# UNIVERSITY OF MINES AND TECHNOLOGY, GHANA

## FACULTY OF GEOSCIENCES AND ENVIRONMENTAL STUDIES

## DEPARTMENT OF GEOLOGICAL ENGINEERING


Tuesday, 25th February 2025

# Presentation Outline

- Introduction
- Overview of Sustainable Development Goals (SDGs)
- What is Medical Geology?
- Role of Medical Geology in Promoting the SDGs
- Case Studies
- Challenges and Opportunities
- Students Trained So Far & Future Directions
- Conclusion
- Acknowledgements

# Introduction

- Medical Geology is an **ancient and re-emerging field** of science that combines elements of earth science and public health.
- The focus of medical geology is to **decipher the impacts of geologic phenomena** and other environmental factors on human health and quality of life.
- Significant issues in medical geology today include toxic and deficient levels of essential and nonessential minerals, exposure to radioactive elements, industrial contribution to toxic exposures, dust, and geologic events such as volcanic eruptions.
- The goals of medical geology are to **identify sources of health hazards in the geologic environment** and prevent or diminish their ill-effect on humans.

# Introduction

Integrating health and environmental sustainability is important because it can improve people's health and well-being and reduce the environmental impact of human activities.

**Health benefits**

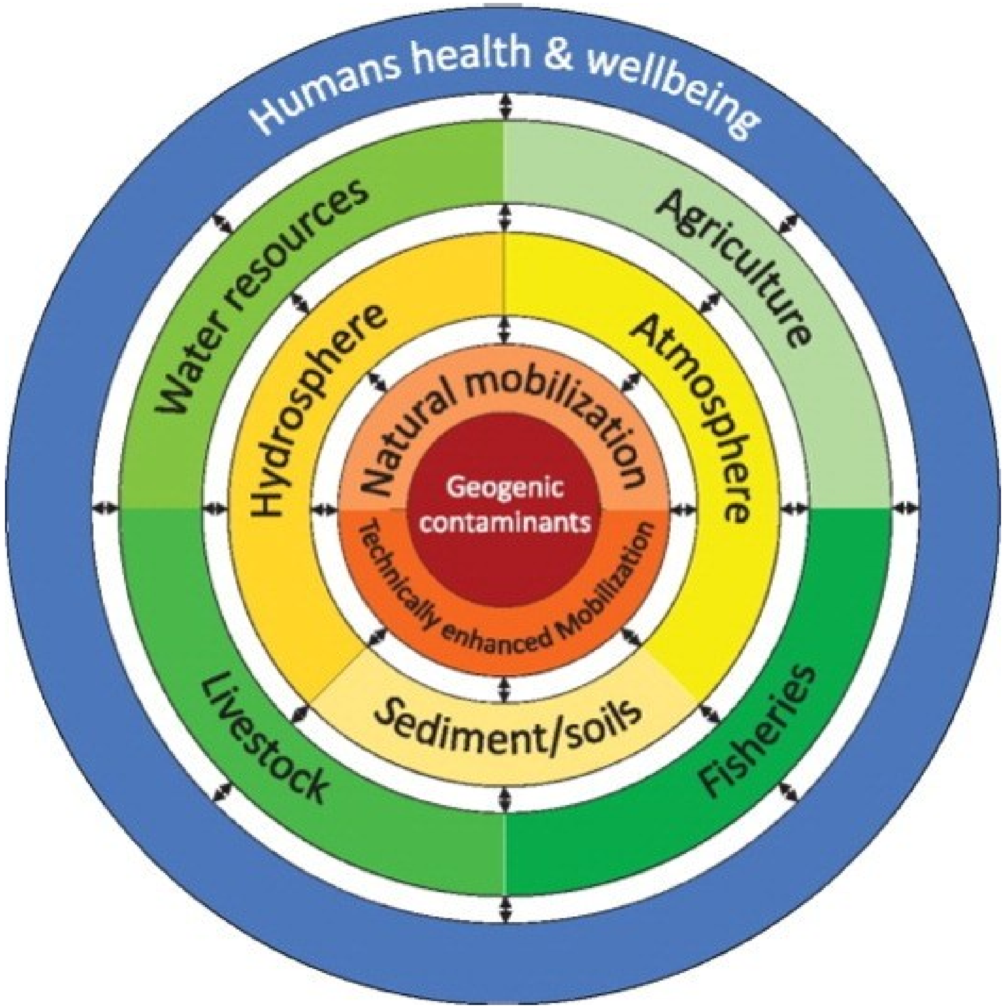
- Reduced exposure to toxins
- Improved air quality
- Better mental health

**Environmental benefits**

- Reduced environmental impact
- Reduced climate change
- Conserved natural resources

# Introduction

The emerging science of **"medical geology"** assesses the complex relationships between geo-environmental factors and their impacts on humans and environments and is related to the majority of the 17 Sustainable Development Goals in the 2030 Agenda of the United Nations for Sustainable Development.




Source: Bundschuh et al. (2017)

# Overview of Sustainable Development Goals (SDGs)

The sustainable development goals are a 'to do list for the planet that will transform the world'.

*– Ban Ki-Moon, Former Secretary-General of the United Nations*

# Overview of Sustainable Development Goals (SDGs)

- The Sustainable Development Goals ( also known as the Global Goals, were **adopted by all United Nations Member States in 2015** as a universal call to action to end poverty, protect the planet and ensure that all people enjoy peace and prosperity by 2030.

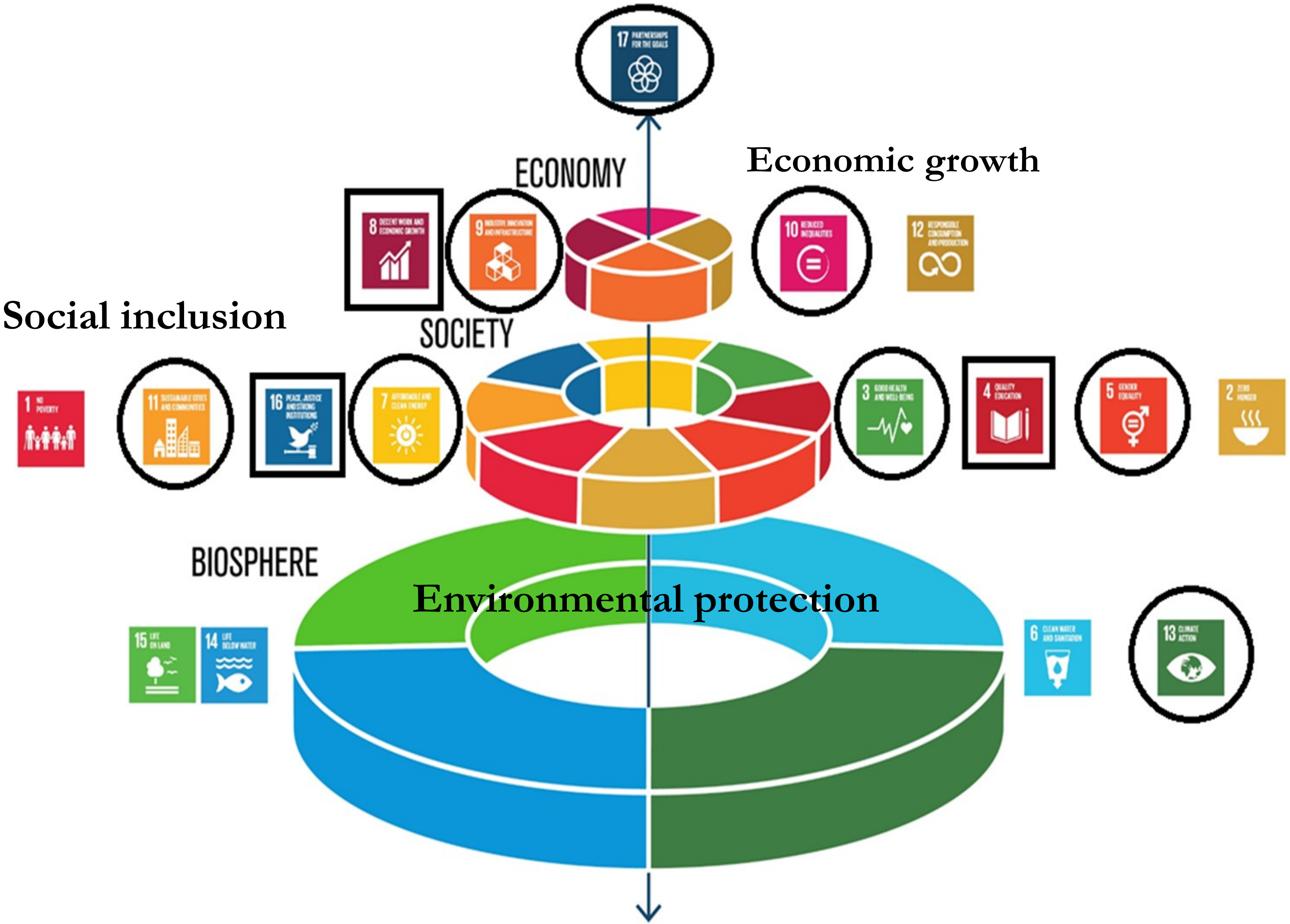
- The 17 SDGs are integrated that is, they recognize that action in one area will affect outcomes in others and that development must balance social, economic and environmental sustainability

# Millenium Development Goals (MDGs)

- The MDGs **did not consider environmental issues,** e.g.
  - Emissions of greenhouse gasses
  - Access to clean drinking water
  - Management of water resources
- New focus on the concept of **‘sustainable development’**
  - Need to consider the relationship between nature and society
  - Social, environmental and economic dimensions

# Sustainable Development Goals (SDGs)

# Pillars of Sustainable Development Goals (SDGs)



# What is Medical Geology?

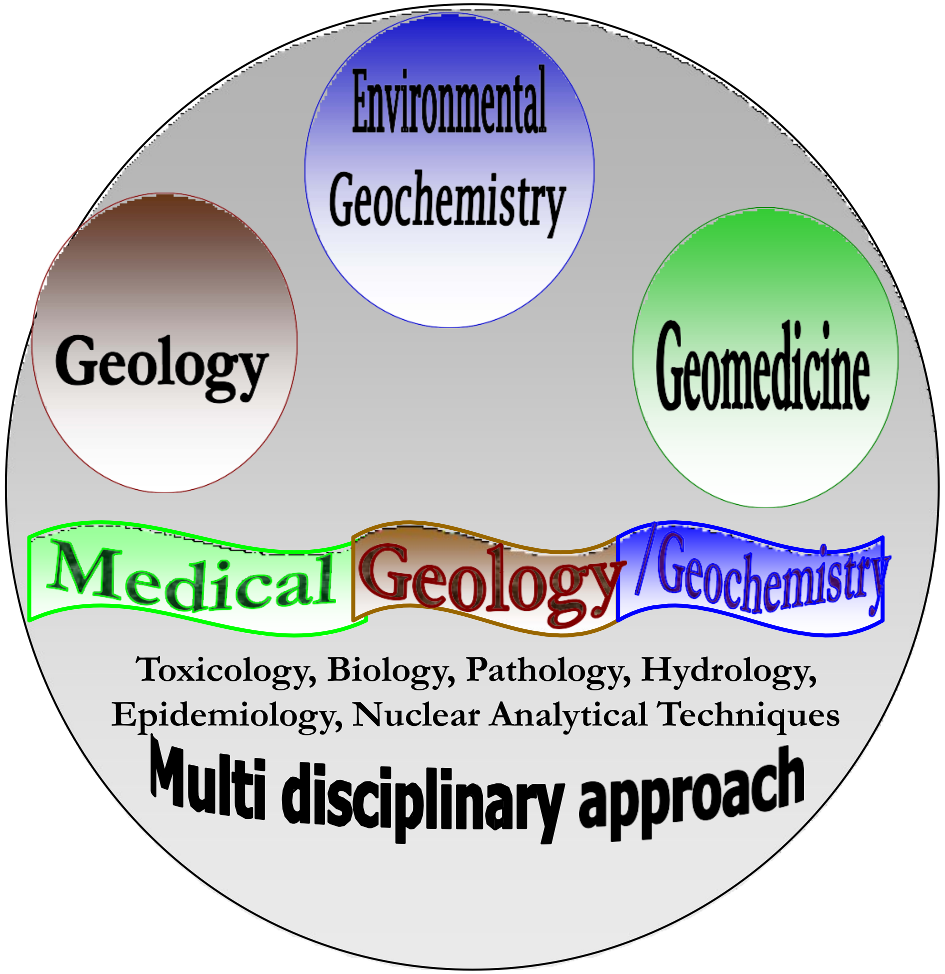
**Medical Geology /Geochemistry**

**Medical geology/geochemistry** looks at the effects of geochemical processes and geological factors on the health of humans, animals, and plants.

**Geomedicine /Geographic Medicine**

"**Medical geography** looks at the geographical distribution of disease while **not focusing** on the underlying geology. It examines the causal associations between specific diseases and the physical and social environments."

# Definition of Medical Geology




**Medical Geology/Geochemistry**

is the study of interaction between abundances of elements and isotopes and the health of humans, animals, and plants.

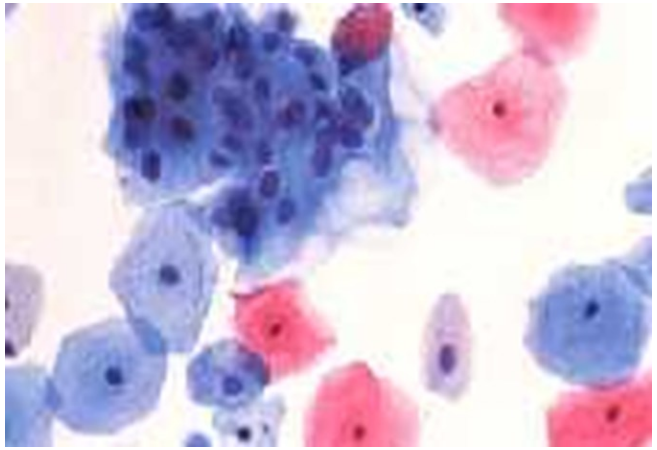
**"If you want to learn about the health of a population, look at the air they breathe, the water they drink, and the places where they live."**

— Hippocrates, 5th Century BC

The interaction between humans and their environment (Source: www3.uakron.edu)

# Scope of Medical Geology

- Medical geology covers a wide range of issues.
- From planetary to microscopic.
- Global warming with its related health impact to how toxic heavy metals may cause cancer.
- Medical geology deals with the ***cause*** of the disease not its ***cure***.



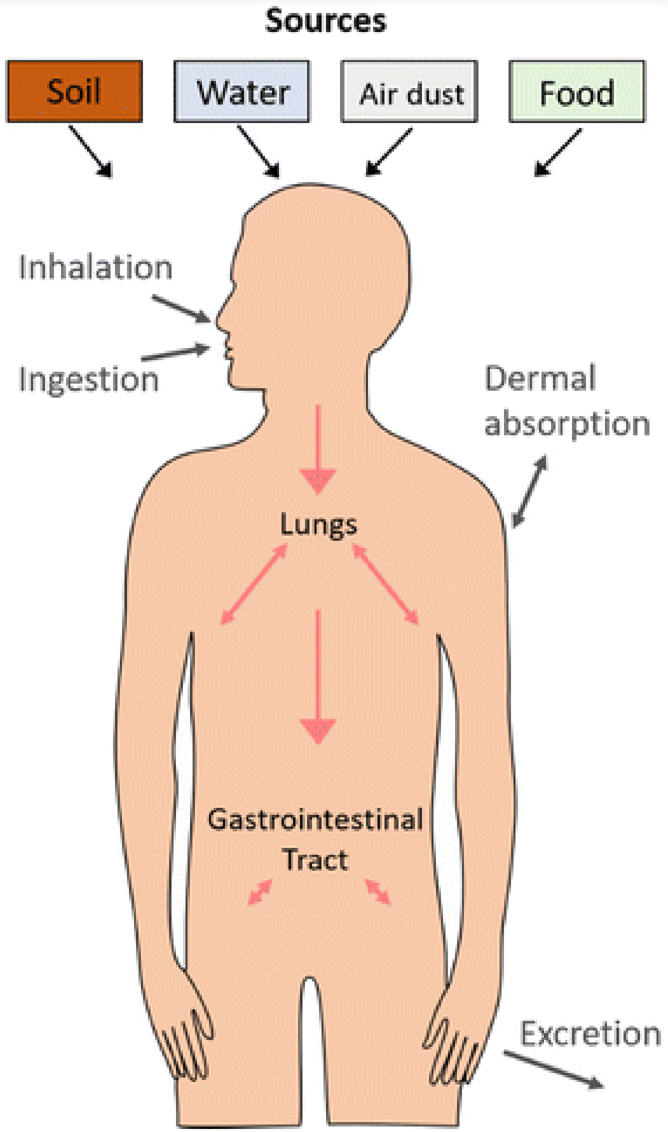
# Sources and Exposure Routes of Contaminants

**Metal-induced Effects**

- ❖ Carcinogenic (can cause cancer)
- ❖ Teratogenic (can cause birth defects)
- ❖ Mutagenic (can cause genetic mutations, or changes, in an organism)

**"All substances are poisons; there is none which is not a poison. Only the dose differentiates a poison and a remedy".**

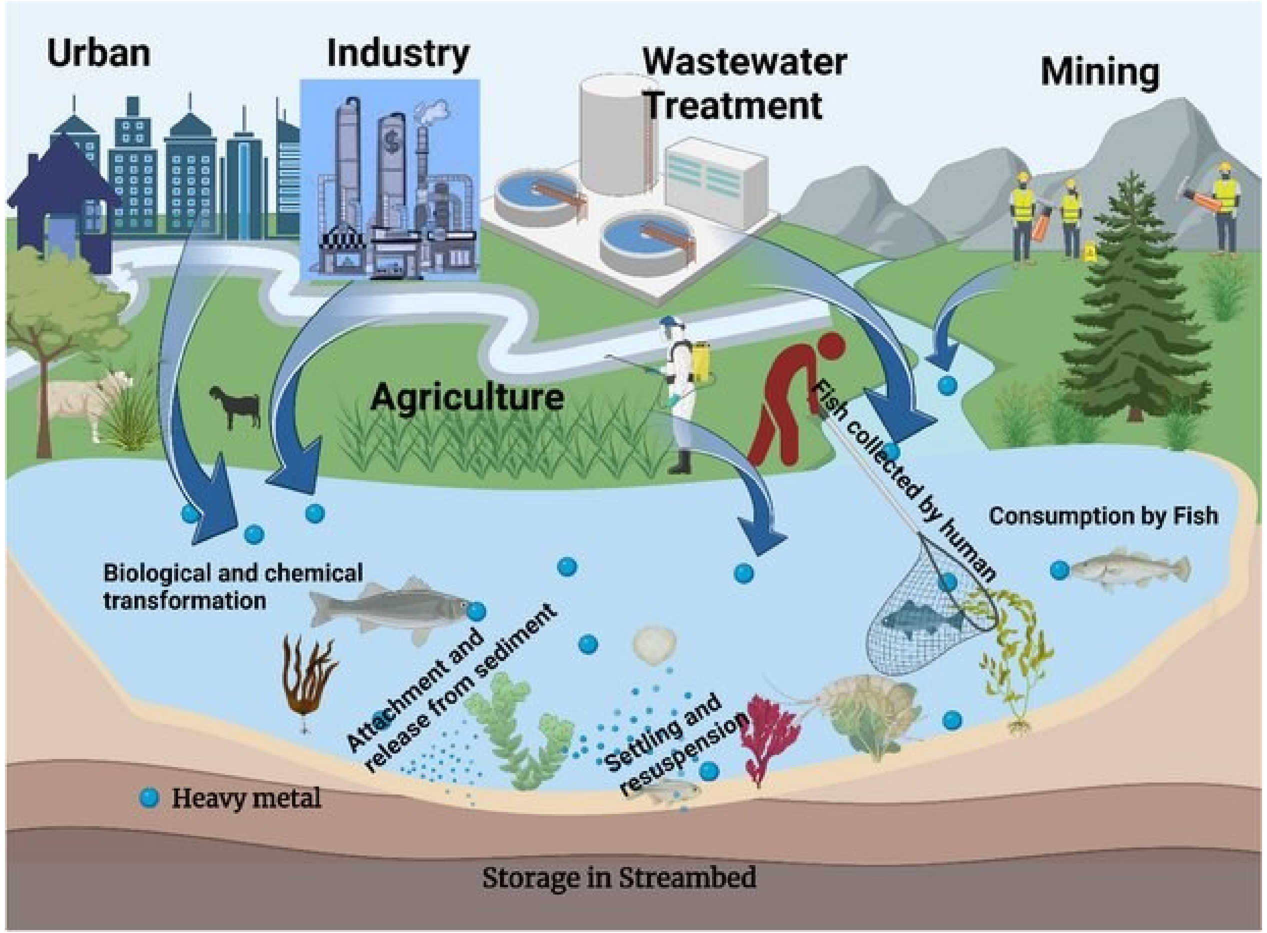
Paracelsus (1493-1541)



# Sources and Exposure Routes of Contaminants

- **Point sources**:-
  Storage tanks, landfills, pipeline discharges etc.

