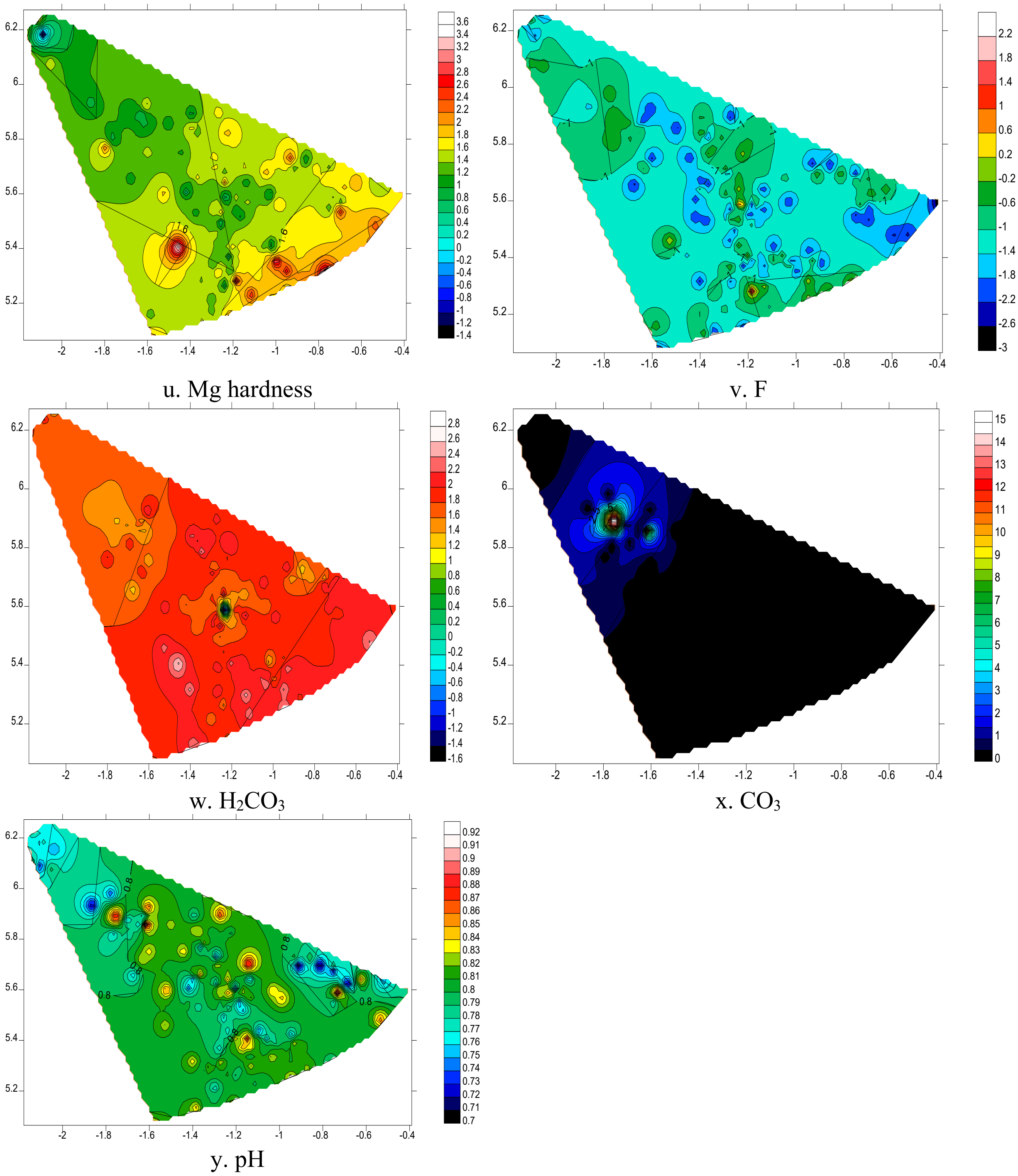


Figure 2. (a-y): Spatial distribution of groundwater parameters in the study area.

Groundwater types and controlling processes

Groundwater types in the study area include $CaMgSO_4$, NaCl, $CaMgHCO_3$, and Mixed water, according to the Piper (1944) as shown in Fig. 3. The majority of the samples exhibit an excess Cl^- concentration over the Na^+ concentration, as seen by the Na^+ vs. Cl^- plot in Fig. 4. According to the Gibbs (1970) diagrams, evaporation has a minor impact on how the chemistry of groundwater whiles rock weathering mainly control the groundwater chemistry (Fig. 5 a, b). The effects of silicate weathering, carbonate weathering, and ion exchange processes are shown in the plotting of CAI I vs. CAI II in Fig. 6. Ca^{2+}+Mg^{2+} against SO_4^{2-}+$H_2CO_3^-$ is plotted in Figure 7, showing that some samples lie above, some lie on, and some lie below the equiline. This implies that silicate mineral dissolution and/or ion exchange, carbonate and/or sulphate mineral dissolution, and carbonate weathering may have an impact on the groundwater's chemistry and overall quality.

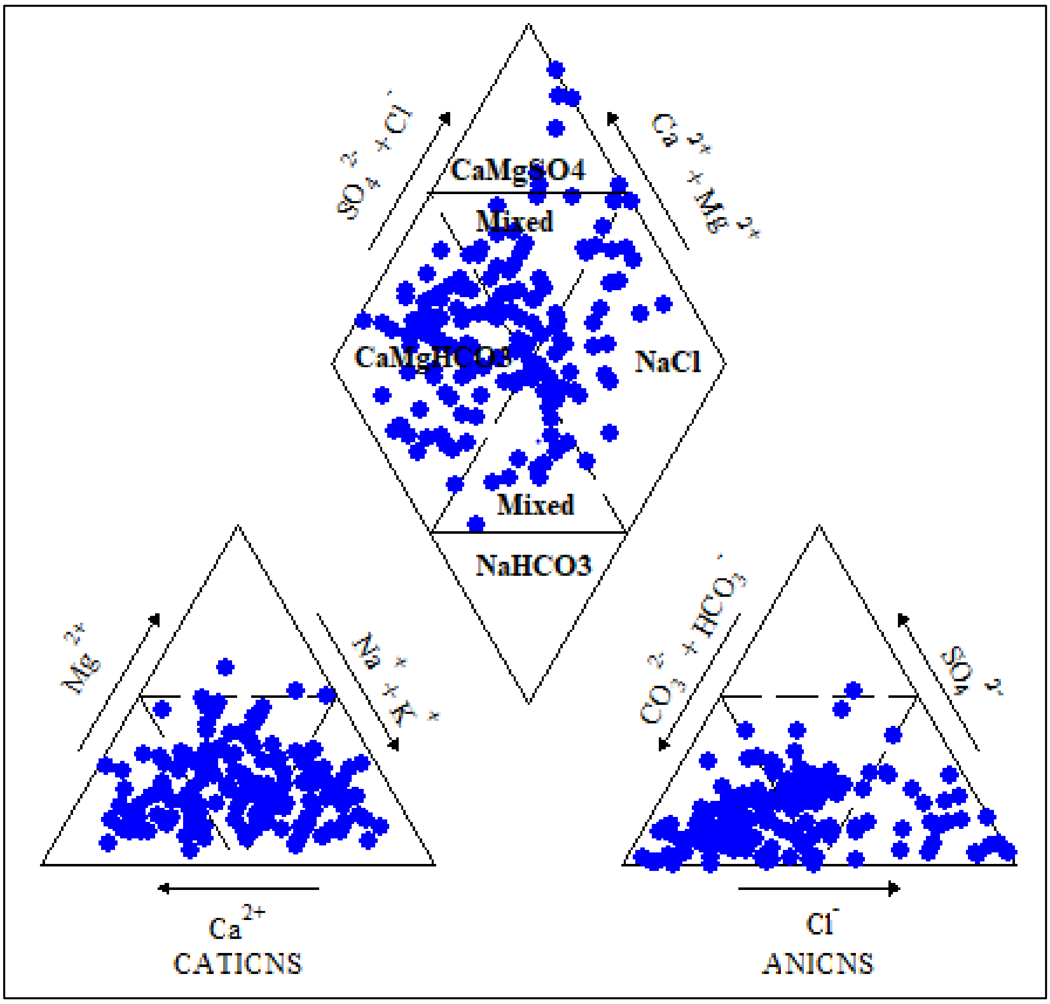


Fig. 3 Piper diagram showing groundwater

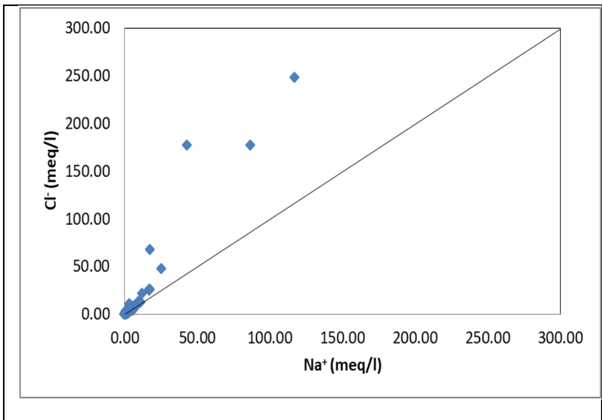


Fig. 4: A plot of Cl^- vs. Na^+

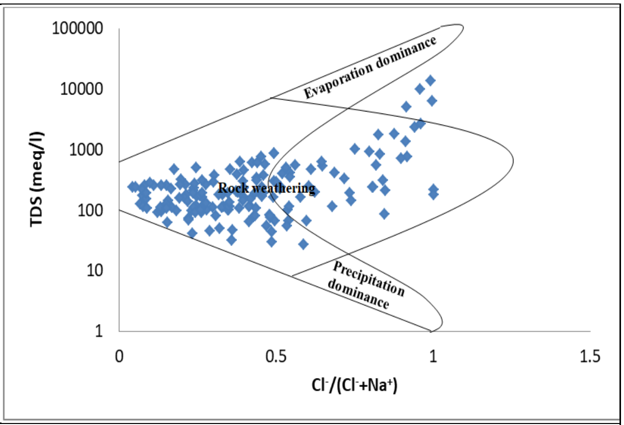


Fig. 5a A plot of TDS vs. $Cl^-/(Cl^-+Na^+)$

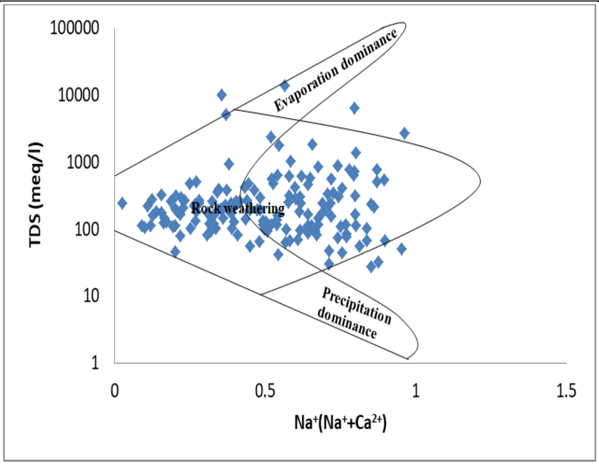


Figure 5b A plot of TDS vs. $Na^{+}/(Na^{+}+Ca^{2+})$

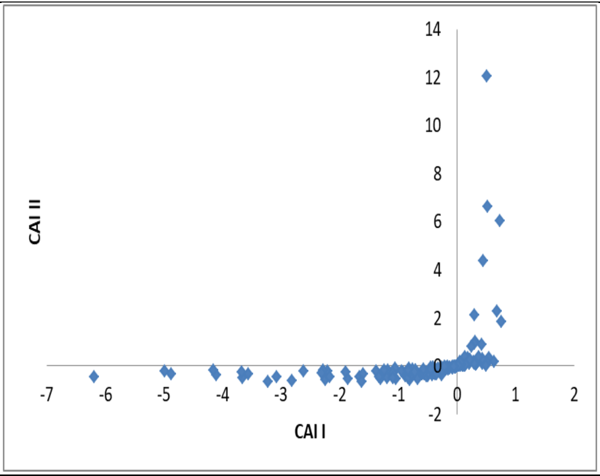


Figure 6. A plot of CAI I vs. CAI II

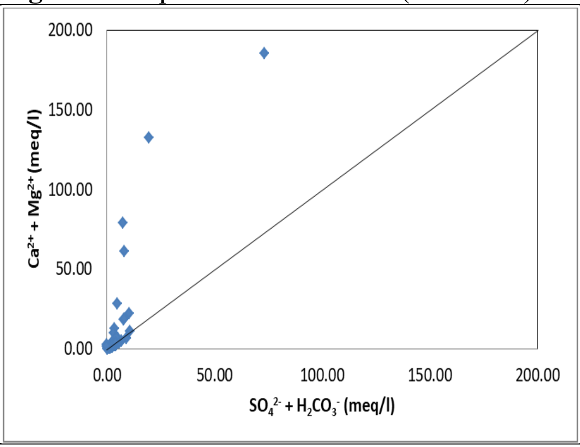


Figure 7. A plot of $(Ca^{2+}+Mg^{2+})$ vs. $(SO_4^{2-}+H_2CO_3^{-})$

Geostatistical Analysis

As shown in Table 4, 82.35% of the total variance was explained by six factors. The component matrix is displayed in Table 5 and the rotated component matrix was displayed in Table 6. The Scree plot of the Eigen values for the various components is shown in Fig. 8. One or more Eigen values were taken into consideration in this study. Fig. 9 displays a component plot in rotated space to demonstrate their spatial relationship. Factor 1 accounted for 36.28%, Factor 2 for 14.14%, Factor 3 for 12.43%, Factor 4 for 8.90%, Factor 5 for 5.81%, and Factor 6 for 4.79%. EC, TDS, Na^{+}, Ca^{2+}, Mg^{2+}, Cl^{-}, SO_4^{2-}, TH, Ca^{2+} hardness, and Mg^{2+} hardness formed the components of factor 1. The components of factor 2 were NH_4, PO_4, NO_2, NO_3, and F^{-}. Turbidity, Mn, Fe, and color were all present in factor 3. $CaCO_3$ and $H_2CO_3^{-}$ made up factor 4. Factor 5 had pH and CO_3 and Factor 6 was made of K^{+}.

The HCA multivariate statistical method can be used to group hydrochemical data so that its members share traits but are different from those of other groups. One benefit of using the method is that the results are displayed as a dendrogram, which is simple to understand, and the HCA can classify water using a variety of characteristics. Additionally, it offers a fairly simple and user-friendly method of data organization. The HCA method is helpful in hydrogeochemical modeling to identify the type of aquifer system, residence time, and potential effects of anthropogenic activities that support the investigation of the properties of groundwater of the various subgroups. In this study, four clusters were revealed by the cluster analysis method (Fig. 10). Turbidity, color, pH, EC, TSS, TDS, Fe, NH_4^{+}, SO_4^{2-}, PO_4, Mn, NO_2, NO_3, $CaCO_3$, Ca^{2+} hardness, Mg^{2+} hardness, F^{-}, $H_2CO_3^{-}$, and CO_3^{2-} were present in Cluster 1. Cl^{-} and TH were in Cluster 2. Only TDS and only EC were present in clusters 3 and 4, respectively. The Correlation analysis technique was applied to determine the sources of groundwater pollution (Hussain, 2019). The technique has been applied by several authors to successfully investigate groundwater pollution (Varol and Davraz, 2014; Agyemang 2022). The correlation outcome is shown in Table 7 of the report.