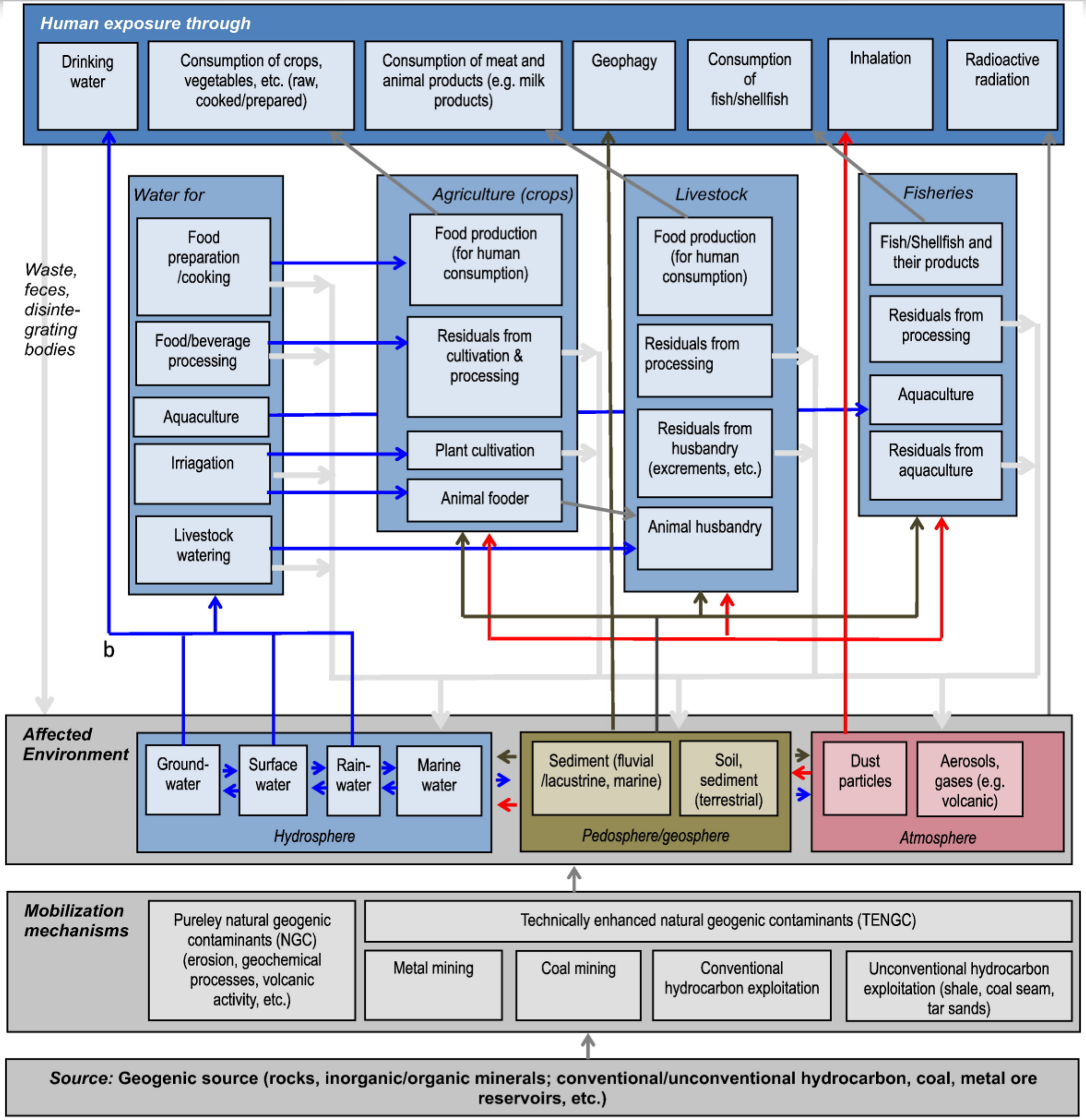
- **Nonpoint (diffused) sources**:-
  Agricultural activities





Medical geology deals with contaminants from only **geogenic sources.**

# Sources and Exposure Routes of Geogenic Contaminants



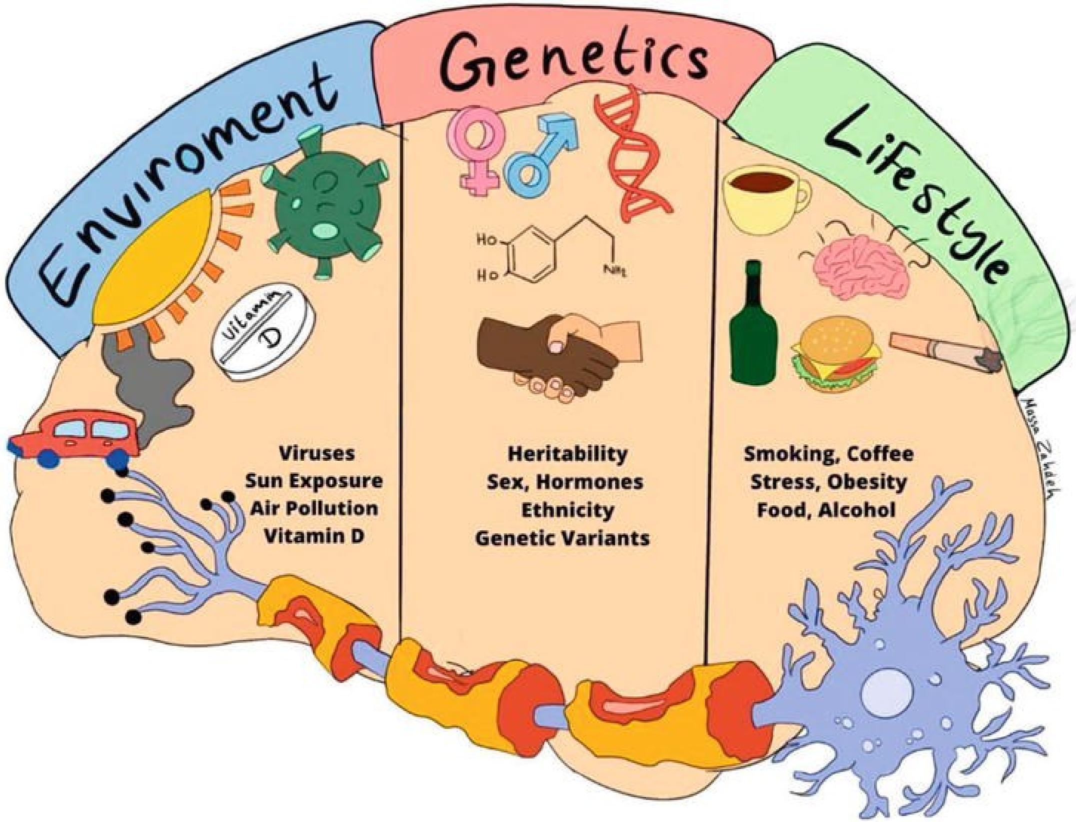

Source: Bundschuh et al. (2017)

# Geophagy as a Source of Geogenic Contaminants

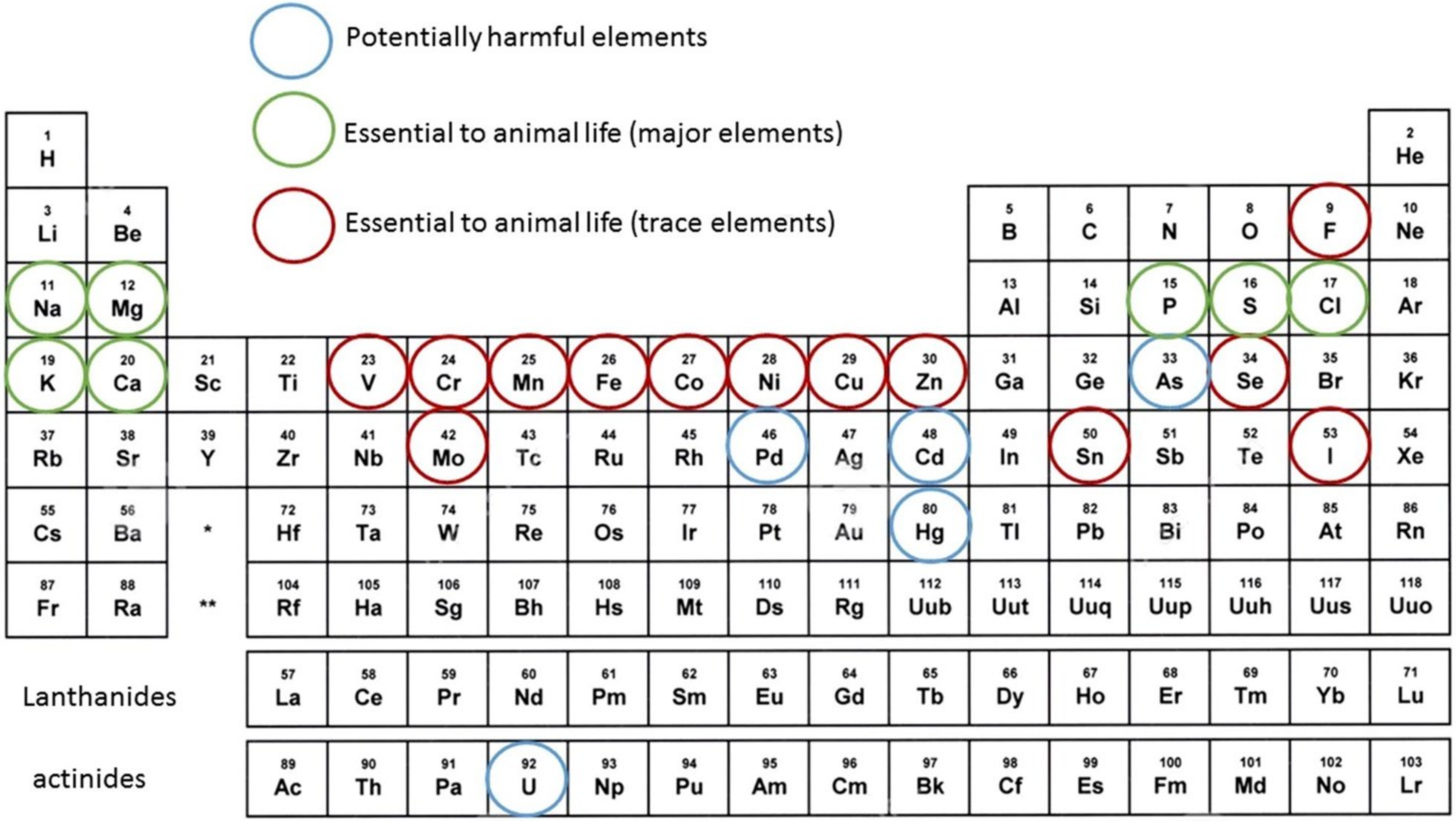
# Causes of Diseases

- ❖ Environmental
- ❖ Genetics
- ❖ Lifestyle/behavioral

Ultimately represents an imbalance between chemical elements and the body.

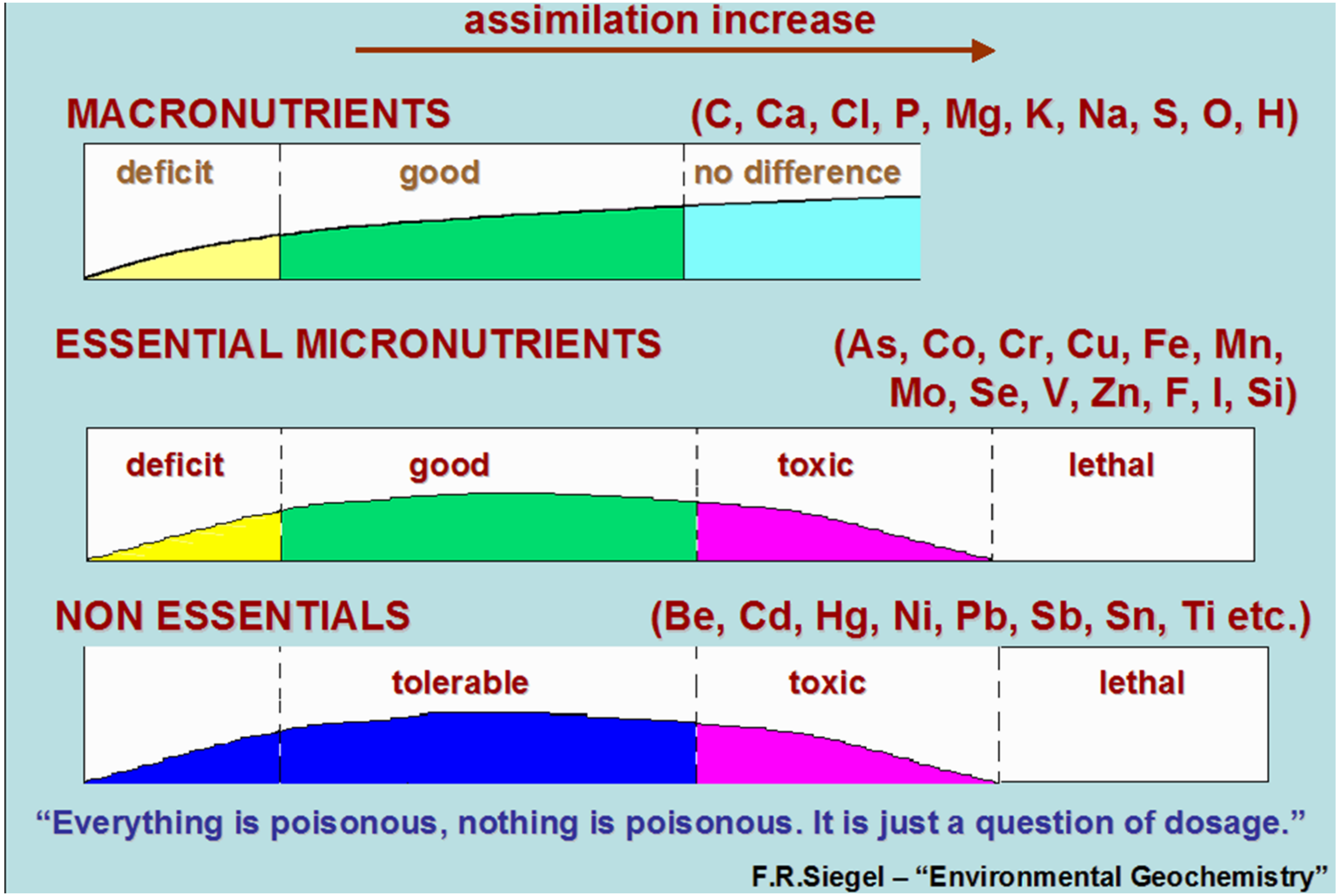


# Periodic Table Noting the Elements that are Potentially Harmful and those that are Essential to Humans




Source: Data from WHO (1996)

# Patterns and Influence of Elements



# Toxicity: Cancer Effects

| Elements | Target organ/site |
|---|---|
| As | Bladder, liver, lung, skin, Vascular and neurological changes |
| Cd | Bladder, kidney, lung, Hypertension, vascular and neurological changes |
| Cr | Kidney, liver, lung |
| Hg | Brain, kidney, lung, neurological changes |
| Pb | Neurological, IQ (children), Anemia |
| Radon | Lung |
| Others | Be (skin, lung), Co (liver,lung), U (skin) |

Based on: Trace elements in environmental health and human diseases, Josè- Diversity of Trace Elements.pdf

# Toxicity: Arsenic-induced Effects

- Pigmentation (hyper and hypo)
- Keratosis
- Bowen's disease
- Squamous cell carcinoma
- Basal cell carcinoma




Based on: Trace elements in environmental health and human diseases, Josè- Diversity of Trace Elements.pdf

# Toxicity: Cardiovascular Diseases

| Elements<br>❖ From epidemiological studies | Effect |
|---|---|
| ❖Co, Hg, Se, Al, As, Au, Cr | Cardiomyopathy |
| ❖ Fe, Se, Ca, Cu, Mg | Atherosclerosis |
| Al, As, Hg, ❖ Pb | Hypertension |

Based on: Trace elements in environmental health and human diseases, Josè- Diversity of Trace Elements.pdf Atherosclerosis: Hardening and thickening of walls of arteries with fatty degeneration

Armed forces

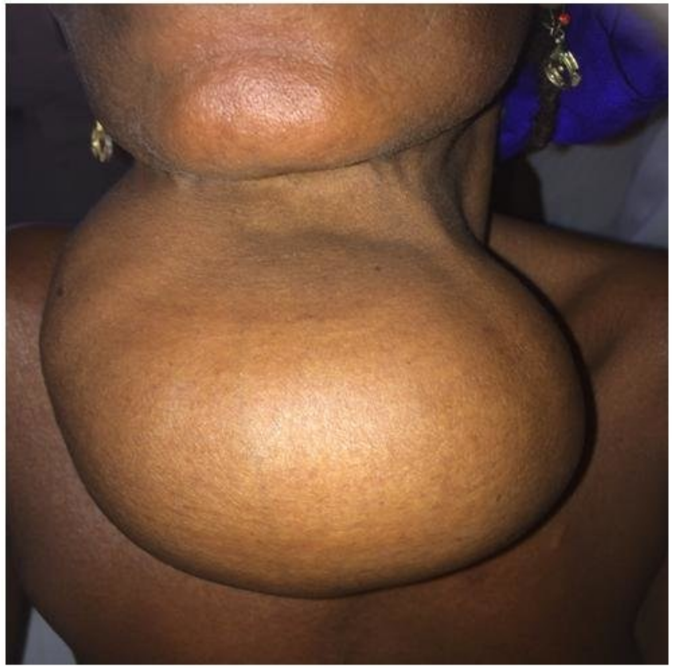
# Toxicity: Lung Diseases

| Elements | Effect |
|---|---|
| Asbestos fibers | Amphipbole types are more pathogenic than serpentine type |
| Beryllium | Presence of granulomas |
| Iron;<br>Iron mixed with free silica | Siderosis;<br>silicosiderosis |

Based on: Trace elements in environmental health and human diseases, Josè- Diversity of Trace Elements.pdf

# Toxicity: Significant Endemic Diseases

| Element | Effect |
|---|---|
| Arsenic | Skin lesions, Cancer |
| Fluoride | Dental and Skeletal |
| Iodine | Goiter and Cretinism |
| Selenium | Kaschin-Beck disease:<br>Degenarative osteoarthropathic disease<br>Keshan disease: Chronic heart disease (cardiomyopathy) |