Table 4: The observed Total Variance and its Explanation

		Initial Eigenvalues			Extraction Sums of Squared Loadings			Rotation Sums of Squared Loadings	
Component	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
1	9.510	38.058	38.058	9.514	38.058	38.058	9.07	36.279	36.279
2	3.560	14.232	52.290	3.558	14.232	52.29	3.535	14.138	50.417
3	3.130	12.514	64.805	3.129	12.514	64.805	3.108	12.434	62.851
4	2.000	7.994	72.798	1.998	7.994	72.798	2.225	8.901	71.752
5	1.35	5.417	78.216	1.354	5.417	78.216	1.452	5.808	77.56
6	1.04	4.138	82.354	1.035	4.138	82.354	1.198	4.794	82.354
7	1.00	3.981	86.335						
8	0.65	2.596	88.931						
9	0.63	2.498	91.429						
10	0.48	1.923	93.352						
11	0.45	1.81	95.162						
12	0.41	1.64	96.802						
13	0.29	1.159	97.961						
14	0.18	0.707	98.669						
15	0.15	0.604	99.273						
16	0.09	0.343	99.615						
17	0.05	0.2	99.815						
18	0.036	0.144	99.959						
19	0.007	0.029	99.988						
20	0.001	0.004	99.993						
21	0.001	0.004	99.997						
22	0.001	0.002	99.999						
23	0	0.001	100						
24	2.43E-05	9.72E-05	100						
25	3.64E-06	1.46E-05	100						

Table 5: Component matrix of the water quality parameters

Parameters	**Component**					
	1	2	3	4	5	6
Turb.	-0.003	-0.087	0.923	-0.215	0.023	-0.041
Col.	-0.013	-0.138	0.896	-0.159	-0.039	0.016
Ph	0.065	0.152	0.289	0.521	0.617	0.036
EC	0.974	0.031	-0.009	-0.123	0.037	0.108
TSS	-0.055	-0.057	0.089	-0.268	-0.227	0.097
TDS	0.973	0.028	-0.01	-0.125	0.037	0.108
Na	0.871	0.034	-0.021	-0.216	0.087	0.345
K	0.533	0.034	0.029	0.205	-0.034	0.709
Ca	0.962	0.011	-0.019	-0.075	0.026	-0.028
Mg	0.93	0.025	-0.012	-0.051	-0.016	-0.234
Fe	-0.011	-0.097	0.929	-0.159	-0.068	0
NH_4	-0.035	0.913	0.102	0.059	-0.047	-0.026
Cl	0.955	0.031	-0.03	-0.2	0.064	0.131
SO_4	0.828	-0.009	-0.006	0.015	-0.039	-0.449
H_2PO_4	-0.042	0.774	0.081	0.022	-0.026	-0.038
Mn	0.058	-0.129	0.654	0.163	-0.118	0.018
NO_2	-0.085	0.67	0.135	-0.032	0.003	-0.1
NO_3	-0.008	0.929	0.075	0.009	-0.102	0
TH	0.986	0.017	-0.014	-0.061	0.004	-0.141
$CaCO_3$	0.445	-0.049	0.146	0.831	-0.205	-0.036
Ca_hard.	0.963	-0.008	-0.019	-0.072	0.026	-0.03
Mg_hard.	0.93	0.023	-0.013	-0.051	-0.016	-0.234
F	0.045	0.829	0.068	0.034	-0.056	0.095
H_2CO_3	0.451	-0.194	0.123	0.808	-0.238	-0.025
CO_3	-0.037	0.009	0.09	0.05	0.876	-0.059

Table 6: Rotated Component Matrix of the water quality parameters

Parameter	**Component**					
	1	2	3	4	5	6
Turb.	0.02	0.018	0.945	-0.101	0.044	-0.046
Col.	-0.012	-0.029	0.92	-0.036	-0.005	0.009
Ph	-0.019	0.144	0.161	0.292	0.786	0.119
EC	0.96	-0.001	0.006	0.054	0.003	0.23
TSS	-0.026	-0.035	0.143	-0.174	-0.303	0.057
TDS	0.96	-0.004	0.006	0.052	0.002	0.228
Na	0.854	-0.01	0.004	-0.091	8.35E-05	0.443
K	0.392	0.017	0.001	0.236	0.002	0.789
Ca	0.954	-0.016	-0.008	0.113	0.015	0.096
Mg	0.941	0.009	-0.004	0.161	0	-0.11
Fe	-0.008	0.018	0.949	-0.023	-0.025	-0.006
NH_4	-0.019	0.922	-0.016	0.013	0.041	0
Cl	0.957	-0.008	-0.005	-0.033	0	0.243
SO_4	0.851	-0.012	-0.002	0.231	0.011	-0.332
H_2PO_4	-0.02	0.779	-0.016	-0.02	0.039	-0.021
Mn	-0.004	-0.035	0.641	0.272	0.003	0.042
NO_2	-0.046	0.682	0.056	-0.07	0.051	-0.092
NO_3	0.013	0.936	-0.034	-0.015	-0.03	0.021
TH	0.987	-0.004	-0.004	0.147	0.008	-0.011
$CaCO_3$	0.255	0.003	0.046	0.932	0.106	0.089
Ca_hard.	0.954	-0.034	-0.005	0.116	0.016	0.094
Mg_hard.	0.941	0.008	-0.004	0.161	0	-0.109
F	0.047	0.829	-0.035	0	0.008	0.124
H_2CO_3	0.259	-0.141	0.047	0.93	0.055	0.093
CO_3	0	-0.053	0.034	-0.245	0.848	-0.026

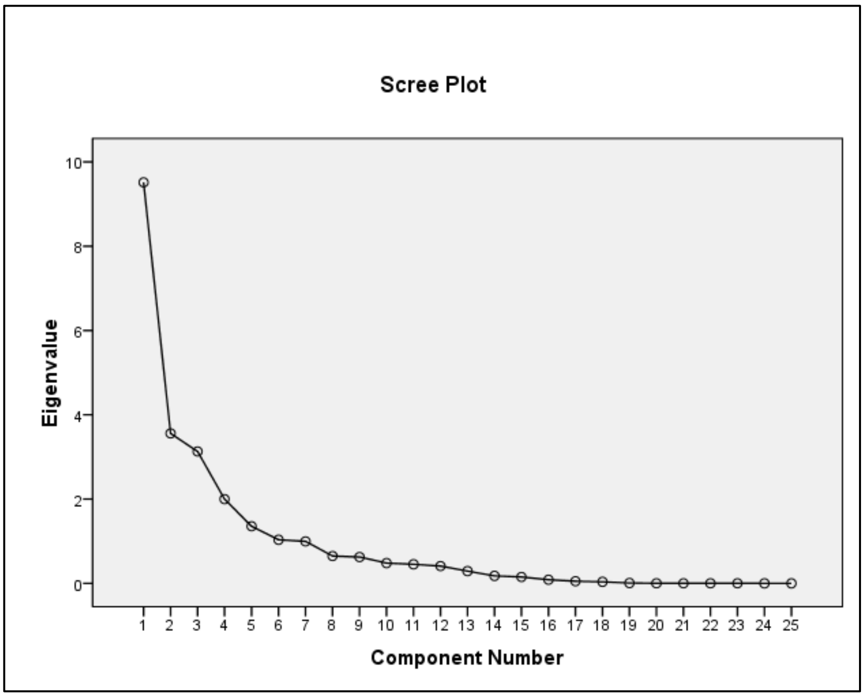


Figure 8: Scree plot showing the Eigen values of the various components

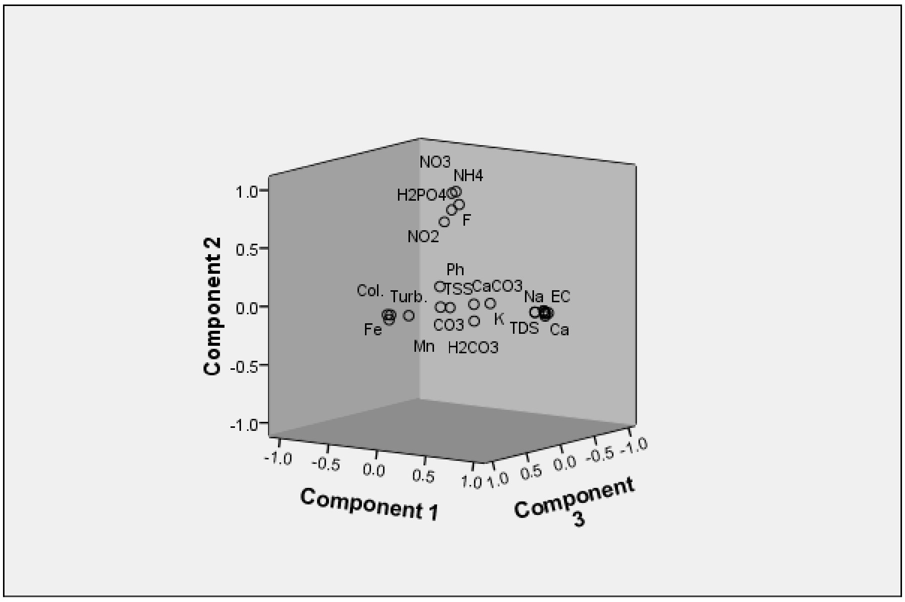


Figure 9: Plot of components in rotated space to show their spatial relationship.

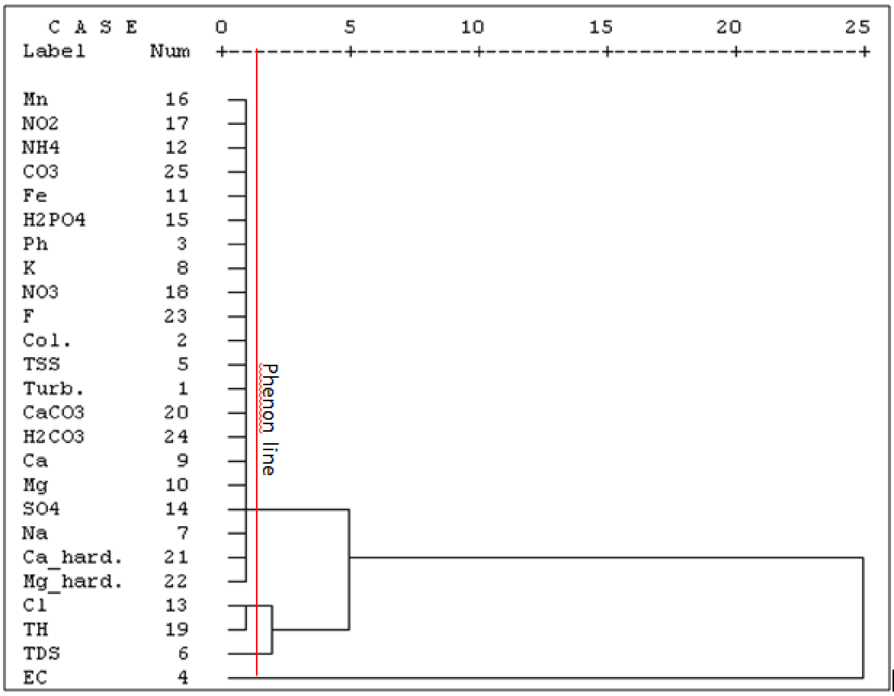


Figure 10: Dendrogram showing the clustering of groundwater parameters.

Table 7: Correlation matrix of the water quality parameters

	Turb.	Col.	Ph	EC	TSS	TDS	Na	K	Ca	Mg	Fe	NH_4	Cl	SO_4	PO_4	Mn	NO_2	NO_3	TH	$CaCO_3$	Ca_hard.	Mg_hard.	F	H_2CO_3	CO_3
Turb.	1	**0.845**	0.137	0.006	0.077	0.006	0.003	-0.026	-0.005	0.002	**0.912**	0.007	0.002	0.013	0.002	0.471	0.077	-0.025	0	-0.033	-0.004	0.003	-0.022	-0.037	0.081
Col.		1	0.125	-0.005	0.203	-0.006	-0.018	0.013	-0.029	-0.014	**0.838**	-0.043	-0.027	-0.014	-0.043	0.439	0.032	-0.055	-0.016	0.036	-0.02	-0.015	-0.043	0.04	0.061
Ph			1	0.028	-0.152	0.025	0.025	0.113	0.038	0.02	0.12	0.174	0.013	0.025	0.128	0.159	0.106	0.078	0.032	0.322	0.038	0.019	0.116	0.274	0.419
EC				1	-0.045	1	**0.927**	**0.526**	**0.968**	**0.857**	-0.006	-0.019	**0.977**	**0.721**	-0.025	0.034	-0.047	0.008	**0.95**	0.324	**0.968**	**0.857**	0.064	0.329	-0.029
TSS					1	-0.	-0.	-0.	-0.	-0.	0.03	-0.	-0.	-0.	-0.	-0.	-0.	0.02	-0.	-0.1	-0.0	-0.03	-0.	-0.0	-0.

						045	033	016	045	031	1	027	034	028	031	015	064	2	04	01	45	1	039	94	02
TDS						1	**0.927**	**0.524**	**0.967**	**0.857**	-0.007	-0.021	**0.976**	**0.72**	-0.027	0.034	-0.05	0.006	**0.95**	0.322	**0.968**	**0.857**	0.062	0.327	-0.029
Na							1	**0.594**	**0.832**	**0.736**	-0.004	-0.029	**0.963**	**0.512**	-0.032	0.04	-0.056	0.005	**0.816**	0.175	**0.831**	**0.736**	0.073	0.183	-0.023
K								1	0.446	0.367	0.004	-0.013	**0.517**	0.236	-0.008	0.023	-0.061	0.032	0.422	0.377	0.444	0.367	0.124	0.381	-0.037
Ca									1	**0.839**	-0.014	-0.008	**0.923**	**0.798**	-0.02	0.03	-0.058	0.011	**0.955**	0.364	**0.999**	**0.839**	-0.014	0.366	-0.026
Mg										1	-0.023	-0.024	**0.872**	**0.887**	-0.027	0.037	-0.075	0.01	**0.961**	0.369	**0.839**	1	0.103	0.373	-0.024
Fe											1	-0.004	-0.018	0.002	-0.002	**0.52**	0.04	-0.011	-0.02	0.014	-0.014	-0.024	-0.011	0.015	-0.014
NH_4												1	-0.024	-0.024	**0.58**	-0.035	**0.526**	**0.927**	-0.018	0.022	-0.028	-0.026	**0.743**	-0.13	-0.011
Cl													1	**0.69**	-0.028	0.034	-0.067	0.01	**0.934**	0.234	**0.922**	**0.872**	0.058	0.24	-0.022
SO_4														1	-0.026	-0.009	-0.048	-0.009	**0.881**	0.388	**0.799**	**0.888**	-0.004	0.391	-0.021
PO_4															1	-0.031	0.475	**0.663**	-0.025	-0.023	-0.032	-0.029	**0.557**	-0.127	-0.006
Mn																1	-0.021	-0.052	0.034	0.221	0.029	0.036	-0.046	0.225	-0.025
NO_2																	1	**0.543**	-0.07	-0.07	-0.069	-0.076	0.405	-0.152	-0.004
NO_3																		1	0.009	0.004	-0.009	0.008	**0.719**	-0.139	-0.024
TH																			1	0.387	**0.956**	**0.961**	0.047	0.39	-0.026
$CaCO_3$																				1	0.368	0.369	0.019	**0.986**	-0.072
Ca_hard.																					1	**0.839**	-0.029	0.373	-0.026
Mg_hard.																						1	0.102	0.373	-0.024
F																							1	-0.097	-0.014
H_2CO_3																								1	-0.122
CO_3																									1

Water quality index

According to Couillard and Lefebre (1985), water is considered to be excellent to drink when the WQI value is between 0 and 50, good to drink when the value is between 50 and 100, poor to drink when the value is between 100 and 200, very poor to drink when the value is between 200 and 300, and unfit to drink when the value is above 300. Following classification, the WQI found that 6% of the groundwater samples had excellent quality, 54% had good quality, 22% had poor quality, 9% had very poor quality, and 9% were unfit for drinking. The spatial distribution of the WQI is shown using a thematic map, as shown in Fig. 11. The map revealed that the region had a dominant class of good groundwater quality. There were sporadic locations with high or low WQI values throughout the study area (Fig. 11).

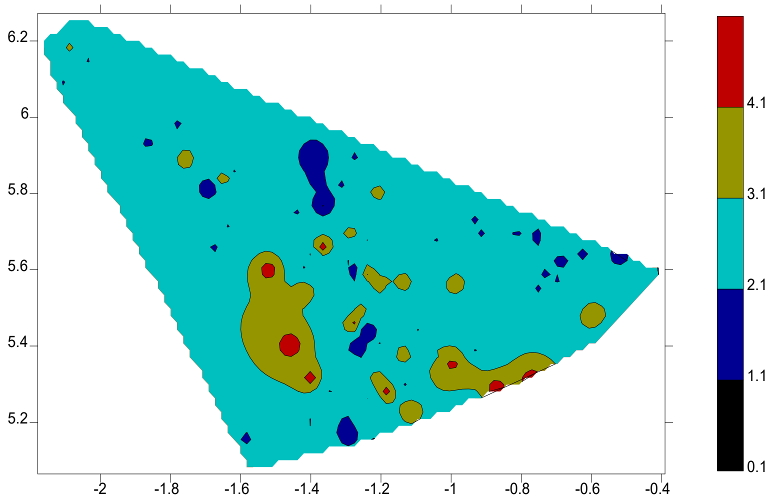


Figure 11: Spatial distribution of WQI

Discussion

Geostatistical techniques have proven to be effective in interpretation of hydrochemical data (Osiakwan et al., 2021). In this study, PCA and HCA were used to, respectively, identify the critical components that control groundwater chemistry and identify hydrochemical clusters that may be important from a geological perspective. The regional distributions of the various water quality parameters have shown how groundwater chemistry is influenced by human activity, seawater intrusion, and rock mineral dissolution. Along the coast, the majority of the metrics had extremely high values that are over the WHO (2012) recommended limits. This finding is consistent with the poor groundwater quality noted by Osiakwan et al (2021). Thematic maps of the various parameters indicate the effects of actions such as applying agrochemicals to farmlands, spreading animal dung on farms, galamsey, maintaining unhygienic conditions around boreholes, using pit latrines in some areas, etc.