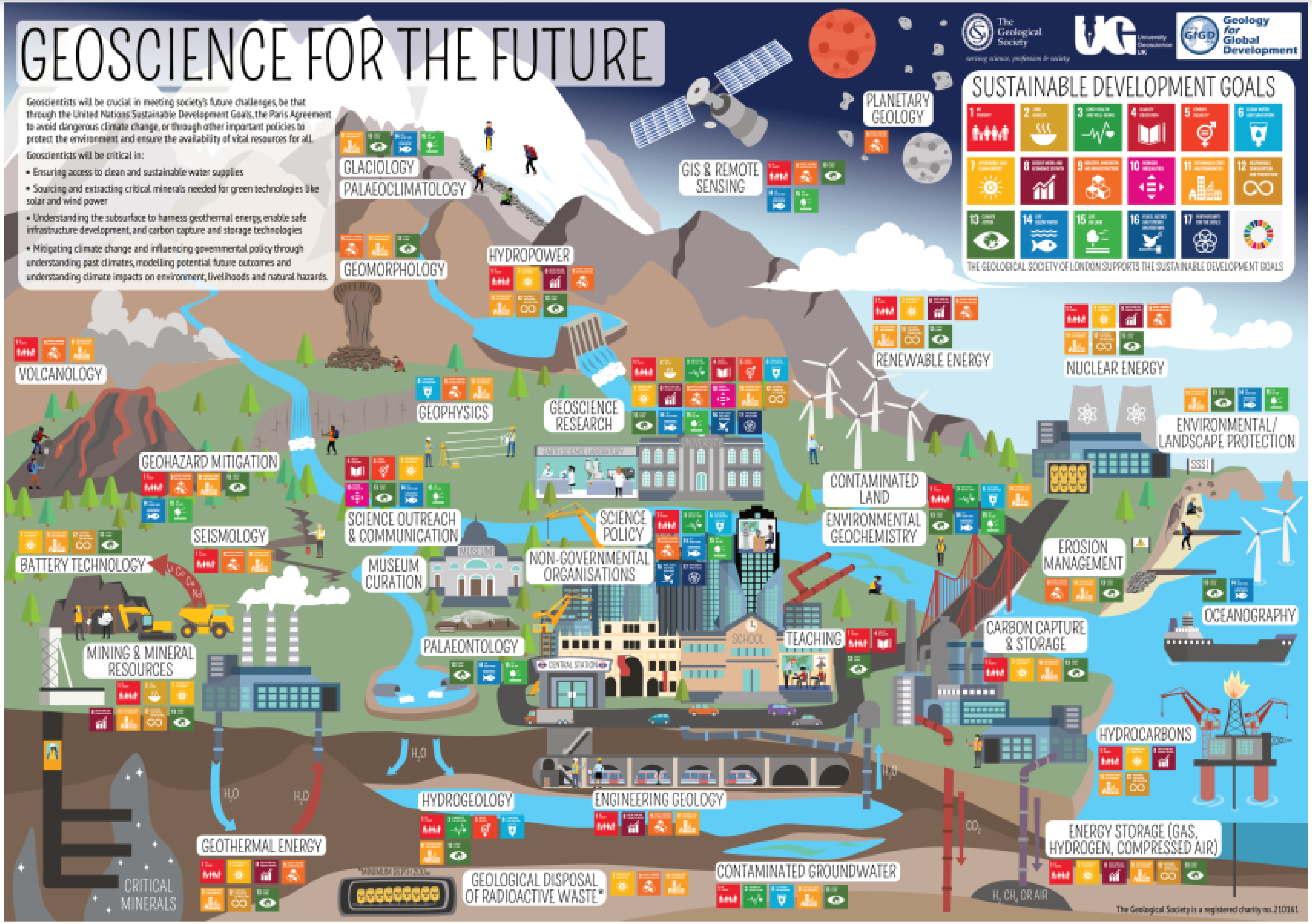
Based on: Trace elements in environmental health and human diseases, Josè- Diversity of Trace Elements.pdf

# Diseases Due to Deficiency and Toxicity of Some Elements

| Element | Deficiency | Toxicity |
|---|---|---|
| Chromium<br><br>Cobalt | Disturbances in the glucose metabolism<br><br>Anemia , "White Liver disease" | Kidney damage (Nephritis)<br><br>Heart failure |
| Copper | Anemia, poor growth, bone decreased in WBC | Idiopathic Cu toxicosis |
| Iron | Anemia | Hemochromatosis |
| Magnesium | Convulsions, malfunctions of the skeleton | |
| Selenium | Liver necrosis | Muscular dystrophy |
| Zinc | Dwarf growth, retarded development of gonads | "Metallic" fever |

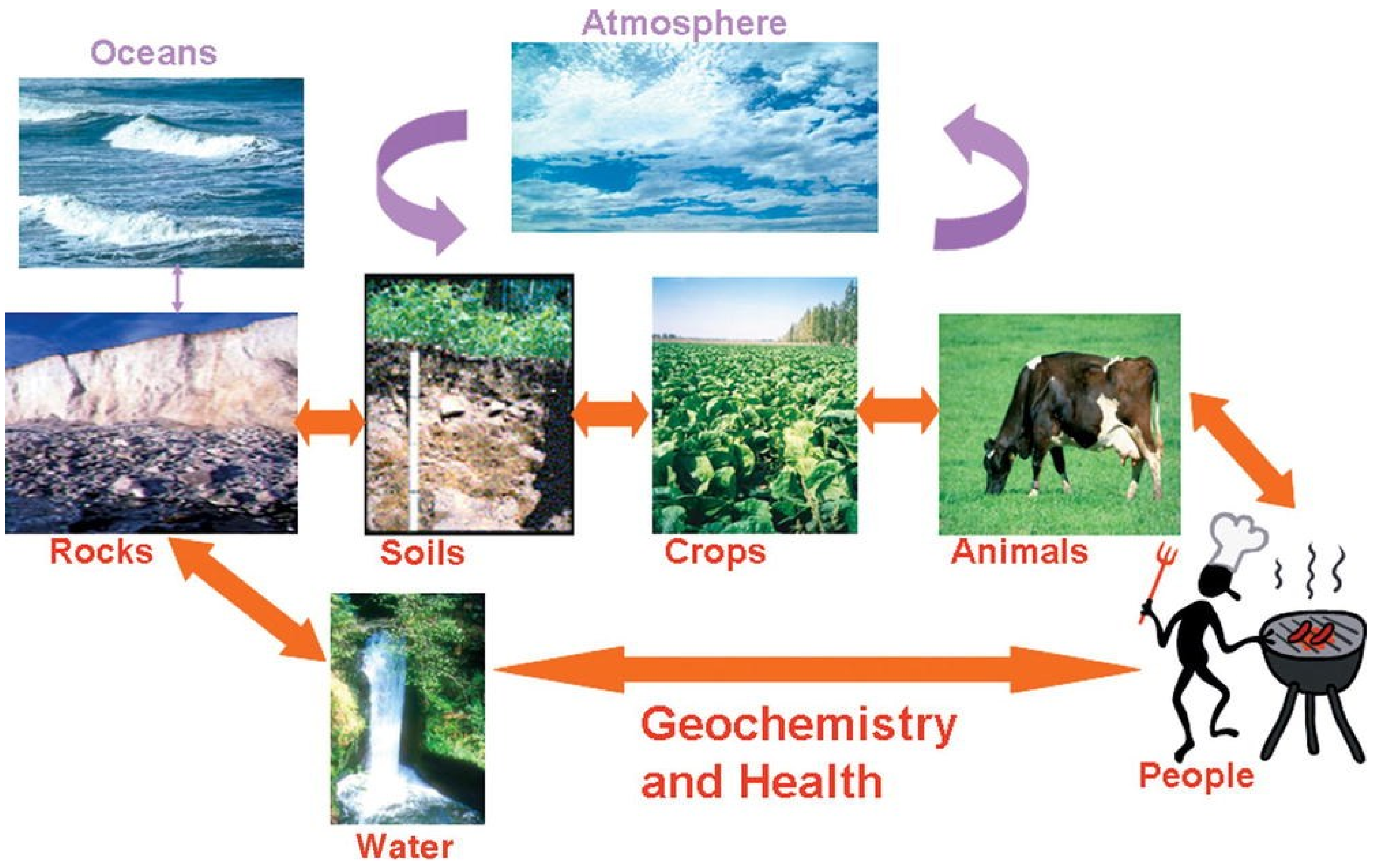
Based on: Trace elements in environmental health and human diseases, Josè- Diversity of Trace Elements.pdf

# Role of Geology in Promoting the SDGs



# What about Medical Geology?

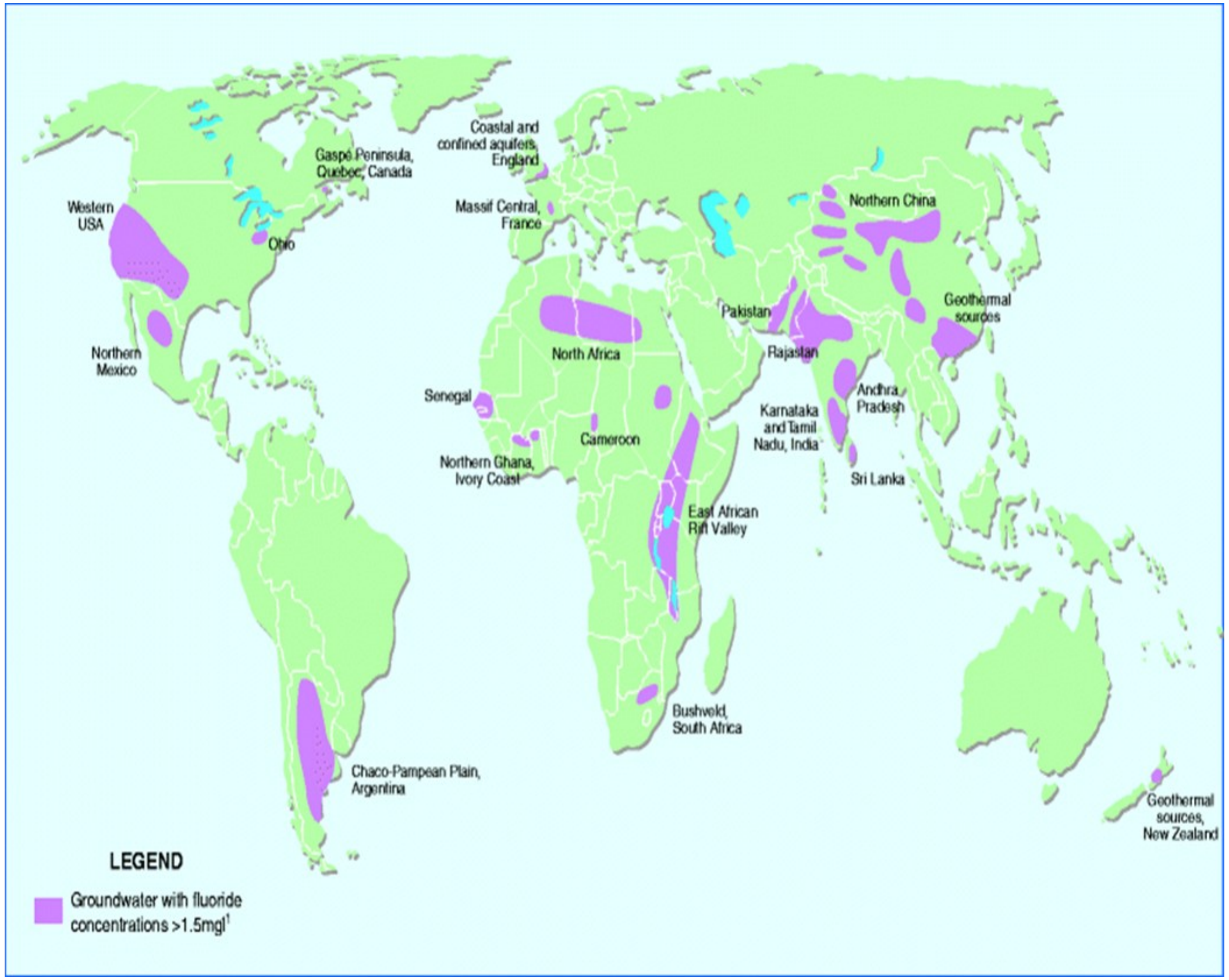
- ❖ Medical geology plays a crucial role in promoting the Sustainable Development Goals (SDGs) by addressing the complex interplay between **geological factors and human health**.



# Role of Medical Geology in Achieving SDG 1 - No Poverty

- By identifying **geogenic health risks** and mitigating their impact, medical geology helps reduce the vulnerability of impoverished communities to health issues, contributing to poverty reduction.

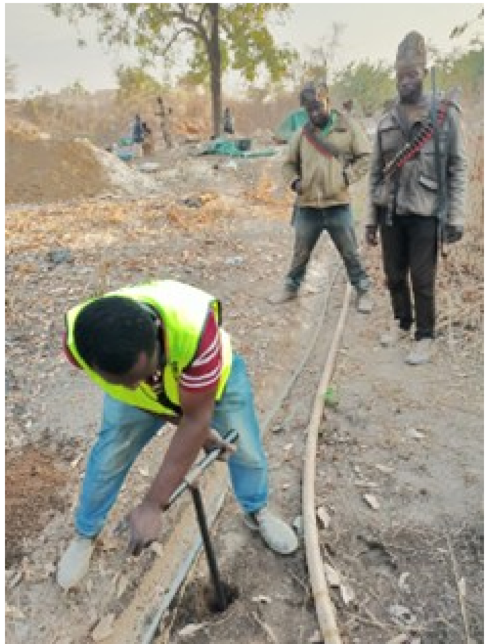
- Ensuring **access to safe water and healthy environments** enhances quality of life and economic productivity, supporting efforts to eradicate poverty.




Source: http://www.bgs.ac.uk/research/groundwater/health/fluoride.html

# Role of Medical Geology in Achieving SDG 2 – Zero Hunger

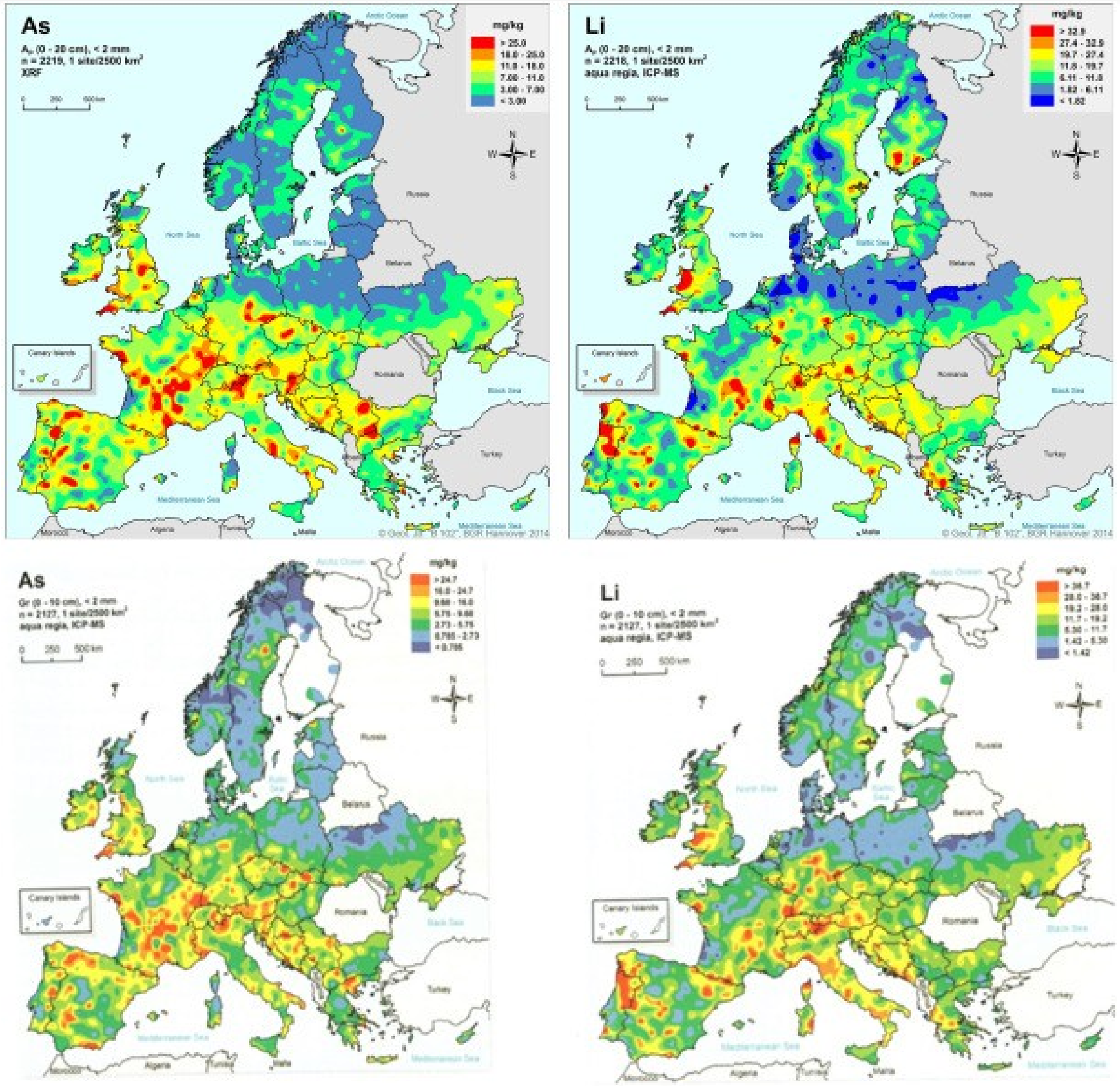
- Medical geology contributes to **understanding soil composition and its impact on agriculture**. Addressing soil contamination and nutrient deficiencies promotes healthier crops and sustainable farming practices.



- Ensuring that **crops and water sources are free from harmful geogenic contaminants** improves food safety and nutrition, contributing to the goal of zero hunger.