Groundwater types

The dissolution of rock minerals and anthropogenic effects may have contributed to the occurrence of the $CaMgSO_4$ groundwater type (Koh et al., 2010; Tiwari and Singh, 2014). The dissolution of pyroxene, anorthite plagioclase, amphibole, and calcite may be the reason for the high Ca^{2+} ion concentration of the groundwater. The dissolution of hornblende, augite, and biotite may have had an impact on the amount of Mg^{2+} in the groundwater. Gypsum dissolution, the oxidation of sulfide-bearing minerals like pyrite and arsenopyrite, and/or human activity are all potential sources of SO_4^{2-} in groundwater. Local anthropogenic activities, such as improper waste management, the use of pit latrines, and unhygienic conditions close to the borehole, may be to blame for the rise in the level of SO_4^{2-} in the groundwater (Koh et al., 2010).

The dissolution of salt minerals like halite, which introduces equal amounts of Na^+ and Cl^- into the groundwater, may influence the occurrence of the NaCl groundwater type (Hem, 1985). However, the majority of samples contain more Cl^- than Na^+, demonstrating that the two parameters enter groundwater in various ways. The idea that the two concentrations entered the groundwater independently is supported by the absence of a clear relationship between them. The main factors affecting the occurrence of the $CaMgHCO_3$ groundwater type are ion exchange processes and/or rock weathering. According to Karnath (1989), the formation of HCO_3^- in groundwater may result from the dissolution of carbonate rocks like limestone and dolomite as well as from the reaction of water and carbon dioxide.

The $NaHCO_3$ groundwater type may develop as a result of meteoric water charged with carbonic acid dissolving Na^+ from Na-bearing minerals like albite and augite, according to Garrels and Mackenzie (1967). The creation of the $NaHCO_3$ groundwater type is caused by the dissolution of CO_2 and this

Na-rich mineral. Additionally, the exchange process where $CaHCO_3$ transforms into $NaHCO_3$ by interacting with the NaCl water type may also result in the formation of $NaHCO_3$ (Yidana et al., 2010). The final chemical makeup of groundwater is altered when two or more of different groundwater types are mixed together. Since there is no single dominant ion in mixed groundwater, it lacks any distinctive characteristics. This kind of groundwater can develop as a result of the blending of several groundwater types or the breakdown of various rock minerals in the groundwater.

Processes controlling the groundwater chemistry

The primary mechanisms that regulate the groundwater chemistry in the region were studied using the Gibbs (1970) diagram. The impact of rock weathering, which is related with moderate TDS and moderate $Cl^-/(Cl^-+Na^+)$ ratio or TDS and moderate $Na^+/(Na^++Ca^{2+})$ ratio, is shown by the graphing of TDS vs. $Cl^-/(Cl^-+Na^+)$ and TDS vs. $Na^+/(Na^++Ca^{2+})$. A few samples, however, showed signs of the potential effects of evaporation since they had high TDS, high $Cl^-/(Cl^-+Na^+)$ ratios, and high $Na^+/(Na^++Ca^{2+})$ ratios. This indicates that, even though rock weathering mostly regulates groundwater chemistry, evaporation also affects groundwater chemistry in some areas of the region.

The plot of $(Ca^{2+}+Mg^{2+})$ vs. $(SO_4^{2-}+HCO_3^-)$ was used to analyze the kind of rock weathering that mostly affects the groundwater of the region since rock weathering is the principal process affecting the chemistry of the groundwater. By using the plot of $(Ca^{2+}+Mg^{2+})$ vs. $(SO_4^{2-}+HCO_3^-)$, excess $SO_4^{2-}+HCO_3^-$ over $Ca^{2+}+Mg^{2+}$ indicates either silicate mineral weathering or ion exchange processes, whereas excess $Ca^{2+}+Mg^{2+}$ over $SO_4^{2-}+HCO_3^-$ indicates carbonate weathering (Tiwari and Singh, 2014). The study showed that the area may experience silicate mineral dissolution and/or ion exchange, carbonate and/or sulphate mineral dissolution, and carbonate weathering. A plot of CAI I vs. CAI II was used to study the effects of ion exchange on groundwater chemistry. Indicators with positive values suggest an interchange of Na^+ or K^+ in groundwater with Mg^{2+} or Ca^{2+} in the aquifer system, while those with negative values imply an exchange of Mg^{2+} or Ca^{2+} in groundwater with Na^+ and K^+ in the rocks, according to Schoeller (1965). Ion exchange is revealed by positive numbers, and reverse ion exchange is revealed by negative values. The majority of the samples in this investigation showed the dominance of reverse ion exchange.

Geostatistical Analysis

The potential processes that could affect the quality of the groundwater were deduced using HCA and FA approaches based on the connections between the elements. CA is a pattern-detection method that identifies the fundamental structure of a dataset and groups the data according to similarities (Otto, 1998). Several factors were deduced from the data set in order to conduct a factor analysis. The factors were ranked based on how much of the variation from the initial set of data they explain. A correlation matrix analysis is a bivariate technique that demonstrates how well one variable predicts the other while also identifying potential ions and chemical processes that are comparable to or identical to those in the understudied groundwater. In order to demonstrate the relationship between the metrics for water quality, the correlation technique was used in this study (McGrorya, 2020). These techniques have been used for hydrochemistry research by numerous authors from different parts of the world and are well documented in the literature (Osiakwan et al., 2021).

Factor Analysis

According to the factor analysis, Factor 1 contains the following variables: EC, TDS, Na^+, Ca^{2+}, Mg^{2+}, Cl^-, SO_4^{2-}, TH, Ca^{2+} hardness, and Mg^{2+} hardness. This grouping shows that weathering of rock minerals, ion exchange and human activities have impacts on groundwater chemistry. The concentrations of Na^+, Ca^{2+}, and Mg^{2+} in the groundwater are regulated by ion exchange activities or the dissolution of rock minerals, as shown by their clustering (Schoeller, 1965; Koh et al., 2010; Tiwari and Singh, 2014). The concentrations of TDS, Na^+, Cl^-, and SO_4^{2-} are grouped together, indicating the presence of rock weathering and the potential influence of anthropogenic activity. The components of factor 2 are NH_4^-, PO_4, NO_2, NO_3, and F^-. This cluster demonstrates the potential effects of anthropogenic activity on the quality of groundwater (Koh et al., 2010). The use of chemicals for galamsey activities, the use of pit latrines in some communities, the use of fertilizers, weedicides, and pesticides for farming, the lack of hygienic conditions around the boreholes, the use of poor waste disposal techniques, etc. that are prevalent in the area, among other factors, may have caused this clustering (Koh et al., 2010).

Turbidity, Mn, Fe, and color all belong to factor 3. This clustering supports the impact of rock weathering on the quality of groundwater (Tiwari and Singh, 2014). The dissolution of minerals containing Fe and Mn regulates the concentrations of the elements. The fact that Fe and Mn are clustered together with color and turbidity indicates that Fe and Mn are responsible for regulating the color and turbidity of the groundwater. $CaCO_3$ and $H_2CO_3^-$ make up factor 4. This cluster demonstrates the influence of dissolved CO_2 on groundwater chemistry and the effects of rock weathering (Karnath, 1989). Factor 5 contains pH and CO_3^{2-}, demonstrating how the concentration of CO_3^{2-} affects the pH of groundwater (Karnath, 1989). Factor 6 solely contains K^+, suggesting that human activity has an impact on the quality of groundwater (Koh et al., 2010). The dissolution of K-bearing minerals may be partially responsible for the K^+ content in the groundwater. The absence of connection with other widespread rock minerals, however, points to various distinct entry points into the groundwater system. The use of K-containing fertilizers on their farmland by the farmers may be the source of this particular route (Koh et al., 2010). The use of the Factor Analysis technique has shown the potential for ion exchange, rock weathering, and the effects of human activity.