# Role of Medical Geology in Achieving SDG 2 – Zero Hunger

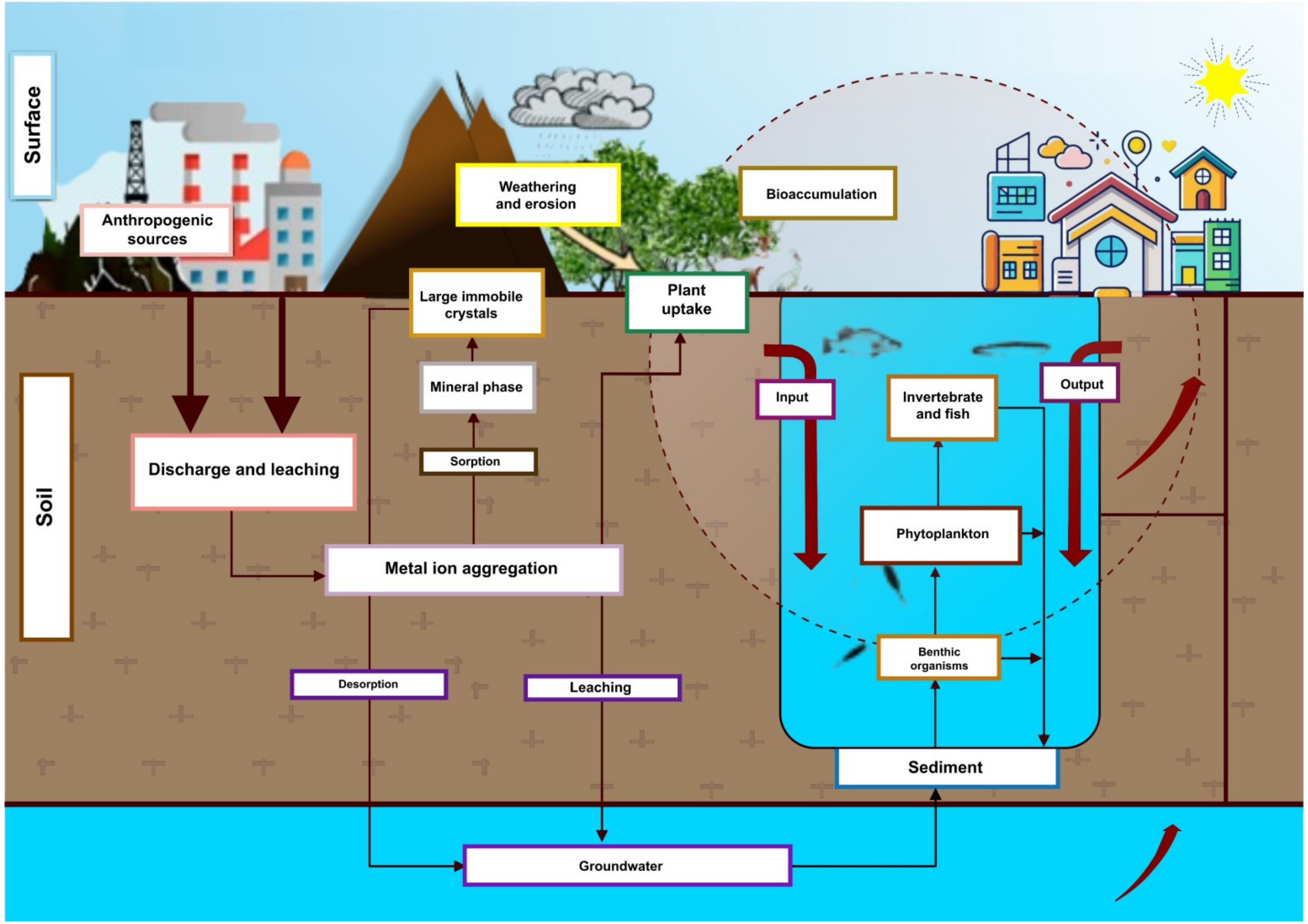
As and Li in agricultural soils (upper) and grazing lands (lower) in Europe.




Source: Finkelman et al. (2018)

# Role of Medical Geology in Achieving SDG 3 – Good Health and Well-being

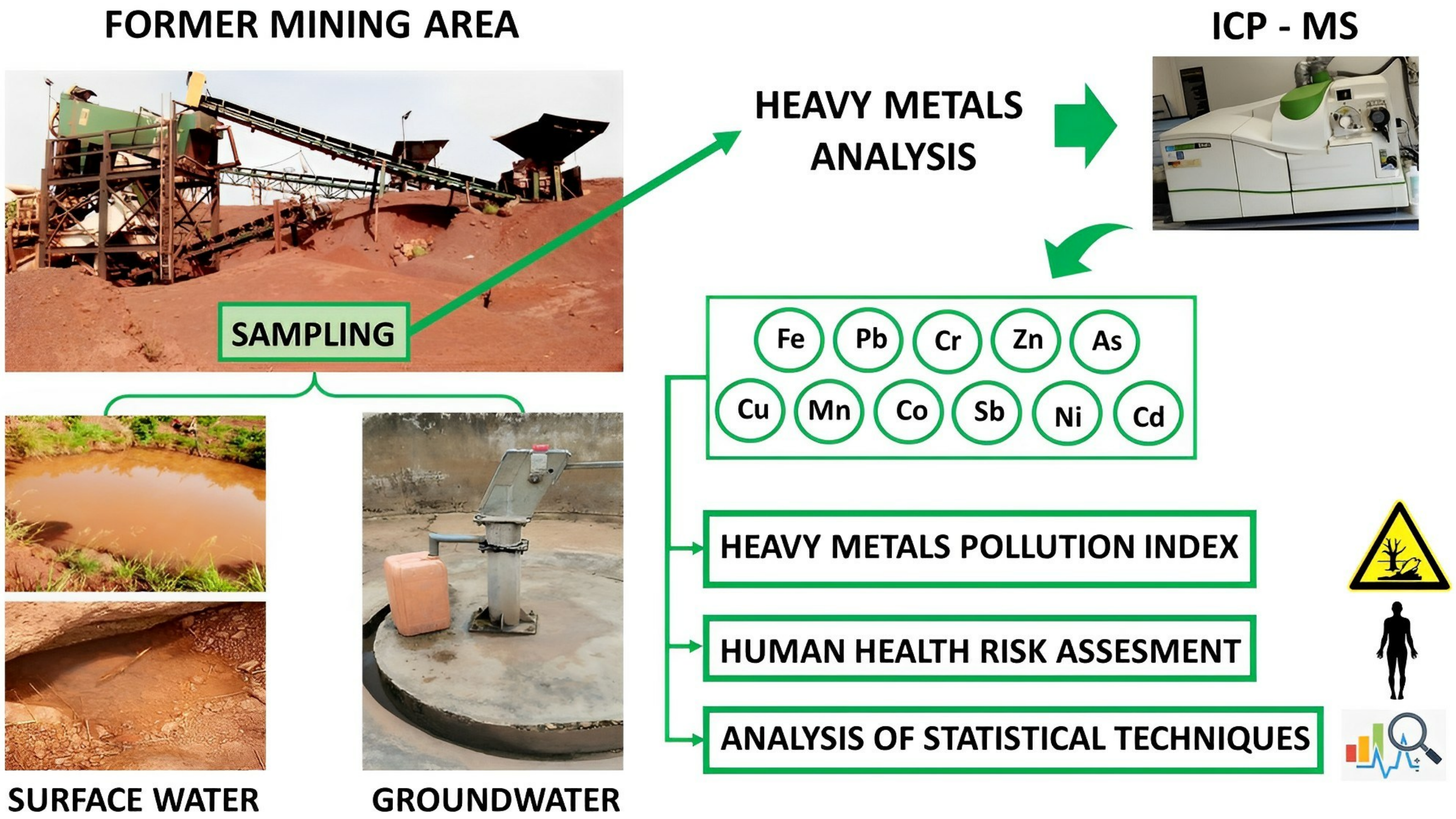
❖ By **understanding the geochemical processes that affect soil and water**, medical geology contributes to reducing exposure to harmful substances, thereby improving public health.




Source: Senne et al. (2025)

# Role of Medical Geology in Achieving SDG 6 – Clean Water and Sanitation

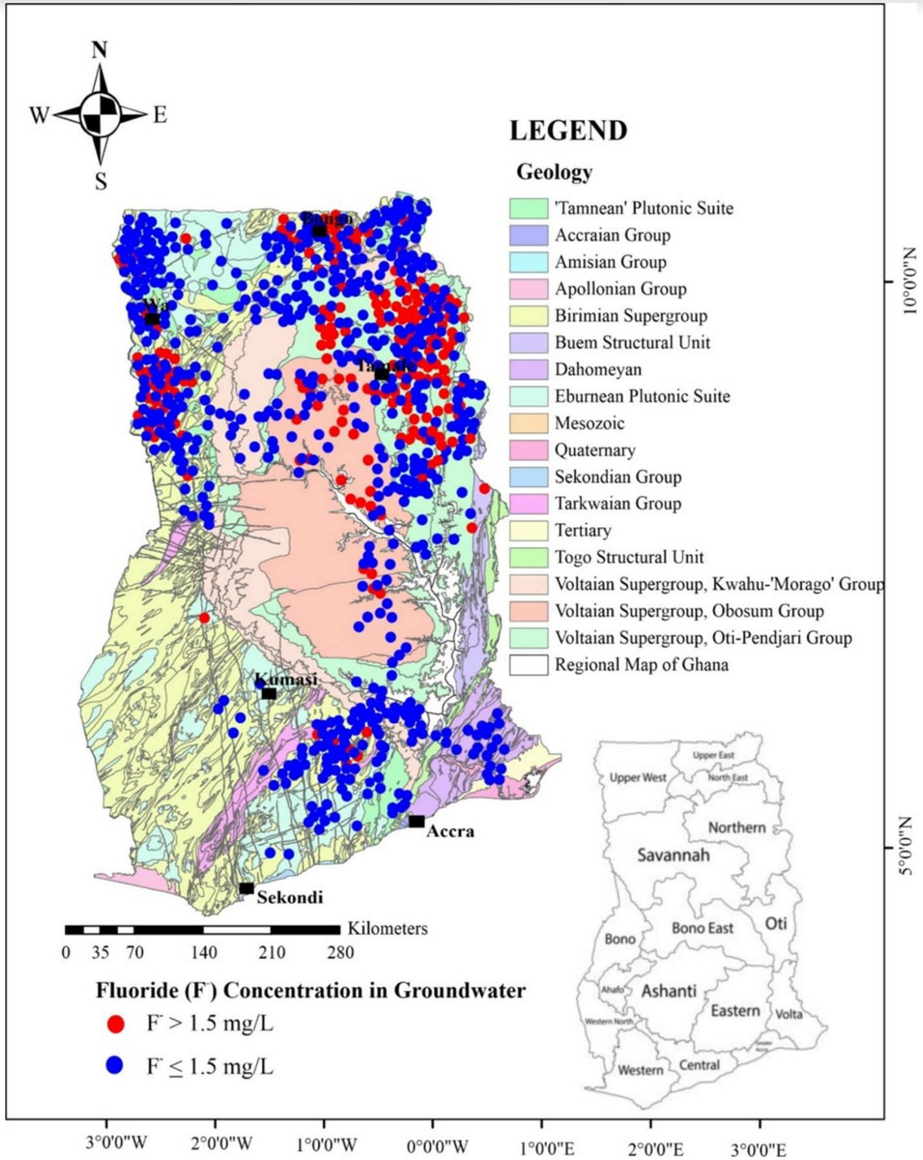
❖ Medical geology helps in **assessing and mitigating the impact of geogenic contaminants** (e.g., heavy metals, radionuclides) on water quality, ensuring safe drinking water for all.




Source: Toi Bissang et al. (2024)

# Role of Medical Geology in Achieving SDG 6 – Clean Water and Sanitation

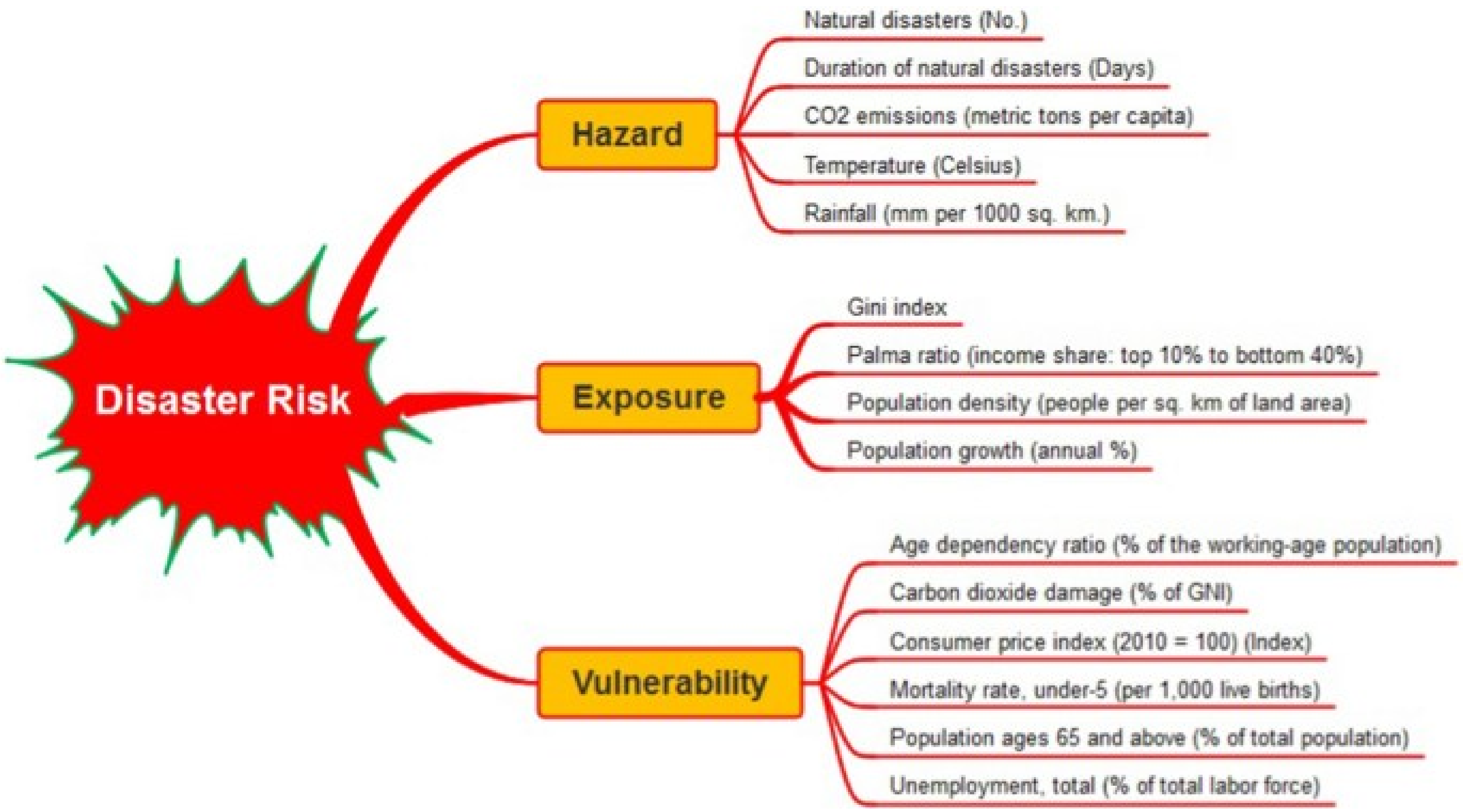
❖ **Spatial distribution maps of groundwater contaminants** can be generated to guide in water quality monitoring and decision making.




Source: Sunkari and Ambushe (2024)

# Role of Medical Geology in Achieving SDG 11 – Sustainable Cities and Communities

- Medical geology aids in **managing natural hazards** (e.g., landslides, earthquakes) and **urban planning**, promoting safer and more resilient communities.



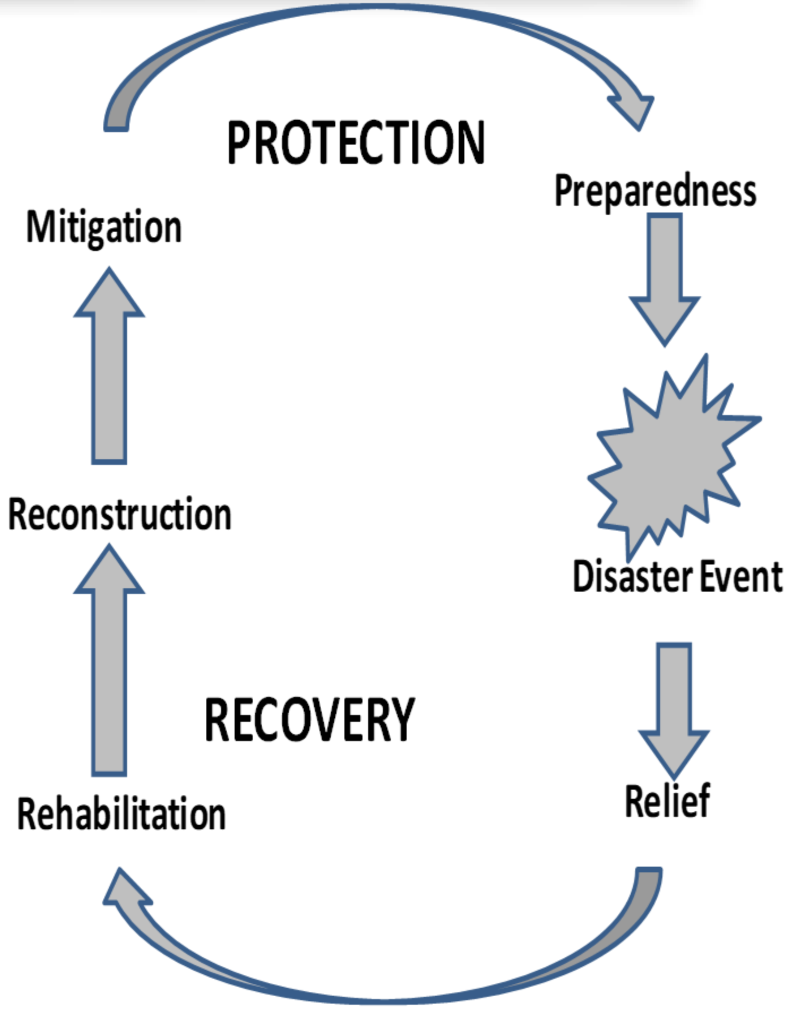

Source: Khan et al. (2023)

# Application of the Disaster Cycle to Mitigate Natural Disasters

## The Recovery Process

Primary concerns of the disaster.

- **Relief:** Satisfy the **immediate and basic needs** of disaster survivors such as for food, clothing, shelter, medical care and emotional security.
- **Rehabilitation:** restoration of the **basic services** necessary to enable the population to return to pre-disaster conditions, e.g. provision of seeds or enabling the re-starting of businesses.
- **Reconstruction:** **Reconstruction of buildings**, with safety as an important element, bringing the situation to normal conditions.




## The Protection Process

Preparing against any future disasters, having learnt from the past.

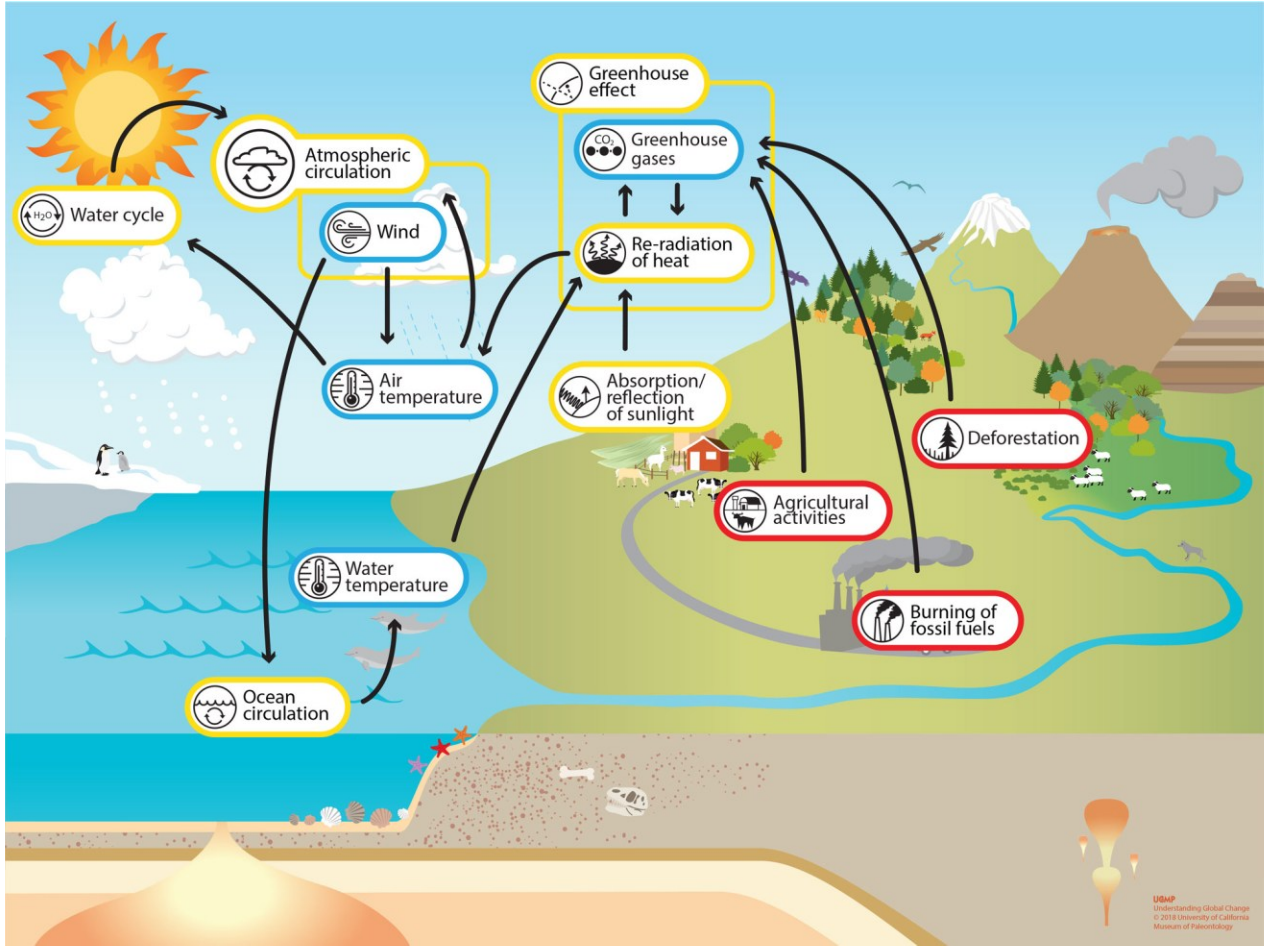
•**Mitigation:** It is a form of preventative action for risk reduction.