Cluster Analysis

The application of the cluster analysis technique was used in this study to identify possible factors affecting the groundwater quality in the region. The technique revealed the effects of sewage contamination of groundwater, groundwater quality, groundwater contamination, the impact of mining and agriculture on groundwater quality, and general hydrochemical investigations (Belkhiri et al., 2010). The use of the Cluster analysis technique in the study is required because, as described in the literature, it is necessary to group samples into various hydrochemical groups that will reveal hidden information about the hydrogeochemistry and potential groundwater pollution (Belkhiri et al., 2010). This analysis combined the Ward's linkage strategy with the Q-mode hierarchical cluster analysis method to achieve its goals.

Four clusters were displayed using the method. Turbidity, color, pH, EC, TSS, TDS, Na^+, K^+, Ca^{2+}, Mg^{2+}, Fe, NH_4, SO_4, PO_4, Mn, NO_2, NO_3, $CaCO_3$, Ca hardness, Mg hardness, F^-, $H_2CO_3^-$, and CO_3^{2-} were present in Cluster 1. The grouping of the parameters shows the effects of rock weathering, potential ion exchange, and impact of anthropogenic activities on the quality of the groundwater (Schoeller, 1965; Koh et al., 2010; Tiwari and Singh, 2014). The clustering of major ions like Na, Ca, and Mg together indicates that dissolution of rock minerals is most likely their sources (Tiwari and Singh, 2014). But the ion exchange process might have an impact on the amount of Na, Ca, and Mg in the groundwater (Schoeller, 1965). Another indication of the potential impact of the rock weathering process on the groundwater chemistry is the clustering of Fe, Mn, and $CaCO_3$ (Tiwari and Singh, 2014).

However, the concentrations of TDS, K^+, NH_4, SO_4, PO_4, NO_2, and NO_3 were grouped together, suggesting the possible effects of anthropogenic activity on the quality of groundwater (Koh et al., 2010). The use of fertilizers containing K may be responsible for the concentration of K^+. The absence of hygienic conditions near boreholes, the use of agrochemicals, the use of chemicals for galamsey activities, etc. may be the influencing factor of the SO_4, NH_4, NO_2, and NO_3 concentrations (Koh et al., 2010). Cl^- and TH are present in Cluster 2, indicating the potential impact of rock weathering on the chemistry of groundwater. Only TDS and only EC are present in clusters 3 and 4, respectively, which indicate that anthropogenic activities have an impact on the chemistry and general quality of groundwater (Koh et al., 2010). The Cluster analysis technique has confirmed that geogenic processes and anthropogenic activities in the Region have impact on the chemistry groundwater.

Correlation Analysis

The use of the correlation analysis technique revealed a substantial association between turbidity, Fe, and color, suggesting that the content of Fe in the groundwater regulates turbidity. Strong correlations between color and Fe imply that the Fe concentration of the groundwater affects the color. The EC is correlated with Mg^{2+} hardness, Na^+, K^+, Ca^{2+}, Mg^{2+}, Cl^-, SO_4^{2-}, TH, and Ca^{2+} hardness, indicating that the concentrations of these parameters affect the EC of the groundwater.

Therefore, factors that regulate the levels of Na^+, K^+, Ca^{2+}, Mg^{2+}, Cl^-, and SO_4^{2-} indirectly affect the EC of the groundwater. As shown by the factor analysis and cluster analysis techniques, geogenic processes and anthropogenic activities may be controlling the concentrations of Na^+, K^+, Ca^{2+}, Mg^{2+}, Cl^-, and SO_4^{2-} in the groundwater. As a result, these factors affect the EC of the groundwater. The fact that TDS closely correlates with Na^+, K^+, Ca^{2+}, Mg^{2+}, Cl^-, SO_4^{2-}, Ca hardness, and Mg hardness suggests that the concentrations of Na^+, K^+, Ca^{2+}, Mg^{2+}, Cl^-, and SO_4^{2-} in the groundwater affect the TDS of the groundwater. This indicates that anthropogenic activities as well as rock weathering affect the TDS.

Strong correlations between Na and K^+, Ca^{2+}, Mg^{2+}, Cl^-, SO_4^{2-}, TH, Ca^{2+} hardness, and Mg^{2+} hardness indicate that the anthropogenic activities have effects on the quality of groundwater (Davalos-Pena et al. 2021). The relationship between K^+ and Cl^- shows that anthropogenic activities have an impact on the chemistry of groundwater and the overall quality of groundwater. The relationship between Ca^{2+} and Cl^-, SO_4^{2-}, Mg^{2+}, TH, Ca^{2+} hardness, and Mg^{2+} hardness suggests that the weathering of rocks has an effect on the quality of the groundwater. Mg correlates with Cl^-, SO_4^{2-}, TH, Ca^{2+} hardness, and Mg^{2+} hardness, illustrating how the weathering of rocks affects the quality of groundwater. Fe and Mn are correlated, which shows that weathering of rocks has an effect of the groundwater chemistry. The relationship between NH_4^+ and F^-, NO_2, NO_3, and PO_4 indicates that anthropogenic activities, such as applying fertilizer to farmland, maintaining unhygienic conditions around boreholes, using chemicals for galamsey activities, using pit latrines, etc., have an impact on the chemistry and general quality of groundwater.

The relationship between Cl^- and SO_4^{2-}, TH, Ca^{2+} hardness, and Mg^{2+} hardness suggests that anthropogenic activities have an impact on groundwater quality. The correlation between SO_4^{2-} and TH, Ca^{2+} hardness and Mg^{2+} hardness suggests that SO_4^{2-} may have an impact on groundwater hardness. PO_4 correlates with NO_3 and F^-, demonstrating how anthropogenic activities affect the quality of groundwater. The relationship between NO_2 and NO_3 implies that the conversion of NO_3 to NO_2 is the primary factor affecting the content of NO_2 in groundwater. NO_3 correlates with F^-, demonstrating that anthropogenic sources account for the majority of the NO_2 entering the groundwater system. A portion of the concentration is changed into NO_2 upon the introduction of NO_3. The use of the correlation analysis technique confirms the potential impact of ion exchange, rock weathering, and anthropogenic activities on the chemistry and general quality of groundwater in the region. The associations of the various parameters reveals the possible effects of mineral dissolution and anthropogenic activities on the chemistry of groundwater (Tiwari and Singh, 2014; Davalos-Pena et al. 2021).

Water quality index

The WQI technique was used in this study to evaluate the suitability of the groundwater for drinking and domestic uses as well as to identify the potential effects of anthropogenic activities on groundwater quality in the region. The study found that while the majority of the groundwater of the region was of “good” quality, the coastal regions and a few isolated localities had less poor water quality. This observation is consistent with what Osiakwan et al. (2021) discovered. The fact that the ‘‘good’’ groundwater type dominates in the region reveals how the geology affects the groundwater resource in the region. That reveals the natural quality of the groundwater as it flows through the aquifer systems in the region. The scattered localities with either high or low WQI values within the region indicate either the effects of anthropogenic activities or the effects of other natural processes aside from rock-water interactions, such as seawater intrusion. Seawater intrusion is primarily responsible for the poor groundwater quality along the coast (Asare et al., 2022; Osiakwan et al., 2021). The study identified Eduafo and Asaman with WQI values of 850.68% and 313.44% respectively as localities where groundwater likely highly polluted by Seawater intrusion.