•**Preparedness:** Includes planning measures and contingency measures.

# Role of Medical Geology in Achieving SDG 13 – Climate Action

❖ Research in medical geology helps in **understanding the geological aspects of climate change**, such as carbon sequestration and the impact of natural resources on greenhouse gas emissions.

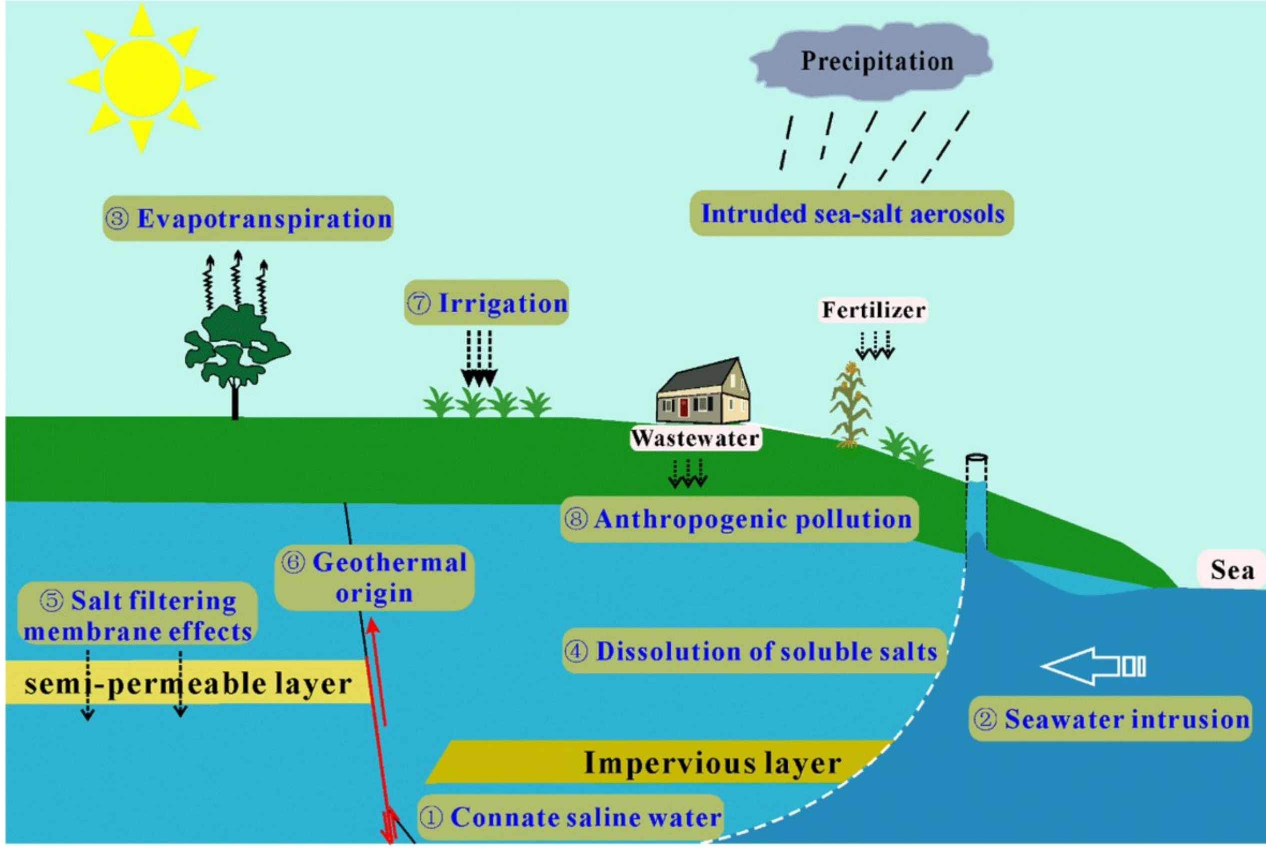
❖ Medical geology plays a crucial role in achieving SDG 13 (Climate Action) by **identifying and mitigating health risks associated with environmental changes caused by climate change**.




Source: https://ugc.berkeley.edu/background-content/atmospheric-circulation/

# Role of Medical Geology in Achieving SDGs 14 & 15– Life Below Water and Life on Land

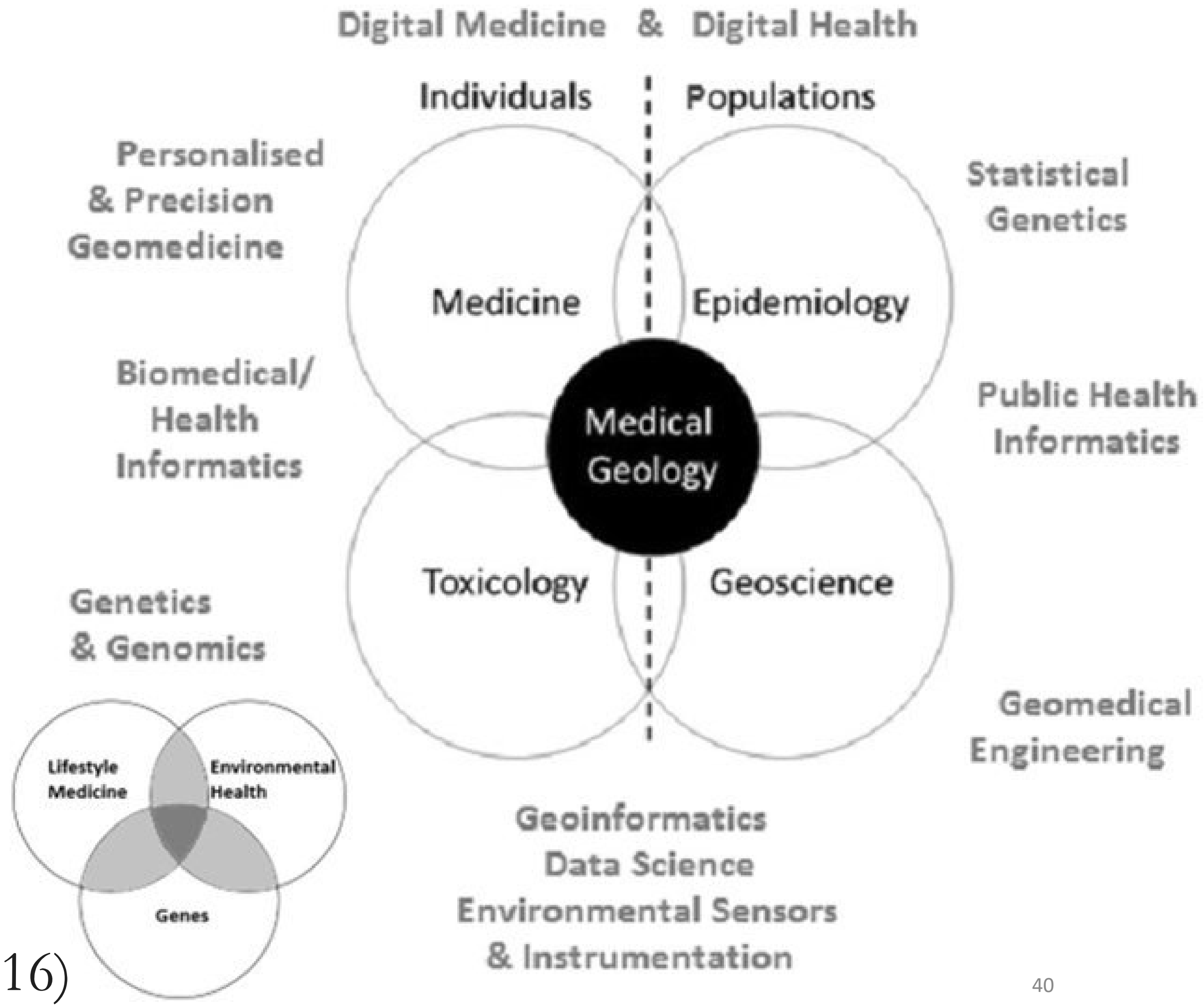
- Medical geology plays a crucial role in achieving SDGs 14 (Life Below Water) and 15 (Life on Land) by **providing critical information about the geological factors impacting water quality, soil composition, and ecosystem health**, which directly influence human health and the overall environmental sustainability of both marine and terrestrial ecosystems




Source: Li et al. (2020)

# Role of Medical Geology in Achieving SDG 17 – Partnerships for the Goals

❖ Medical geology **fosters interdisciplinary collaborations**, bringing together geoscientists, health professionals, and policymakers to develop integrated solutions for sustainable development.




Source: Boulos and Le Blond (2016)

# Case Studies

**My Research Team (Applied Geochemistry Research Group – AGReG) has published over 50 scientific articles predominantly in Elsevier and Springer Nature journals on all aspects of Medical Geology in promoting the Sustainable Development Goals.**

**Max. $F^-$ in Northern Ghana = 4.0 mg/L**
**Max. $F^-$ in Southern Ghana = 0.8 mg/L**

Earth Systems and Environment
https://doi.org/10.1007/s41748-018-0044-z

ORIGINAL ARTICLE

# Comparative Analysis of Fluoride Concentrations in Groundwaters in Northern and Southern Ghana: Implications for the Contaminant Sources

Emmanuel Daanoba Sunkari[1] · Musah Saeed Zango[2] · Harriet Mateko Korboe[3]

Received: 21 September 2017 / Accepted: 28 March 2018


**Abstract**
Bongo and Sekyere South districts, both in the northern and southern parts of Ghana, respectively, have high populations living in rural areas and most of them use groundwater for drinking purposes. The groundwater in these areas is prone to contamination from natural and/or artificial sources. Therefore this study aims; (1) to present a comparative analysis of the fluoride concentration in groundwater samples from Bongo and Sekyere South districts and the associated groundwater–rock interaction that may be the cause for the varied fluoride concentrations, (2) to determine the leaching potential of fluoride from the host rocks as the possible mechanism for groundwater contamination. Sixty (60) groundwater samples from active pumping wells and twelve (12) rock samples from outcrops were collected from various communities in the two districts for fluoride concentration and mineralogical analysis. Based on the variations in fluoride concentration, fluoride spatial distribution maps were prepared using empirical Bayesian kriging interpolation method and analysed by means of hierarchical cluster analysis. The fluoride concentration in Bongo district varies between 1.71 and 4.0 mg/L, whereas that in Sekyere South district changes from 0.3 to 0.8 mg/L. From the mineralogical studies, biotite has the highest percentage in the Bongo district and has positive correlation with fluoride concentration in the analysed water samples than in the Sekyere South district. The elevated fluoride concentration in the Bongo district relative to the Sekyere South district is due to the dissolution of biotite in the groundwater and the sufficient groundwater–rock interaction since the water samples are mainly sourced from deeper boreholes. This high fluoride concentration has resulted in a plethora of reported cases of dental fluorosis and other health-related issues in Bongo.

**Keywords** Spatial distribution · Fluoride concentration · Groundwater · Mineralogical analysis · Empirical Bayesian kriging interpolation · Hierarchical cluster analysis · Ghana

## 1 Introduction

Groundwater is the most appropriate portable and widely used source of drinking water for many rural communities in the world and its quality has special health significance and needs great attention of all concerned (Wright et al. 2004; Furi et al. 2011; Kanyerere et al. 2012; Sunkari and Danladi 2016; Raj and Shaji 2017; Rashed and Niyazi 2017). However, natural processes and increased human activities that release harmful chemicals pose a great threat to the groundwater quality. One of these released chemical constituents is fluoride which exists in ionic form ($F^-$) in aqueous solution (Sreedevi et al. 2006; Jabal et al. 2014). Fluoride concentration in groundwater is of enormous importance and must be known due to its health-related issues. For example, in lower concentrations below 1.5 mg/L (World Health Organisation—WHO guideline), fluoride has a significant mitigating

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Published online: 02 April 2018



**Max. $F^-$ in Bongo District, Northern Ghana = 4.0 mg/L**

Sustainable Water Resources Management
https://doi.org/10.1007/s40899-019-00335-0

ORIGINAL ARTICLE

# Hydrochemistry with special reference to fluoride contamination in groundwater of the Bongo district, Upper East Region, Ghana

Emmanuel Daanoba Sunkari[1] · Mahamuda Abu[2]

Received: 20 February 2019 / Accepted: 12 July 2019


**Abstract**
This study was conducted to understand the hydrochemistry of groundwater in the Bongo district and unravel the source of fluoride in the groundwater using an integrated hydrochemical analysis and multivariate geostatistical analysis. A total of thirty (30) borehole water samples were collected in various communities in the district during the dry season. The district is dominated by Upper Birimian (Paleoproterozoic) metavolcanics and granitoids known as the Bongo granitoids. Hydrochemical facies identified in the area include Ca–Na–$HCO_3$ (70%) and Ca–Mg–$HCO_3$ (30%) water types. The Ca–Na–$HCO_3$ water types are hosted in fractured bedrocks of the Upper Birimian metavolcanics and the K-feldspar rich Bongo granitoids, whereas the Ca–Mg–$HCO_3$ water types are within the Upper Birimian volcanic/metavolcanic sequences. All the hydrochemical parameters show acceptable concentrations for drinking purposes except fluoride (1.71–4.0 mg/L). The high fluoride concentrations in the groundwater are largely due to intense dissolution of the Bongo granitoids, which contain biotite and muscovite as the dominant fluoride-bearing minerals. The pH, $Ca^{2+}$, $SO_4^{2-}$, $HCO_3^-$ and $CO_3^{2-}$ concentrations have weak positive correlations with $F^-$ concentrations of the groundwater implying some dependent relationship and different source for the fluoride. Principal component analysis performed on the hydrochemical data resulted in three principal components (PCs), which explain 76.251% of the total variance. The three PCs represent the dominant processes influencing the groundwater chemistry, which include water–rock interaction, mineral dissolution, and ion exchange reactions, respectively, with water–rock interaction as the most dominant process. However, anthropogenic sources such as the use of phosphate fertilizers cannot be precluded from contributing to the groundwater fluoride contamination.

**Keywords** Groundwater · Hydrogeochemistry · Fluoride · Geogenic source · Anthropogenic sources · Bongo district

## Introduction

Many parts of the world are affected by high fluoride groundwater especially in arid to semi-arid regions. These areas are common in Pakistan, India, Sri Lanka, China, Spain, Mexico, western USA, many parts of South America, and Africa (Edmunds and Smedley 2005). The World Health Organization (WHO) permit a maximum limit of 1.5 mg/L of fluoride in drinking water (WHO 2017) and above this threshold, groundwater is said to be contaminated in terms of fluoride. The adverse effects of elevated fluoride concentrations in drinking water are well known in the literature and include dental mottling, skeletal fluorosis, physiological disorders, kidney malfunction, and thyroid changes (Grandjean et al. 1992; Reddy et al. 2010; Sunkari et al. 2018). In view of the several health challenges fluoride contaminated water pose to people across the globe, there has been an overwhelming pool of researches focused on understanding the origin and chemistry of fluoride in groundwater. Most of these researches involve a wide range of hydrochemical and multivariate statistical analysis as well as appropriate techniques for mitigation of the groundwater fluoride menace.

Rocks having granitic compositions contain several fluoride-bearing minerals such as micas (biotite and muscovite), amphibole and apatite. Moreover, in typical granitic rocks, the dominant fluoride-bearing mineral is fluorite ($CaF_2$), mostly occurring as an accessory mineral phase.

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Published online: 18 July 2019

**Max $F^-$ in North East Region, Northern Ghana = 13.29 mg/L**

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journal homepage: www.elsevier.com/locate/gexplo

ELSEVIER

# Hydrogeochemical controls and human health risk assessment of groundwater fluoride and boron in the semi-arid North East region of Ghana

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ARTICLE INFO

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Groundwater
Fluoride
Boron
Risk assessment
Northeastern Ghana

ABSTRACT

In this study, eighty-eight (88) samples were collected from active boreholes in the North East region of Gha and analyzed for concentrations of the hydrogeochemical parameters. This helped in understanding the h drogeochemistry, spatial distribution, origin of groundwater $F^-$ and B and the level to which the underlyi geology influences the $F^-$ and B. Human health risks of $F^-$ and B were also assessed based on the model of t US Environmental Protection Agency. Groundwater is alkaline in this area and the dominant hydrochemi facies is Na-$HCO_3$ facies, which is a reflection of the predominant carbonate lithology of the Oti/Pendjari Gro in the region. The study reveals that the $F^-$ concentrations range from 0.05 to 13.29 mg/L with an average val of 3.26 mg/L, suggesting that majority of the boreholes have $F^-$ concentrations higher than the acceptable lin (1.5 mg/L) of WHO. The B concentrations also vary from 0.03 to 5.13 mg/L with an average of 1.52 mg/L excess of the guideline value of 0.5 mg/L. The groundwater $F^-$ and B threats, respectively affect about 70% a 82% of boreholes in the region particularly around the northeastern, southeastern, central, and western parts. I and B are mainly coming from geogenic sources and are controlled by hydrogeochemical factors such as sen arid climatic conditions of the region, alkaline nature of the water, water-rock interaction, intense weatherin ion exchange, mineral dissolution and precipitation. The human health risk assessment reveals that non-car nogenic risk for $F^-$ and B is higher in children than the adult population. About 89% of children in the study ar are exposed to initial symptoms of dental and skeletal fluorosis and have higher chances of cardio-protecti since no health threat is currently reported for high B in drinking water. We recommend immediate acti towards mitigating the high groundwater $F^-$ to safeguard the health and livelihood of the people.

## 1. Introduction

Fluorine in the form of fluoride ion ($F^-$) in drinking water plays a significant role in human health and wellbeing. In levels < 1.5 mg/L, it is required for good dental health; the reason for fluoride addition to toothpaste (Chuah et al., 2016) and good bone development (Mondal et al., 2014). However, $F^-$ levels > 1.5 mg/L have been reported to have deleterious effect on tooth and skeletal development (WHO, 2017). According to the World Health Organization, $F^-$ concentrations in groundwater that exceed the threshold value of 1.5 mg/L can expose people to dental and skeletal fluorosis (WHO, 2017). These diseases have been reported in several countries with high groundwater $F^-$ concentration (e.g., Gao et al., 2013; Wen et al., 2013; Machender et al., 2014; Ali et al., 2016, 2018; Yeşilnacar et al., 2016; Guissouma et al., 2017; Maity et al., 2018). Almost 80% of the diseases across the globe are caused by poor quality drinking water and only $F^-$ concentrations in drinking water account for 65% of global endemic fluoros (Felsenfeld and Roberts, 1991). Though estimates are not well esta lished, it is thought that about 200 million people are globally drinki water with fluoride concentrations higher than the WHO maximu permissible limit and tens of millions of people in Africa alone are at great risk (Edmunds and Smedley, 2013).

The vital role fluorine plays in human health and wellbeing h inspired many scientists to conduct several researches regarding i levels in groundwater (e.g., Apambire et al., 1997; Zhao and She 1999; Ravindra and Garg, 2006; Tekle-Haimanot et al., 2006; Sub Rao et al., 2012; Machender et al., 2014; Li et al., 2015; Ali et al., 201 Huang et al., 2017; Sunkari et al., 2018; Sunkari and Abu, 2019). The workers all agree that due to the high electronegativity and solubility $F^-$ coupled with complex local geochemical processes, it occurs varied concentrations in drinking water. The amount of $F^-$ occurri naturally in groundwater is controlled by several factors includi

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**Max $F^-$ in Northern Ghana = 8.40 mg/L**

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ELSEVIER

# Hydrogeochemical characterization and assessment of groundwater quality in the Kwahu-Bombouaka Group of the Voltaian Supergroup, Ghana

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ARTICLE INFO

*Keywords:*
Hydrochemistry
Groundwater quality
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Northeastern Ghana

ABSTRACT

The Kwahu-Bombouaka Group of the Voltaian Basin, which defines the northern fringe of the basin, constitutes a significant part of the North East Region of Ghana. Most of the inhabitants in the region depend on groundwater for domestic and irrigation purposes. Therefore, a geochemical characterization and assessment of groundwater quality in the area was carried out using hydrochemical, GIS-based ordinary kriging interpolation and multivariate statistical methods on fifty-five (55) borehole water samples. The aim of this study was to determine the concentrations and spatial distribution of various ions, groundwater quality issues and the geochemical processes contributing to groundwater chemistry. The area is largely underlain by sandy shales and mudstones of the Poubogou Formation and feldspathic, quartzitic sandstones with conglomeratic lenses of the Panabako Formation. The abundance of major cations in the groundwater is in the order: $Na^+ > Ca^{2+} > K^+ > Mg^{2+}$ whereas that of the major anions vary in the order: $HCO_3^- > SO_4^{2-} > Cl^-$. Na–HCO3 water type is common in the area, which may be due to dissolution from silicate minerals (albite and microcline) in the basement rocks. The results indicate that fluoride (0.01–8.40 mg/L, mean of 0.58 mg/L) and boron (0.01–4.81 mg/L, mean of 0.28 mg/L) contamination is a threat to groundwater quality with respect to their guideline values provided by the World Health Organization. The groundwater chemistry is primarily controlled by ion exchange reactions, weathering of silicate minerals residing in the Panabako Formation and anthropogenic activities from agriculture. Groundwater in the area is largely suitable for drinking purposes although some few boreholes in the northwestern and southeastern parts have high fluoride and boron concentrations. The sodium percentage (11–99%, mean of 70%), magnesium ratios (2.05–57, mean of 29) and sodium adsorption ratio (0.15–38, mean of 4.72) are quite high in some of the communities in the southeastern part of the area. This suggests that water in this part of the area is not entirely suitable for irrigation purposes.

## 1. Introduction

The demand for groundwater has undoubtedly increased across the globe due to its suitability for domestic, agricultural and industrial purposes. However, groundwater in most aquifer systems is in contact with different rock units and dissolved molten materials have the tendency of mixing with the groundwater (Singh et al., 2015; Yetiş et al., 2019). Accordingly, hydrogeochemical characteristics of groundwater are vital for understanding the quality of groundwater and determining its suitability for various uses. In this regard, several works have pointed out that natural and anthropogenic factors influence groundwater chemistry (e.g., Davraz and Ozdemir, 2014; Berhe et al., 2017; Sunkari and Abu, 2019; Sunkari et al., 2018, 2019a; Zango et al., 2019; Abanyie et al., 2020) and thus, hydrogeochemical surveys give vital information regarding the contribution of these factors to groundwater chemistry.

The constituents of groundwater come from different sources and are controlled by complex geochemical processes operating in aquifers (Yetiş et al., 2019). Some of the natural mechanisms that introduce dissolved constituents in groundwater include ion exchange reactions, water-rock interaction, evaporation, mineral precipitation and dissolution (Redwan et al., 2016; Sako et al., 2018). However, it is now commonplace to associate groundwater contamination with anthropogenic sources such as indiscriminate sewage disposal, mining, industrial activities, agrochemical application on farms and even excessive abstraction (Lermi and Ertan, 2019; Sunkari and Danladi, 2016).

To understand the adverse effects of the controlling factors of

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## Max $F^-$ in Upper East Region, Northern Ghana = 4.10 mg/L

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ORIGINAL ARTICLE

Check for updates

# Assessment of the quality of water resources in the Upper East Region, Ghana: a review

Samuel Kojo Abanyie[1] · Emmanuel Daanoba Sunkari[2] · Ohene Boansi Apea[3] · Samson Abagale[3] · Harriet Mateko Korboe[4]

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**Abstract**

Water is an indispensable resource for human health and social well-being. However, the quality of this critical resource is being threatened by both natural and anthropogenic sources. Surface and groundwater resources in the Upper East Region of Ghana are poorly managed and monitored. The water resources in this part of Ghana are contaminated with coliforms, toxic trace metals, and agrochemicals. Most of the parameters for drinking water quality are seriously being violated in various parts of the region. The major sources of surface water and groundwater pollution in the region are the dissolution of minerals, the widespread application of agrochemicals on farms, biological contamination resulting from human and animal fecal matter due to open defecation and mining activities. These have resulted in diverse health-related problems in the region since the contaminated water sources are the only drinking water supplies for rural folks. Fluoride contamination of the groundwater resources is also a major problem in the region, especially in the Bongo District and the Bolgatanga Municipality, which has resulted in cases of dental fluorosis in these parts of the region. There exists no comprehensive review on the water quality in the Upper East Region of Ghana. Therefore, this review is aimed at discussing the quality of the water resources in the region from previously published works in various parts of the region. The review highlights the major pollutants, pollution sources, and the associated health problems. Recommendations have been offered based on the findings to serve as a framework for policy-making in regard to the water resources in the region.

**Keywords** Water quality · Major pollutants · Fluoride contamination · Pollution sources · Health problems · Ghana

## Introduction

Water is a critical resource for the socioeconomic advancement of life on earth since it is indispensable for human health and social well-being. The significant role this resource plays and the need for high-quality water for human consumption necessitated the UNO Secretary General in 2002 to release a press statement declaring that "An estimated 1.1 billion people lack access to safe drinking water, 2.5 billion people have no access to proper sanitation, and more than 5 million people die each year from water-related diseases—10 times the number killed in wars, on average, each year. All too often, water is treated as an infinite free good. Yet even where supplies are sufficient or plentiful, they are increasingly at risk from pollution and rising demand. By 2025, two-thirds of the world's population is likely to live in countries with moderate or severe water shortages" (UN 2002). Following the 2002 press release, the United Nations also declared the years 2005–2015 as the global decade for

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## Max $F^-$ in Vea Catchment, Northern Ghana = 3.95 mg/L

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Check for updates

# Hydrogeochemical and isotopic controls on the source of fluoride in groundwater within the Vea catchment, northeastern Ghana

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ARTICLE INFO

*Keywords:*
Groundwater
Fluoride contamination
Stable isotopes
Vea catchment
Ghana

ABSTRACT

Groundwater consumption is considered as a major exposure route to fluoride in humans. Therefore, this study unraveled the sources and sinks of groundwater fluoride in the Vea catchment of northeastern Ghana using an integration of litho-petrography, hydrogeochemical analysis, multivariate statistical analysis, and stable isotope analysis. In this regard, 70 groundwater samples were collected from boreholes and analyzed for major ions and stable isotopes using standard procedures whilst 10 rock samples were collected from the crystalline basement rocks of the Birimian Supergroup and used for the petrographic studies. The petrographic results revealed the dominance of quartz, microcline, plagioclase (albite), biotite, muscovite and hornblende in the lithological units. The order of dominance of fluoride in the various lithologies is K-feldspar-rich granitoid > hornblende-biotite granitoid > basaltic flow > hornblende-biotite tonalite > hornblende biotite granodiorite > biotite granitoid. The groundwater fluoride concentrations varied from 0.35 to 3.95 mg/L with a mean concentration of 1.68 mg/L. Almost 61% of the samples have fluoride concentrations above the World Health Organization's maximum permissible limit of 1.5 mg/L. Groundwater is supersaturated with respect to albite due to silicate weathering and undersaturated with respect to fluorite and calcite. This enhanced ion exchange and fluoride mobilization in the groundwater from progressive calcite precipitation. The fluoride concentrations show positive correlations with $Na^+$, $Mg^{2+}$, $HCO_3^-$, and $SO_4^{2-}$, confirming that fluoride enrichment is due to silicate weathering and ion exchange reactions. The $\delta^{18}O$ and $\delta^2H$ values with respect to V-SMOW vary between −4.15 and −2.75‰ and −22.49 and −13.74‰, respectively suggesting considerable isotopic variation of the groundwater. Enriched isotopic composition is observed with low fluoride concentration whilst depleted isotopic composition is observed with a higher concentration of fluoride in groundwater. The stable isotopic compositions of the groundwater also indicated meteoric origin with an evaporative effect, which partly influences the groundwater chemistry.

## 1. Introduction

Fluoride ($F^-$) in drinking water is now a global health concern. Although $F^-$ is required for proper tooth functioning in desired levels, concentrations exceeding 1.5 mg/L may cause significant health problems (WHO, 2017). High levels of $F^-$ occurs in several parts of the world including Africa, Asia, and Middle East (e.g., Adimalla and Li, 2019; Li et al., 2019; Ganyaglo et al., 2019; Zango et al., 2019). In most of these areas, prolonged drinking of groundwater with high $F^-$ levels has led to incidences of dental fluorosis. For instance, in parts of the Indo-Gangetic Alluvial plains, Kumar et al. (2019) reported $F^-$ concentrations up to 5.8 mg/L leading to severe cases of dental fluorosis and bone deformities in children. Based on petrographic analysis of the host rocks in the area as well as molar ratios of chemical species, Kumar et al. (2019) stated that the high groundwater $F^-$ is due to intense water-rock interaction and dissolution from fluoride-bearing minerals in the granitic basement of

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## Max F⁻ in Bongo District, Northern Ghana = 4.0 mg/L

# Geochemical Controls on Fluoride Enrichment in Groundwater of a Geologically Heterogeneous Part of Ghana: Implications for Human Health Risk Assessment

Check for updates

**Emmanuel Daanoba Sunkari, Moses Boakye Okyere, Salaam Jansbaka Adams, Musah Saeed Zango, Prosun Bhattacharya, and Shakir Ali**

## Contents



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## Max F⁻ in Saboba District, Northern Ghana = 4.70 mg/L

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ELSEVIER

Research paper

# Hydrogeochemistry, sources, enrichment mechanism and human health risk assessment of groundwater fluoride in Saboba District in the Oti sub-basin of the Volta River Basin, northern Ghana

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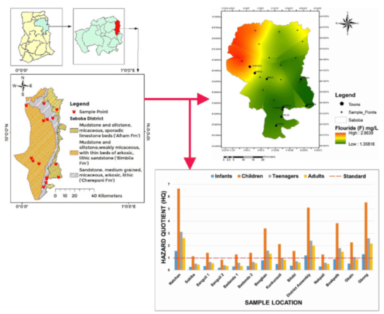
### HIGHLIGHTS

- The predominant water type in the area is K–$HCO_3$ type.
- Groundwater fluoride concentrations varied from 0.6 to 4.7 mg/L.
- About 57% of the studied groundwater samples have elevated fluoride concentrations.
- Geogenic processes primarily contribute to groundwater fluoride enrichment.
- Children are more susceptible to health risks associated with fluoride exposure.

### GRAPHICAL ABSTRACT




### ARTICLE INFO

*Keywords:*
Geogenic
Fluorosis
Hydrogeochemistry
Fluoride contamination in Ghana
Human health risk assessment
Medical geology

### ABSTRACT

This study was aimed at appraising the hydrogeochemistry of groundwater and the possible health hazards linked to elevated fluoride ($F^-$) levels in the Saboba District within the Oti sub-basin of the Volta River Basin of northern Ghana. Multivariate statistical analysis, hydrogeochemistry, thermodynamic calculation of mineral saturation indices, and an evaluation of the risk to human health were all used in this assessment. A tFrilinear Piper diagram revealed that K–$HCO_3$ was the predominant water type, reflecting the local geology. Groundwater $F^-$ content varied, with an average of 1.33 mg/L and a range of 0.6–4.7 mg/L, with elevated values mainly in the northwestern fringe of the district. Groundwater $F^-$ is mostly enriched by geogenic processes including mineral

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# Assessment of borehole water quality in Nwadzekudzeku village, Giyani, Limpopo Province, South Africa: Implication for potential human health risks

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ARTICLE INFO

*Keywords:*
Groundwater quality
Water hardness
Nitrate contamination
Health risk assessment
Potentially toxic elements

ABSTRACT

*Introduction:* Due to a lack of potable water supplies in rural areas of South Africa, most rural communities depend on groundwater for subsistence. Concerns have been raised about the quality of Nwadzekudzeku village borehole water.

*Methods:* This study investigated physicochemical parameters, anions and potentially toxic elements (PTEs) in drinking water to evaluate the borehole water quality from Nwadzekudzeku village. A multi-methods approach involving water quality analysis, geospatial mapping, multivariate statistical analysis, and human health risk analysis were employed in this study.

*Results and Discussion:* The results showed that borehole water had a pH ranging from 6.96 - 7.76, an electrical conductivity (EC) of 132 - 2740 μS.cm$^{-1}$, total dissolved solids (TDS) of 381 - 1336 mg.L$^{-1}$, resistivity in the range of 62 - 1030 Ω, salinity from 0.32 - 1.34 ppt and an oxidation–reduction potential (ORP) of 9.20 - 233 mV. Most borehole water samples were found to have all physicochemical parameters above the maximum permissible levels (MPLs) set by the World Health Organization (WHO) and South African National Standards (SANS) except for pH and temperature. Concentrations of anions were determined in the mg.L$^{-1}$ range with $Cl^-$ (44.0 – 853 mg.L$^{-1}$) and $NO_3^-$ (25.0 – 127 mg.L$^{-1}$) as the only anions above WHO and SANS stipulated limits for drinking water. The results of cations showed that Na is the dominant cation with concentrations ranging from 42.8 – 241 mg.L$^{-1}$, which exceed the WHO MPL. Based on the cation and anion dominance in the borehole water, the water is predominantly Na-Cl water type. The concentrations of PTEs in water were within the MPLs set by WHO. Multivariate statistical analysis revealed that the hydrochemical parameters were enriched in the aquifer through ion exchange reaction, dissolution of silicate minerals from the mafic-ultramafic lithologies, and agricultural activities. Children are the hypersensitive population with respect to nitrate toxicity in water as they show cumulative hazard index (HI) values ranging from 0.02 - 6.59 with an average value of 2.49, whereas HI for adults ranged from 0.02 - 4.71 with an average value of 1.78.

*Conclusion:* This suggests that there is a high non-carcinogenic risk in the Nwadzekudzeku village because of the concentration of nitrate, as indicated by the average cumulative HI for children and adults being higher than the recommended value of 1.

## 1. Introduction

South Africa (SA) is one of the semi-arid regions with inadequate freshwater supply. As a result, ensuring an adequate fresh water supply remains a significant concern. According to the Department of Water and Sanitation (DWS), about 14.1 million individuals in SA have no access to safe water [1,2]. The drought brought by global and climate change continues to be a serious worry. Similarly, the increasing population growth, development of industries, and high living standards contribute to the lack of potable water [3–7]. According to literature [1], about 56 % of SA's water treatment facilities are operational and the other 44 % are in poor condition. Therefore, due to all these factors, most villages in rural areas across SA use water from unsafe sources including rivers, dams, lakes and boreholes for consumption [8,9].

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# Groundwater fluoride contamination, sources, hotspots, health hazards, and sustainable containment measures: A systematic review of the Ghanaian context

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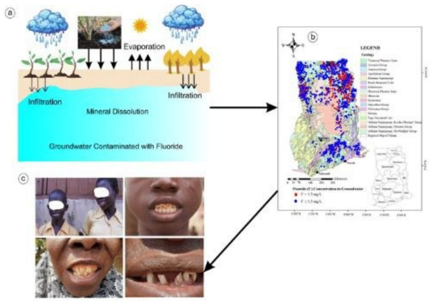
HIGHLIGHTS

- Lithology type influences fluoride enrichment in aquifers in Ghana.
- Groundwater fluoride hotspots in Ghana are restricted to the northern fringe.
- The southern regions are less explored scientifically for fluorosis.
- Dental fluorosis is the main health hazard in the fluorosis-endemic parts.
- Low-cost defluoridation technologies and community-based initiatives are encouraged.

GRAPHICAL ABSTRACT




ARTICLE INFO

*Keywords:*
Birimian and Voltaian supergroups
Dental fluorosis
Fluoride
Geogenic
Groundwater
Sustainable defluoridation techniques

ABSTRACT

Groundwater quality is globally threatened by geogenic and human activities. These activities release high levels of potentially toxic elements, such as fluoride ($F^-$), which pose significant threats to human health. This has become a global issue, especially in developing countries such as Ghana. Despite efforts to address this issue, knowledge gaps still need to be addressed to ensure safe and healthy drinking water for all Ghanaians. Moreover, Ghana has been reported to be a fluorosis-endemic country but the sources and exact hotspots of $F^-$ enrichment in the aquifers on a countrywide scale are lacking in the available literature. Understanding the quality of water used for diverse purposes in Ghana is necessary to achieve the United Nations Sustainable Development Goals like good health and well-being (SDG 3) and clean water and sanitation (SDG 6), among others. Therefore, this study synthesized all previous studies on groundwater $F^-$ contamination in Ghana, to identify the sources of $F^-$

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CHALLENGES IN MANAGING AND RISK ASSESSMENT OF EMERGING ENVIRONMENTAL POLLUTANTS

# Pollution and probabilistic human health risk assessment of potentially toxic elements in the soil-water-plant system in the Bolkar mining district, Niğde, south-central Turkey

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## Abstract

Globally, potentially toxic elements (PTEs) are regarded as an important group of pollutants for the wider environment because of their intrinsic toxicity and probable accumulation in the soil-water-plant system. In this regard, this study assessed the pollution levels and probable human health risks of PTEs in the soil-water-plant system in the Bolkar mining district of the Niğde Province in south-central Turkey. Pollution assessment using contamination factor, enrichment factor, index of geoaccumulation, and soil pollution index reveals moderate to extremely high pollution of PTEs in the soil, exposing the soils to extreme toxicity levels. The areas that fall under the toxic to extremely toxic categories are in proximity to the ore slags and agricultural lands towards the central and southern domains of the study area. The water hazard index (WHI) values indicate that 100% of the samples collected in both winter and fall seasons are of extreme toxicity (WHI > 15). Arsenic is the dominant contaminant among the PTEs in the soil and water samples. The bioconcentration factor values of the PTEs in most of the fruit plants are > 1, indicating very high levels of element transfer from the soil and water to the plants. The probabilistic human health risk assessment involved exposure to arsenic in groundwater (a major pathway to humans) since it is the only carcinogenic element in this study. The estimated daily intake of arsenic-contaminated water exceeds the safe limit of $5 \times 10^{-8}$ mg/kg/day. About 33.3% and 55.6% of the groundwater samples have higher hazard quotient and carcinogenic risk values of arsenic in the winter and fall seasons, respectively. This implies that the people are more exposed to the carcinogenic effects of drinking arsenic-contaminated water.