However, anthropogenic activities are primarily responsible for the poor water quality seen in the sporadic locations away from the coast. As was already mentioned, the majority of the population in the area is rural and relies on agrochemicals like weedicides, pesticides, fertilizers, etc. for both large- and small-scale farming. Once more, the abundance of gold-bearing minerals in the area continues to draw legitimate large- and small-scale mining operations as well as galamsey activities. By exposing the subsurface rock materials to the atmosphere through mining and related activities, different chemicals are released into the groundwater through processes like acid rock drainage. Chemicals are introduced into the soil through mining and related activities, where they dissolve and enter the water table during rainfall. When surface water is contaminated by galamsey activities, groundwater may also become contaminated as a result of groundwater-surface water interactions. Most people in rural areas practice open defecation, which has an impact on groundwater quality. The use of animal dung as manure and improper domestic and industrial waste disposal pollute the environment and groundwater resources. The study identified Eduafo, Asaman, Nyamebekyere, Bosomatwe, Asempanyin, Abora, Dadieso, Mesomagor, Mankata, Afadzato, Congo 1, Gyankrom 1, Gyankrom 2, Ayigbo, Aygbo with WQI of 850.68%, 313.44%, 616.04%, 212.10%, 478.12%, 614.10%, 206.97%, 225.99%, 286.25%, 2180.01%, 216.63%, 578.73% 327.28% 2166.94% 4805.85% respectively as localities where groundwater is likely highly polluted by anthropogenic activities (Fig. 11).

Conclusion

An integration of geostatistical and GIS techniques has been applied to investigate anthropogenic impact on groundwater quality in the Central Region of Ghana. In the region, there are four different forms of groundwater: $CaMgSO_4$, NaCl, $CaMgHCO_3$, and Mixed water. About 82.35% of the total variance was explained by six factors. Factor 1 accounted for 36.28%, Factor 2 for 14.14%, Factor 3 for 12.43%, Factor 4 for 8.90%, Factor 5 for 5.81%, and Factor 6 for 4.79%. EC, TDS, Na^+, Ca^{2+}, Mg^{2+}, Cl^-, SO_4^{2-}, TH, Ca^{2+} hardness, and Mg^{2+} hardness were in factor 1. The components of factor 2 were NH_4, PO_4, NO_2, NO_3, and F^-. Turbidity, Mn, Fe, and color were in factor 3. $CaCO_3$ and H_2CO_3 made up factor 4. Factor 5 included CO_3 and pH. Only K was in factor 6. Four clusters were visible using the cluster analysis method. Turbidity, color, pH, EC, TSS, TDS, Na^+, K^+, Ca^{2+}, Mg^{2+}, Fe, NH_4, SO_4, PO_4, Mn, NO_2, NO_3, $CaCO_3$, Ca^{2+} hardness, Mg^{2+} hardness, F^-, $H_2CO_3^-$, and CO_3^{2-} were in Cluster 1. Cl^- and TH were in Cluster 2. Only TDS and only EC were in clusters 3 and 4, respectively.

According to this classification, the WQI showed that 6% of the groundwater samples had excellent quality, 54% had good quality, 22% had poor quality, 9% had very poor quality, and 9% were unfit for drinking. The natural groundwater quality was within the ‘‘good’’ class. The poor groundwater quality in some localities within the region was attributed to geogenic, seawater intrusion process and anthropogenic activities. Eduafo and Asaman with WQI values of 850.68% and 313.44% respectively were identified as locality of likely groundwater high pollution due to Seawater intrusion. Eduafo, Asaman, Nyamebekyere, Bosomatwe, Asempanyin, Abora, Dadieso, Mesomagor, Mankata, Afadzato, Congo 1, Gyankrom 1, Gyankrom 2, Ayigbo, Aygbo with WQI of 850.68%, 313.44%, 616.04%, 212.10%, 478.12%, 614.10%, 206.97%, 225.99%, 286.25%, 2180.01%, 216.63%, 578.73% 327.28% 2166.94% 4805.85% respectively were identified as communities of likely high groundwater pollution due to anthropogenic activities.

The study has shown that anthropogenic activities, seawater intrusion, ion exchange, rock weathering, and evaporation are factors that affect the quality of groundwater in the region. The anthropogenic activities affecting groundwater quality in the region include application of agrochemicals to farmlands, spreading animal dung on farms, galamsey, lack of hygienic conditions around boreholes, and the pit latrines. The study has demonstrated the significance of the integration of the GIS and geostatistical techniques in groundwater pollution investigation. Such an integration techniques aids in groundwater resources management and promotes the achievement of the Sustainable Development Goal Six (SDG 6), which calls for integrated water resource management.

Compliance with Ethical Standards

Ethical responsibilities of Authors: *The author has read, understood, and have complied as applicable with the statement on "Ethical responsibilities of Authors" as found in the Instructions for Authors”*

Funding: *No funding was received by the author.*

Acknowledgment: *The author is grateful to the Management of the Community Water and Sanitation Agency, Cape Coast for making the data available for this study.*

Conflict of Interest: *The author declares that he has no conflict of interest.*

Availability of data: *All data used for this study are included within the manuscript.*

Change of Authorship: *The author has read, understood, and have complied as applicable with the statement on "Ethical responsibilities of Authors" as found in the Instructions for Authors and are aware that with minor exceptions, no changes can be made to authorship once the paper is submitted.*

References

Agyemang VO, (2022) "Application of geostatistical techniques in the assessment of groundwater contamination in the Afigya Kwabre District of Ghana". *App. Water Sci.* **12**, Article number: 53 (2022). https://link.springer.com/article/10.1007/s13201-022-01582-x

America Public Health Association (1995) Standard methods for the examination of water and wastewater, 19th edition, Washington, DC. https://www.scirp.org/(S(351jmbntvnsjt1aadkposzje))/reference/ReferencesPapers.aspx?ReferenceID=1883439

Anku YS, Banoeng-Yakubo B, Asiedu DK, Yidana SM, (2009). "Water Quality Analysis of Groundwater in Crystalline Basement Rocks, Northern Ghana", *Environ-mental Geology*, **58**(5), pp. 989-997. DOI: https://doi.org/10.1007/s00254-008-1578-4

Aral MM, Maslia ML, Ulirsch GV, Reyes JJ, (1996). Estimating Exposure to Volatile Organic Compounds from Municipal Water-Supply Systems: Use of a Better Computational Model. Archives of Environ. Health: An Int. J., **51**(4), 300-309. DOI: 10.1080/00039896.1996.9936029

Asante-Annor A, Acquah J, Ansah E, (2018) Hydro-geological and Hydrochemical Assessment of Basin Granitoids in Assin and Breman Districts of Ghana. J..Geoscience & Environ. Protec., **6**. DOI: 10.4236/gep.2018.69004

Asare A, Appiah-Adjei EK, Owusu-Nimo F, Ali B, (2022) Lateral and vertical mapping of salinity along the coast of Ghana using Electrical Resistivity Tomography: The case of Central Region. Results in Geophys. Sci. 12 (2022) 100048. https://doi.org/10.1016/j.ringps.2022.100048

Banoeng-Yakubo B, Yidana SM, Anku Y, (2009). "Water quality characterization in some Birimian aquifers of the Birim Basin, Ghana: *KSCE J.Civil Engin.*. Volume 13, Issue 3, pp 179–187. https://link.springer.com/article/10.1007/s12205-009-0179-4

Belkhiri L, Abderrahmane B, Mouni L, (2010) A multivariate Statistical Analysis of Groundwater Chemistry Data. Int. J. Environ. Res., **5**(2):537-544, Spring 2011 ISSN: 1735-6865. https://www.researchgate.net/publication/236612300_A_multivariate_Statistical_Analysis_of_Groundwater_Chemistry_Data

Celesceri L, Greenberg AE, Eaten AD, (1998) Standard methods for the examination of water and waste water. *Am. Public Health Assoc.n*, Washington, p 134. https://www.worldcat.org/title/Standard-methods-for-the-examination-of-water-and-wastewater/oclc/40733179

Couillard D, Lefebvre Y, (1985). Analysis of Water Quality Indices. J. of Environ. Management **21**:161-179.https://scholar.google.com/scholar_lookup?title=Analysis%20of%20water%20quality%20indices&journal=Journal%20of%20Environmental%20Management&volume=21&pages=161-179&publication_year=1985&author=Couillard%2CD&author=Lefebvre%2CY

Davalos-Pena I, Fuentes-Rivas RM, Fonseaca-Montes de Oca RMG, Ramos-Leal JA, Moran-Ramirez J, Alva GM, (2021) Assessment of physicochemical groundwater quality and hydrogeochemical processes in an area near a municipal landfill site: A case study of the Toluca Valley. Int. J. Environ. Res. Public Health **18**(21):11195. doi:10.3390/ijerph182111195