**Keywords** Anthropogenic activities · Human health risk assessment · Ore slags · Pollution assessment · Potentially toxic elements · Arsenic contamination

**Highlights**
- Pollution assessment reveals moderate to extremely high pollution of PTEs in the soil.
- Water hazard index values indicate that 100% of the samples are of extreme toxicity.
- Bioconcentration factors show high levels of element transfer from the soil and water to the plants.
- About 55.6% of the samples have high carcinogenic risk values of arsenic in drinking water.

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## Introduction

Potentially toxic elements (PTEs) are naturally dispersed through various environmental media with acceptable concentrations. However, due to the increasing rate of anthropogenic activities, the PTEs are being re-dispersed resulting in elevated concentrations (Elnazer and Salman 2020). Globally, it is well documented that the main anthropogenic sources of PTEs in the soil-water-plant system are mining activities, agricultural activities, sewage disposal, and industrial and vehicular emissions (Lermi and Ertan 2019; Zango et al. 2019; Kovacheva et al. 2020; Liu et al. 2020; Nganje et al. 2020; Çiner et al. 2021). Among these, mining activities are the dominant routes of PTEs in the soil-water-plant system in metallogenic provinces. Ore slags left after mining can weather thereby releasing PTEs into the soil, which can in turn be

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# Geochemical evolution and tracing of groundwater salinization using different ionic ratios, multivariate statistical and geochemical modeling approaches in a typical semi-arid basin

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A R T I C L E I N F O

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Semi-arid Pru Basin


A B S T R A C T

The vulnerability of semi-arid basin aquifers to long-term salinization due to the dissolution of groundwater chemical constituents is a major global problem. Despite this, resilient techniques of tracing the sources of groundwater salinization in semi-arid basin aquifers are still evolving due to the aquifer complexities. This study proves the effectiveness of the use of different ionic ratios, multivariate statistical, and geochemical modeling approaches to understand groundwater evolution and trace salinization in the semi-arid Pru Basin of Ghana. The basin is homogeneously composed of argillaceous sediments of the Oti/Pendjari Group of the Voltaian Supergroup. A total of 81 samples from hand-dug wells and boreholes within the Pru Formation of the Oti/Pendjari Group in the basin were collected for this study. Quantitative analysis of the data shows that the abundance of major ions follows the order: $Na^{+} > Ca^{2+} > Mg^{2+} > K^{+}$ and $Cl^{-} > HCO_3^{-} > SO_4^{2-}$. The groundwater evolved from Na-HCO3, Na-HCO3-Cl, Na-Ca-HCO3 to Na-Mg-HCO3 water types in a decreasing order of abundance. Calculated meteoric genesis index (r2) indicates the dominance of deep meteoric water percolation effects on groundwater chemistry. Groundwater chemistry is principally controlled by water-rock interaction, ion exchange reactions, weathering (carbonate and silicate), salinization, and anthropogenic activities. Different ionic ratio plots and spatial distribution maps reveal the prevalence of salinization in the aquifer system, especially around the southwestern part of the basin. Revelle index assessment of the groundwater salinization level indicates that about 19.8% of the groundwater samples with RI values >0.5 is influenced by salinization. The groundwater salinization results from saline water intrusion from adjacent aquifers, mixing effects, ion exchange reactions, water-rock interaction, and anthropogenic activities. The geochemical modeling involving thermodynamic calculation of mineral saturation indices in PHREEQC indicates that groundwater is largely saturated with respect to majority of the carbonate and silicate mineral phases.


## 1. Introduction

The demand for groundwater for various purposes, starting from the home to the industry keeps increasing owing to the increasing global population. The hike in global population has also led to urbanization, industrialization, increasing commercial agricultural activities, and demand for food, which make it important to continuously assess the chemical quality of groundwater (Sunkari et al., 2020). Although the demand for quality groundwater to support the ever growing global population is on the rise, the aforementioned activities, which are equally necessary for a sustainable growing population have adverse effects on the quality of groundwater available for domestic, agricultural and industrial usage (Yidana et al., 2018; Sunkari et al., 2019, 2020). The safe usage of groundwater for agricultural, domestic and industrial purposes depends on the chemistry of the groundwater (Rufino et al., 2019). It is widely known that the chemistry of groundwater is controlled by several geogenic factors including precipitation composition, weathering, geology and mineralogy of aquifers, and geochemical processes occurring in aquifers (Belkhiri et al., 2012; Sunkari et al., 2018; Kaur et al., 2019; Karunanidhi et al., 2020). Interaction among all

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# Hydrogeochemical evolution and assessment of groundwater quality in the Togo and Dahomeyan aquifers, Greater Accra Region, Ghana

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ABSTRACT

Groundwater quality is generally better than surface water quality but this is not sacrosanct because during recharge and abstraction, groundwater may be subjected to variations due to influence from natural and anthropogenic processes. The Togo and Dahomeyan aquifers are threatened by several anthropogenic activities like dumping of domestic and industrial wastes in open landfill sites. These activities can be sources of groundwater constituents and can pose adverse health effects on humans and the ecosystem but little is known about the hydrogeochemical characteristics of groundwater and its quality in the area. Therefore, the present study is aimed at unravelling the hydrogeochemical characteristics and quality of groundwater in the Togo and Dahomeyan aquifers in the Greater Accra Region of Ghana. A total of 37 groundwater samples were collected and analysed for the concentrations of major ions, minor ions, and trace elements. The results were used to compute water quality parameters like electrical conductivity, sodium adsorption ratio, sodium percent, and magnesium ratio to assess the quality of the water for irrigation purposes. Groundwater shows acidic to slightly alkaline pH and evolved from Mg–Na–$HCO_3$, Ca–Na–Mg–$HCO_3$, Na–Ca–Mg–$HCO_3$–Cl to Na–Mg–Ca–$HCO_3$ with other mixed water types, which reflect the local geology. Geochemical modelling indicates that groundwater is supersaturated with respect to goethite and hematite and saturated with respect to calcite, aragonite, and dolomite in some samples. Hydrochemical graphing and multivariate statistical analysis indicate that the chemistry of groundwater in the area is primarily controlled by an interplay of chemical weathering, mineral dissolution, ion exchange reactions, agricultural activities, and sewage disposal. The groundwater is not entirely suitable for drinking purposes because of high concentrations of EC, TDS, $Na^+$, $Cl^-$, $F^-$, Fe, Mn, Pb, Cr, and Ni, which exceed their maximum permissible limits provided by the World Health Organization. The computed parameters for assessing the quality of the water for irrigation reveal that 64.9% of the samples are suitable for irrigation purposes. However, 35.1% of the samples show very high salinity and sodium hazard and thus, are unsuitable for irrigation purposes. Therefore, it is recommended that mixing of the high salinity and sodium water with low salinity and sodium water can improve crop yields.

## 1. Introduction

Good quality water is primarily defined by its chemistry and is vital for the socio-economic well-being of humans. The provision of good quality water for human populations across the globe is one of the major goals of the Sustainable Development Goals (SDG 6). This implies that all nations are entreated to make good quality water freely accessible to their citizens. Several studies have reported that poor quality water adversely affects human health and even some aspects of the ecosystem (Anim-Gyampo et al., 2018; Sunkari et al., 2018, 2022; Zango et al., 2019; Abanyie et al., 2020; Çiner et al., 2021). Groundwater quality is generally better than surface water quality but this is not sacrosanct because during recharge and abstraction, groundwater may be subjected to variations due to influence from natural and anthropogenic processes (Anim-Gyampo et al., 2018; Sunkari et al., 2019, 2020, 2021a).

The contribution of natural processes to groundwater chemistry is controlled by very complex geochemical mechanisms in aquifer systems (Hem, 1985; Yetiş et al., 2019; Karunanidhi et al., 2020). Accordingly, the dominant natural processes that contribute to groundwater chemistry include water-rock interaction, weathering, mineral dissolution,

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# Geochemical and Multivariate Statistical Evaluation of Trace Elements in Groundwater of Niğde Municipality, South-Central Turkey: Implications for Arsenic Contamination and Human Health Risks Assessment

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**Abstract**

This study was conducted to determine the concentrations of trace elements, their sources, and human health risks associated with arsenic contamination in groundwater of the Niğde Municipality, south-central Turkey. Fourteen groundwater samples were collected from groundwater supply sources fed by the Niğde water distribution system and were analysed for Al, Cr, Mn, Fe, Co, Ni, Cu, Zn, As, Se, and Ba concentrations. Multivariate statistical analyses were applied to decipher the source and interrelationships among trace elements in groundwater. The groundwater is mainly tapped from Quaternary alluvial and volcanic aquifers of the Niğde Massif. The pH of groundwater is slightly acidic to neutral, which controls the solubility and mobility of the trace elements. The mean concentrations of the trace elements vary in the order Zn > Fe > Ba > As > Cr > Ni > Se > Cu > Co > Mn > Al. All of the trace element concentrations comply with the maximum permissible values provided by the Turkish Standards Institution and the World Health Organization, except Zn, Cr, and As. However, approximately 7.14% of the studied samples are contaminated with Zn and Cr, whereas 86% are contaminated with As. The As concentrations range from 9.47 to 32.9 μg/L with an average value of 16.8 μg/L. Contamination assessment indicates that the As contamination is dominant in the southern and southwestern parts of the area. The primary source of As in groundwater is attributed to geogenic processes involving weathering and dissolution of bed rocks and other factors, such as pH conditions, adsorption, and surface complexation. Three bimetallic complex associations are distinguished in groundwater: Fe-coordination group, As-coordination group and Ba-coordination group, all showing strong positive correlation with Cu and Ni. The As-coordination group is the most dominant in groundwater, which resulted in the high As content of groundwater. Multivariate statistical analyses indicate that As mobilization in groundwater is associated with pH, EC, Ni, Cu, and Ba depending on the redox conditions of the aquifer, controlled mainly by geogenic processes. The carcinogenic risk of arsenic affecting children and adults reaches $2 \times 10^{-4}$ and $3 \times 10^{-4}$, respectively, exceeding the guideline value of $1 \times 10^{-4}$. The estimated hazard quotient for children is in the range of 1.79–6.21, whereas that of adults is 0.77–2.66, indicating that children in the municipality are more exposed to the noncarcinogenic effects of the consumption of high groundwater arsenic.

Water is vital for the livelihood and health of people and ecosystems and is a basic need in the development of countries (Adjei-Mensah and Kusimi 2019; Abanyie et al. 2020; Spring 2020; Talukder and Hipel 2020). With the increasing population, industrialization, and global warming, the demand for water resources is increasing rapidly, and the usable water resources are decreasing (Sunkari et al. 2019a, 2020). The per capita water consumption in the world is approximately 800 $m^3$ per year. Approximately 1.4 billion people, who correspond to approximately 20% of the world population lack sufficient drinking water and 2.3 billion people cannot access clean and potable water (Mekonnen and Hoekstra 2016). Estimates show that more than 3 billion people will face water scarcity by 2025 (Kulshreshtha 1998; Güneş Durak et al. 2011). Rapid population growth,

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Research paper

# Hydrogeochemical appraisal of groundwater quality in the Ga west municipality, Ghana: Implication for domestic and irrigation purposes

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Ghana

ABSTRACT

This study was conducted to appraise the quality of groundwater for irrigation and domestic water supply in the Ga West Municipality, Ghana. A total of 29 borehole water samples were collected for hydrogeochemical analysis and interpreted using hydrogeochemical plots and multivariate statistical analysis. The relative abundance of the major ions in the analyzed water samples were in the order $Na^+ > Ca^{2+} > Mg^{2+} > K^+$ and $HCO_3^- > Cl^- > SO_4^{2-}$. Trilinear Piper plot shows that $Na-HCO_3-Cl$ and $Na-Ca-HCO_3-Cl$ are the dominant water types in the area. The $Ca^{2+}$ and $HCO_3^-$ in these type of waters are primarily from dissolution of carbonate minerals whilst the $Na^+$ and $Cl^-$ may have been input from water-rock interaction with granitic rocks, seawater intrusion, and anthropogenic activities in the watershed. All the analyzed physico-chemical parameters are within the acceptable limits of the World Health Organization (WHO) for drinking except TDS, total hardness, $Na^+$, and $Cl^-$ which could be as a result of solid waste leachate and marine water intrusion. The samples have low to medium sodium hazard values with high to very high salinity hazard values when plotted on the Wilcox diagram. This suggests that the water is suitable for irrigation purposes with regard to sodium hazard but a mixing of the high salinity water with low salinity water is highly recommended prior to irrigation to reduce the salinity hazard in the area. However, if the crops are salt tolerant, then mixing is not necessary. Three factors explain 99.8% of the total variance and suggest that water–rock interaction is the most important factor that controls the groundwater chemistry. Besides, some contribution from agricultural activities and seawater mixing are the other factors influencing the groundwater chemistry. These factors are indicated by the positive correlation among the individual hydrochemical parameters.

## 1. Introduction

Groundwater has been widely recommended notwithstanding its scarce accessibility, availability and cost for usage in domestic and irrigational purposes due to its less susceptibility to anthropogenic activities and climate variability (Mahlknecht et al., 2004; Sunkari et al., 2018). Groundwater according to Yidana et al. (2010) does not require rigorous treatment processes to make it suitable for usage. However, the quality of groundwater for both domestic and irrigational purposes requires periodic assessment (Li et al., 2016; Berhe et al., 2017) since irrigation schemes play a fundamental role in developing economies that rely heavily on agriculture for food and cash crop production (Boateng et al., 2012).

In Ghana, irrigation farming has a stake in eradicating poverty and to a larger extent, unemployment. However, the unpredictable nature of the rainfall pattern in Ghana has had a great deal of negative impact on crop yields which for some time now has resulted in reduction in foreign exchange earnings from crop production. Although the role of irrigation schemes in safeguarding global food security cannot be overemphasized, it is worthwhile to decipher the rippling effects of using irrigation waters that are of very poor quality in view of their contribution to human sustainability through crop production. The quality of irrigation soils can be affected by using water that is highly saline and highly sodic. This has affected crop production even in larger economies like China and India which practice irrigation farming on a larger scale (Adomako et al., 2011). Continuous use of such water renders the soil unsuitable for productive irrigation with the attendant failure of crop production overtime. On this basis, assessment of the quality of groundwater for utilization in irrigation schemes and even for domestic purposes should be done regularly across the globe. Such an

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ORIGINAL PAPER

# Appraisal of subsurface hydrogeochemical processes in a geologically heterogeneous semi-arid region of south India based on mass transfer and fuzzy comprehensive modeling

**D. Karunanidhi · P. Aravinthasamy · M. Deepali · T. Subramani · Emmanuel Daanoba Sunkari**

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**Abstract** The main aim of the present study was to examine the quality of the groundwater and decipher the sources of groundwater fluoride through mass balance modeling based on fluoride exposure in a geologically heterogeneous semi-arid region of southern India. This was achieved by hydrogeochemical analysis, graphical methods, and mass transfer modeling approaches. Fuzzy comprehensive technique was applied to evaluate the quality of groundwater for groundwater management. In this regard, 61 groundwater samples were obtained from open wells and bore wells and analyzed for different physicochemical parameters. The major cation and anion abundances follow the order $Na^+ > Ca^{2+} > Mg^{2+} > K^+$ and $Cl^- > HCO_3^- > SO_4^{2-} > NO_3^- > PO_4^{3-}$. About 88.4% and 34.4% of the total water samples were dominated with $Na^+$ and $Cl^-$ ions in this region, respectively. The fluoride level in groundwater ranged from 0.10 to 3.30 mg/l with a mean value of 1.04 mg/l. Nearly 25% of the groundwater samples collected from 15 villages showed fluoride concentrations exceeding the maximum permissible limit of 1.5 mg/l as per the World Health Organization recommendations for human intake. More than 85% of the samples fell under strong acid ($Cl^-$ and $SO_4^{2-}$) type. The amount of groundwater salinization in this region was 70.5% since the Revelle index (RI) was excess in the groundwater samples (RI > 0.5 meq/l). Silicate weathering, cation exchange, and gypsum dissolution were the dominant geogenic processes in the aquifer system influencing groundwater chemistry and nullified the possibility of carbonate dissolution. Saturation indices revealed the contribution of sequestration of $CaCO_3$ in $F^-$ enrichment. Total dissolved solids showed strong positive correlations with $Na^+$, $Ca^{2+}$, $Mg^{2+}$, $Cl^-$, $SO_4^{2-}$ and $NO^{3-}$ indicating the contribution of anthropogenic inputs to groundwater chemistry in addition to geogenic sources. The results of the fuzzy comprehensive method indicated that 33% of the groundwater samples fell under fair water type, 2% and 11% of the samples fell under poor and very poor quality water types, respectively. Therefore, this work will be helpful for the decision-makers to plan for the sustainable management of groundwater resources.

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Research article

# Application of machine learning techniques to predict groundwater quality in the Nabogo Basin, Northern Ghana

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ABSTRACT

The main objective of this study was to map the quality of groundwater for domestic use in the Nabogo Basin, a sub-catchment of the White Volta Basin in Ghana, by applying machine learning techniques. The study was conducted by applying the Random Forest (RF) machine learning algorithm to predict groundwater quality, by utilizing factors that influence groundwater occurrence and quality such as Elevation, Topographical Wetness Index (TWI), Slope length (LS), Lithology, Soil type, Normalize Different Vegetation Index (NDVI), Rainfall, Aspect, Slope, Plan Curvature (PLC), Profile Curvature (PRC), Lineament density, Distance to faults, and Drainage density. The groundwater quality of the area was predicted by building a Random Forest model based on computed Arithmetic Water Quality Indices (WQI) (as dependent variable) of existing boreholes, to serve as an indicator of the groundwater quality. The predicted WQI of groundwater in the study area shows that it ranges from 9.51 to 69.99%. This implied that 21.97 %, 74.40 %, and 3.63 % of the study area had respectively the likelihood of excellent. The models were found to perform much better with an RMSE of 23.03 and an $R^2$ value of 0.82. The study conducted highlighted an essential understanding of the groundwater quality in the study area, paving the way for further studies and policy development for groundwater management.

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# Geochemistry, risk assessment, and Pb isotopic evidence for sources of heavy metals in stream sediments around the Ulukışla Basin, Niğde, southern Turkey

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**Abstract:** Concentrations of selected elements (Al, Fe, Mn, Mo, As, Cd, Cu, Cr, Ni, Co, Pb, Sb, and Zn) and Pb isotope ratios were determined in 53 sediments from Alihoca, Gümüş, Horoz, and Çakıt streams around the south-central Taurides (Ulukışla Basin), Niğde, which is a known mining province in Turkey. Several pollution and risk assessment indices were used to assess possible heavy metal pollution in the stream sediments and the associated potential ecological risks. Concentrations of As, Cd, Cu, Cr, Ni, Co, Pb, Sb, and Zn were elevated in the streams located near ancient mines, active mines, and slag piles in the area, suggesting an influence from mining activities. The pollution assessment indices indicated that the sediments were significantly polluted by As, Cd, Sb, Zn, and Pb and moderately polluted by Cu, Ni, Cr, and Co. The sediments show very high potential ecological risk with As, Cd, Sb, and Pb as the principal contributors. Ni, Cr, As, Pb, Zn, and Cd exceeded the probable effect concentrations in most of the samples implying that their concentrations may frequently affect sediment-dwelling organisms. Multivariate statistical analyses indicate that the accumulation of heavy metals in the stream sediments is due to an interplay of anthropogenic activities (mining and agrochemical application) and geogenic processes (weathering of bedrocks and supergene alteration of base metal-rich mineralization). Pb isotopic tracing indicates that total Pb in the sediments ($^{206}Pb/^{207}Pb$ = 1.09–1.29) is primarily from weathering and dissolution of ultrapotassic rocks ($^{206}Pb/^{207}Pb$ up to 1.20) and galena ($^{206}Pb/^{207}Pb$ up to 1.21) from the Pb-Zn-Au deposits in the area with some anthropogenic input from mine slag piles ($^{206}Pb/^{207}Pb$ = 1.10).