Ewusi A, Kuma JS, (2010), "Calibration of Shallow Borehole Drilling Sites Using the Electrical Resistivity Imaging Technique in the Granitoids of Central Region, Ghana", *Natural Resources Research,* **20**, pp. 57-63. https://doi.org/10.1007/s11053-010-9129-6

Foster S, Pulido-Bosch A, Vallejos Á, Molina L, Llop A, MacDonald AM (2018). Impact of irrigated agriculture on groundwater-recharge salinity: a major sustainability concern in semi-arid regions. *Hydrogeo. J.*, **26**(8), 2781–2791. https://link.springer.com/article/10.1007/s10040-018-1830-2

Galloway JN, Townsend AR, Erisman JW, Bekunda M, Cai Z, Freney JR, Martinelli LA, Seitzinger SP, Sutton MA (2008). Transformation of the Nitrogen Cycle: Recent Trends, Questions, and Potential Science, **320**(5878), 889 LP – 892. DOI: 10.1126/science.1136674

Ganyaglo SY, Osae S, Akiti T, Armah T, Gourcy L, Vitvar T, Otoo IA, (2017) Application of geochemical and stable isotopic tracers to investigate groundwater salinity in the Ochi-Narkwa Basin, Ghana. Hydrol. Sci. J. **62** (8), 1301–1316. DOI: 10.1080/02626667.2017.1322207

Garrels RM, Mackenzie ET, (1967) Origin of the chemical compositions of some springs and lakes. *Advance Chemical.* Ser. 67: 222-242. Géology Minière, France. 88: 402 p. DOI: 10.1021/ba-1967-0067.ch010

Ghana Statistical Services (2010) Population and housing census. https://statsghana.gov.gh/gssmain/fileUpload/pressrelease/2010_PHC_National_Analytical_Report.pdf

Gibbs RJ, (1970) Mechanisms controlling world water chemistry. Science Journal **170**:795–840. DOI: 10.1126/science.170.3962.1088

Hem JD, (1985). Study and Interpretation of the Chemical Characteristics of Natural Water. 3rd Edition. *U.S. Geological Survey Water-Supply* Paper **2254**, 263. https://doi.org/10.3133/wsp2254

Hussain MS, Abd-Elhamid HF, Javadi AA, Sherif MM, (2019). Management of Seawater Intrusion in Coastal Aquifers: A Review. Water, 11(12) *(Advances in Groundwater and Surface Water Monitoring and Management),* **2467**. DOI: 10.3390/w11122467

Jean-Claude R, (1995). The evolution of groundwater quality in France: perspectives for enduring use for human consumption. *Sci. Total Environ. J.* **171**(1995). pp3-16. DOI: 10.1016/0048-9697(95)04695-x

Karanth KR, (1989). Groundwater assessment, Development and Management.Tata McGraw-Hill, New Delhi. https://link.springer.com/article/10.1007/s10661-010-1422-7

Koh DC, Mayer B, Lee KS, Ko KS, (2010). Land-use controls on sources and fate of nitrate in shallow groundwater of an agricultural area revealed by multiple environmental tracers. *J. Cont.n Hydrology* **118**:62–78. DOI: 10.1016/j.jconhyd.2010.08.003

Kortatsi BK, (2007). Hydrochemical framework of groundwater in the ankobra basin, Ghana. *Aquatic Geochem,* **13**: 41-74. DOI: 10.1007/s10498-006-9006-4

Lapworth DJ, MacDonald AM, Kebede S, Owor M, Chavula G, Fallas H, Wilson P, Ward JST, Lark M, Okullo J, Mwathunga E, Banda S, Gwengweya G, Nedaw D, Jumbo S, Banks E, Cook P, Casey V, (2020). Drinking water quality from rural handpump-boreholes in Africa. *Environmental Research Letters,* 15(6), 64020. DOI: 10.1088/1748-9326/ab8031

Leube A, Hirdes W, Mauer R, Kesse GO, (1990). The Early Proterozoic Birimian Supergroup of Ghana and Some Aspects of Its Associated Gold Mineralization. *Precambrian Res.* **46**, 139–165. https://doi.org/10.1016/0301-9268(90)90070-7

McGrorya E, Holianb E, Morrison L, (2020) Assessment of groundwater processes using censored data analysis incorporating non-detect chemical, physical, and biological data. *Journal of Contaminant Hydrology.* Volume 235, November 2020, 103706. https://doi.org/10.1016/j.jconhyd.2020.103706

Morel N, Bouryi V, Gomez JP, Godfraind T, (1996). Molecular selectivity of the action of calcium channel antagonists. *Arch. Int. Pharmacodyn. Ther.,* 331, 332. DOI: 10.1038/sj.bjp.0702162

National Groundwater Association News (2016) Groundwater **54**(2):150-150. https://www.ngwa.org/publications-and-news/Newsroom

Osiakwan GM, Appiah-Adjei EK, Kabo-Bah AT, Gibrilla A, Anornu G, (2021) Assessment of groundwater quality and the controlling factors in coastal aquifers of Ghana: An integrated statistical, geostatistical and hydrogeochemical approach. *J.African Earth Sci..* **184**, December 2021, 104371. https://doi.org/10.1016/j.jafrearsci.2021.104371

Otto M, (1998) Multivariate methods. In: Kellner, R., Mermet, J.M., Otto, M., Widmer, H.M. (Eds.), Analytical Chemistry. WileyeVCH, Weinheim. https://link.springer.com/article/10.1007/s10661-006-9497-x

Piper AM, (1944) A graphic procedure in the geochemical interpretation of water analyses. – *Trans. Am. Geophy.l Union,* **25**, 914–928. https://doi.org/10.1029/TR025i006p00914

Schoeller H, (1965). Qualitative evaluation of groundwater resource. In: Methods and techniques of groundwater investigation and development. *UNESCO,* pp 54-83. DOI: 10.12691/ajwr-1-4-1

Selmane T, Dougha M, Hasbaia M, Ferhati A, Redjem A, (2022) Hydrogeochemical processes and multivariate analysis for groundwater quality in the arid Maadher region of Hodna, northern Algeria. Acta Geochim (2022) **41**(5): 893–909. https://english.gyig.cas.cn/pu/papers_CJG/202209/P020220922508944108707.pdf

Singh S, Jayaram R, (2022) Attainment of water and sanitation goals: a review and agenda for research. *Sust. Water Reso. Manag.* **8**; 146 (2022). https://link.springer.com/article/10.1007/s40899-022-00719-9

Spalding RF, Exner ME, (1993). Occurrence of Nitrate in Groundwater—A Review. *J. Environ. Quality,* **22**(3), 392–402. https://doi.org/10.2134/jeq1993.00472425002200030002x

Tiwari AK, Singh AK, (2014) Hydrogeochemical Investigation and Groundwater Quality Assessment of Pratapgarh District, Uttar Pradesh. *Journal of the Geological Society of India*, 83(3):329-343p. DOI: 10.1007/s12594-014-0045-y

Varol S, Davraz A, (2014) Evaluation of the groundwater quality with WQI (Water Quality Index) and multivariate analysis: a case study of the Tefenni plain (Burdur/Turkey). *Environ Earth Sci*. doi:10.1007/s12665-014-3531-z.

World Health Organization (2008) Guidelines for drinking-water quality: incorporating 1st and 2nd addenda, **1,** Recommendations 978 92 4 1547611. https://www.who.int/publications/i/item/9789241547611

World Health Organization (2012) Edition of the Drinking Water Standards and Health Advisories Environmental Protection Agency 822-S-12-001 Washington, DC. https://rais.ornl.gov/documents/2012_drinking_water.pdf

Yidana SM, Yidana A, (2010). Assessing water quality using water quality index and multivariate analysis. *J.Environ. Earth Sci.* **59**:1461–1473. https://link.springer.com/article/10.1007/s12665-009-0132-3

Yidana SM, (2008) A multivariate statistical analysis of surface water chemistry data-The Ankobra Basin, Ghana: *J. Environ. Manag.*. **86**, 1, 80-87. DOI: 10.1016/j.jenvman.2006.11.023

Yogendra K, Puttaiah ET, (2008) “Determination of water quality index and suitability of an urban waterbody in Shimoga Town, Karnataka”, Proceedings of 12th World Lake Conference, pp. 342-346.https://www.academia.edu/32049089/Determination_of_Water_Quality_Index_and_Suitability_of_an_Urban_Waterbody_in_Shimoga_Town_Karnataka