**Key words:** Heavy metals, stream sediments, risk assessment, Pb isotopic tracing, Ulukışla Basin, southern Turkey

## 1. Introduction

Stream sediments are known to be the best sampling media for assessment of heavy metal pollution in streams as they record the environmental impact on fluvial systems over time (Etler et al., 2006). Globally, the increase in anthropogenic activities such as agriculture, mining, urbanization, industrialization, transportation, and energy production, as well as geogenic processes, have caused the influx of pollutants such as heavy metals that drain into streams and rivers. Discharged heavy metals in a stream or a river system due to anthropogenic and/or geogenic inputs during the course of their transport are usually dispersed between the liquid phase and bottom sediments (Sin et al., 2001; Varol, 2011). Subsequently, geochemical processes such as adsorption, hydrolysis, and coprecipitation acting on the discharged heavy metals cause only a small fraction of metal ions to remain dissolved in water while the remaining portion settles in the sediments (Gaur et al., 2005). Heavy metals in ecological environments may accumulate in aquatic living organisms, which may finally enter into the human food chain and cause several health-related issues (Mucha et al., 2003; Varol, 2011; Omwene et al., 2018). The speciation, distribution, ecological risk, health risk, and source allotment of heavy metals have been widely studied (Vrhovnik et al., 2013; Eker et al., 2017; Jiang et al., 2017; Potra et al., 2017; Kumar et al., 2018; Pobi et al., 2019; Ustaoğlu and Tepe, 2019). Several assessment methods such as geoaccumulation index ($I_{geo}$), contamination factor (CF), enrichment factor (EF), pollution load index (PLI), and potential ecological risk index (RI) are used in evaluating heavy metal pollution in sediments. These methods have some constraints such as they are geochemical normalization approaches and are not adequate for evaluating the source and distribution of heavy metals in sediments (Zhao et al., 2015). Thus, there is the need to integrate and interpret the mentioned methods with multivariate statistical analysis. In this regard, factor, principal component, and hierarchical cluster analyses are widely and effectively used multivariate statistical techniques for identifying the sources of heavy metals in

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# Evaluation of groundwater vulnerability using GIS-based DRASTIC model in Greater Monrovia, Montserrado County, Liberia

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Greater Monrovia

ABSTRACT

To ensure that groundwater resources are effectively protected and to improve the quality of life, it is vital to take into consideration all polluting activities that could pose a potential risk to the resource. Groundwater potential research conducted only covers 5% of Montserrado County excluding Greater Monrovia in Liberia. Although this little percentage of groundwater potential research is well known, studies on the vulnerability of the aquifer to pollution are non-existent. Therefore, this study aims at assessing groundwater vulnerability in Greater Monrovia, Montserrado County, Liberia, which will help in optimizing water well drilling activities and protecting the resource. A groundwater vulnerability map for the study area using the Geographic Information System (GIS) based DRASTIC Model was developed and the results suggest that 73% of the study area is very sensitive to pollution, whereas 15% and 11% are moderately and weakly sensitive to pollution, respectively. The key pollution areas identified within the study area were communities of intensive anthropogenic activities and associated geological contamination. The effectiveness of the GIS-based DRASTIC Model in groundwater vulnerability assessment was validated and nearly 60% of the wells contained fluoride concentrations that exceeded the Liberia Water Quality Standard (LWQS) permissible limit. The findings suggest that even though the water table is relatively shallow, future projects in the high and moderate sensitivity zones should be handled carefully. Planners, groundwater managers, and decision-makers may utilize the maps created by this study as a general point of reference for vulnerability when making attempts to safeguard this delicate resource.

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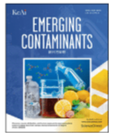

# Sources and factors influencing groundwater quality and associated health implications: A review

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ABSTRACT

Groundwater is essential for man's well-being and survival and is imperative for promoting public health. A wide range of groundwater quality studies have been conducted globally. However, there is no categorical study that specifically synthesizes the sources and factors that threaten groundwater quality. This study considered 15 countries in this review. The review showed that globally groundwater systems are predominantly contaminated with microorganisms, heavy metals, trace elements, organic compounds, and agrochemicals (dichlorodiphenyltrichloroethane/1,1,1-trichloro-2,2-bis(p-chlorophenyl) ethane (DDT) and dichlorodiphenyldichloroethylene (DDE)). Though organic matter levels in groundwater is less studied in groundwater, it also poses debilitating health risks including bladder, rectum, and colon cancers. Geologic processes and lithological and pedological factors, climate change, environmentally-unfriendly agricultural activities, poor sanitation practices and landfill management are the most dominant factors that impact groundwater quality. Based on these, it is required that realistic and implementable policies and regulations related to groundwater protection are formulated and enforced. Also, groundwater systems are sited properly to reduce anthropogenic impacts and the likely occurrence of adverse health effects.


## 1. Introduction

Groundwater is an essential resource for man's survival and is imperative for public health [1]. Statistically, groundwater constitutes 97% of the global freshwater and is a major drinking water source and a critical resort for water resources for domestic and public use [2,5]. Besides, it is a precious resource in arid areas due to erratic rainfall and limited surface water resources [3]. Nearly half of groundwater used in urban areas in less-developed countries is sourced from springs, boreholes, and wells [4]. Despite the increasing demand for groundwater, its quality is threatened by the geogenic processes, geological characteristics, anthropogenic activities and withdrawal, and storage [5,6] (see Table 1).

Groundwater contaminations have been reported and outbreaks of water-related diseases emanating from groundwater contamination have also been reported globally. Nonetheless, some groundwater resources naturally have elements of health concern attributed to $F^-$, As and a host of other heavy metals and organic compounds [5]. [7–9] revealed that groundwater quality is significantly influenced by atmospheric inputs, geogenic and natural processes including groundwater velocity, groundwater interaction with the local lithology, lithological characteristics, interaction with other aquifers and characteristics of recharge waters, and anthropogenic factors such as urban development, industrial and agricultural activities, landfill, and improper methods of exploitation groundwater resources.

Considering Ghana for instance Ref. [10], stated that about 34% of the population of Ghana depends directly on groundwater as the number of sited groundwater supply systems exceeds 60,000. In the Upper Region (now Upper East and Upper West Regions) of Ghana [11], also reported the existence and construction of about

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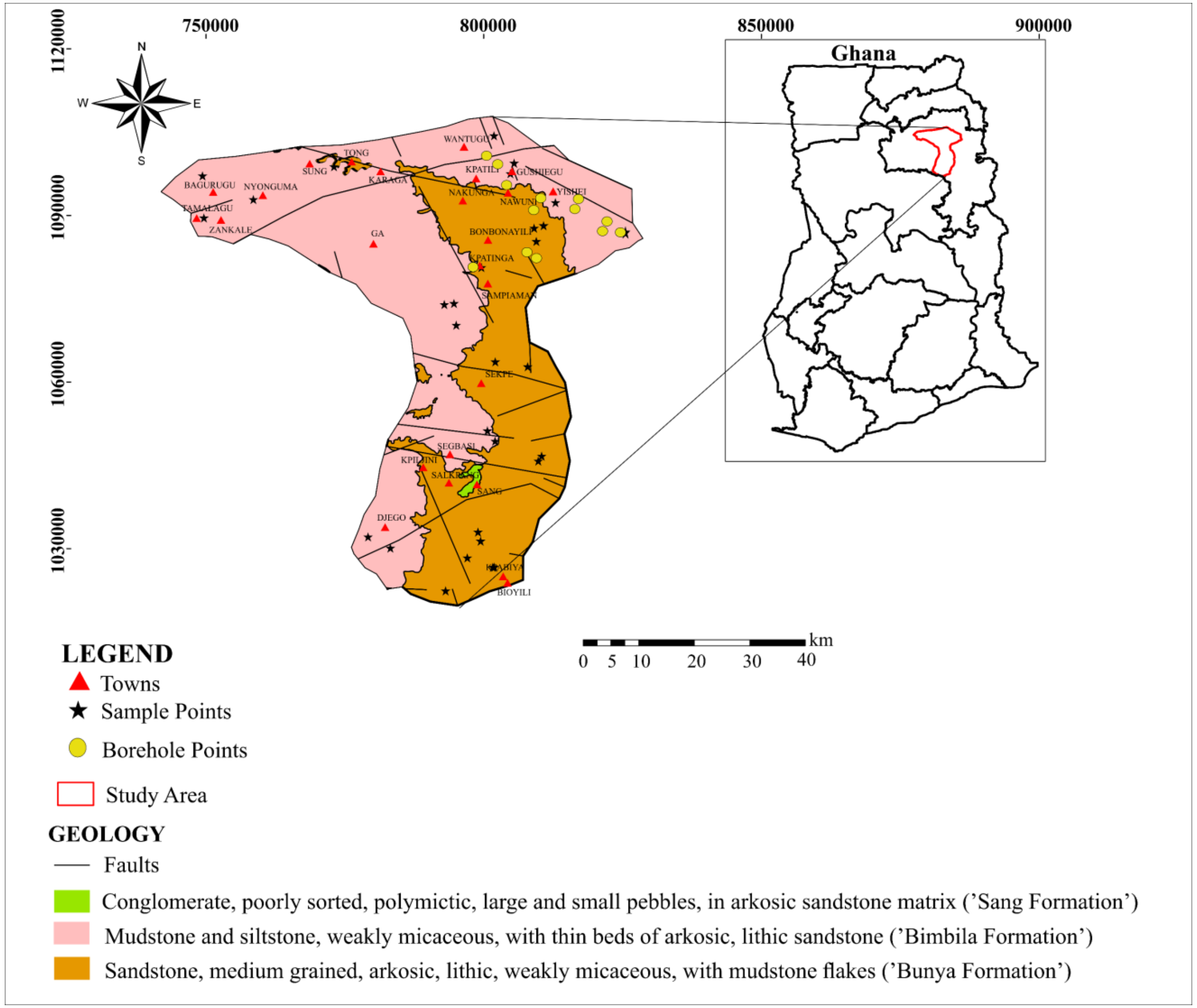
# Case Study in the Voltaian Supergroup

**Hydrogeochemistry and human health risk assessment of fluoridated groundwater in some parts of the largest semi-arid sedimentary basin in Ghana: Insights from a medical geology approach**




Location and Geology Map

# Objectives of the Research

- To determine the physicochemical parameters and the hydrogeochemical characteristics of the groundwater.
- To establish the minerals contributing to enrichment of ions in the groundwater within the lithologies through petrographic and X-ray Diffraction mineralogical studies.
- To identify the sources of groundwater contamination and factors that influence the mobility of fluoride in the groundwater.
- To quantify how much fluoride is ingested by humans through drinking water and assess any possible health hazards linked to elevated $F^-$ concentrations through deterministic and probabilistic health risk assessment methods.
- To establish the relationship between local population health outcomes and groundwater $F^-$ levels, with a particular emphasis on dental and skeletal fluorosis through a health survey.

# Methods Used

**Literature Review**

**Sample collection**

- Rock sample from outcrops.

**Data Acquisition**

- Secondary Hydrochemical data of existing boreholes;
- Data from health centers in the study area;
- Administering of questionnaire.
- Boreholes log

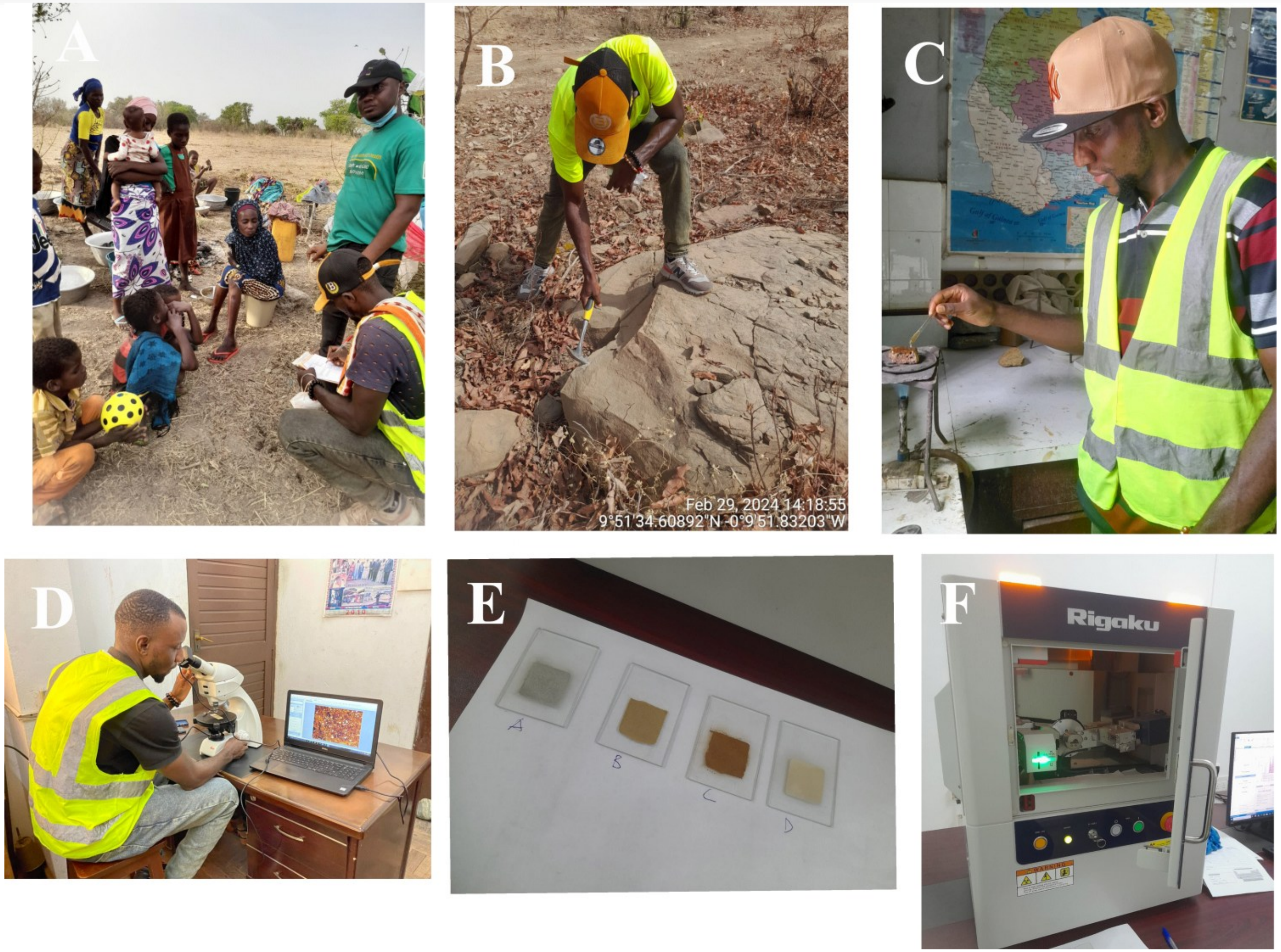
**Laboratory Analysis**

- Major and minor ions;
- Petrographic thin sections;
- XRD.

**Data Analysis**

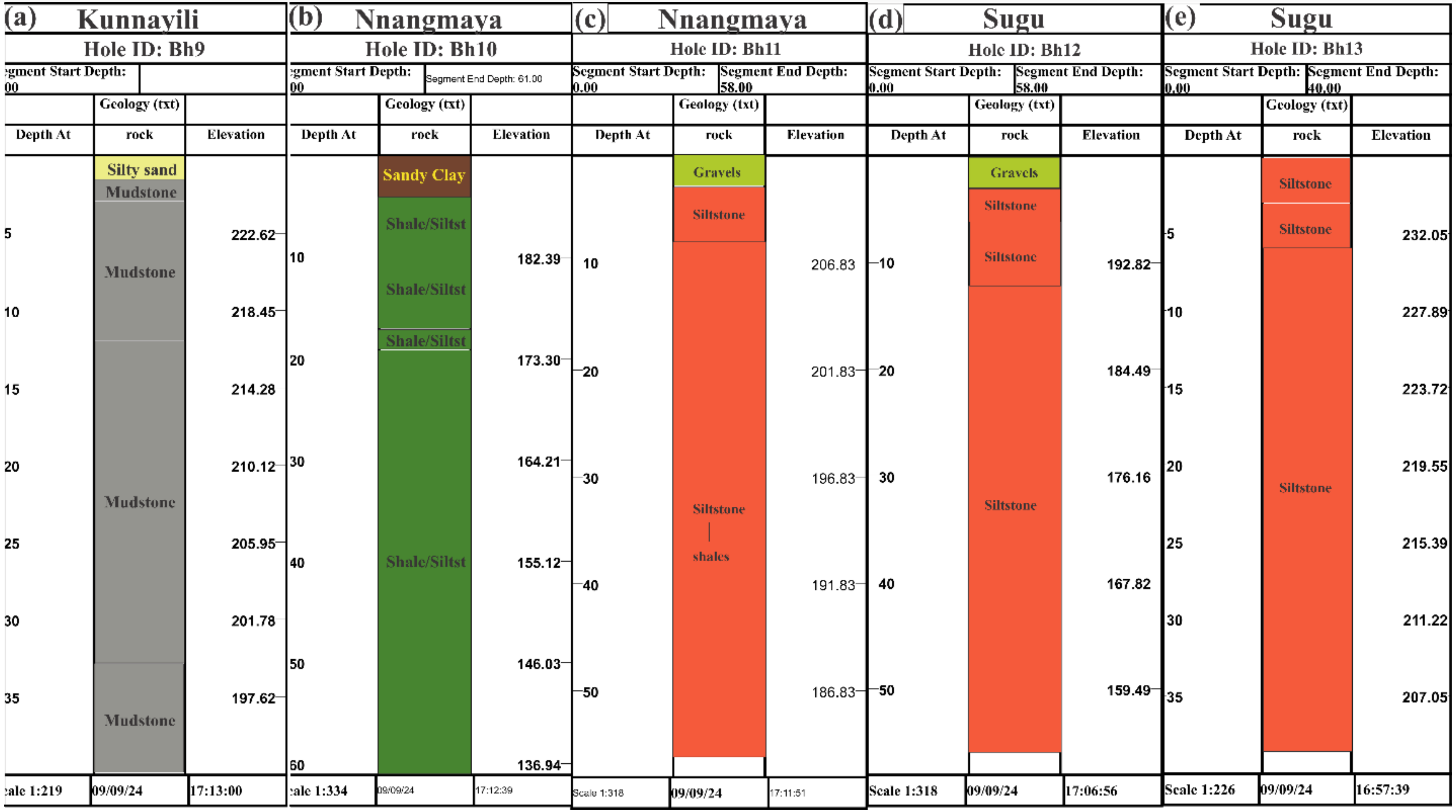
- Maps creation (ArcGIS 10.8);
- Trilinear Piper Diagram, Gibbs plots, and bivariate plots (**AquaChem Software version 4.0**);
- FA, PCA, HCA, and correlation analysis(IBM SPSS statistics version 26.0);
- Monte Carlo Simulation for Health risk (Python).

# Methods Used Con’t….




Field and Laboratory Work

# Results and Discussion




Boreholes Log of Some Drilled Wells

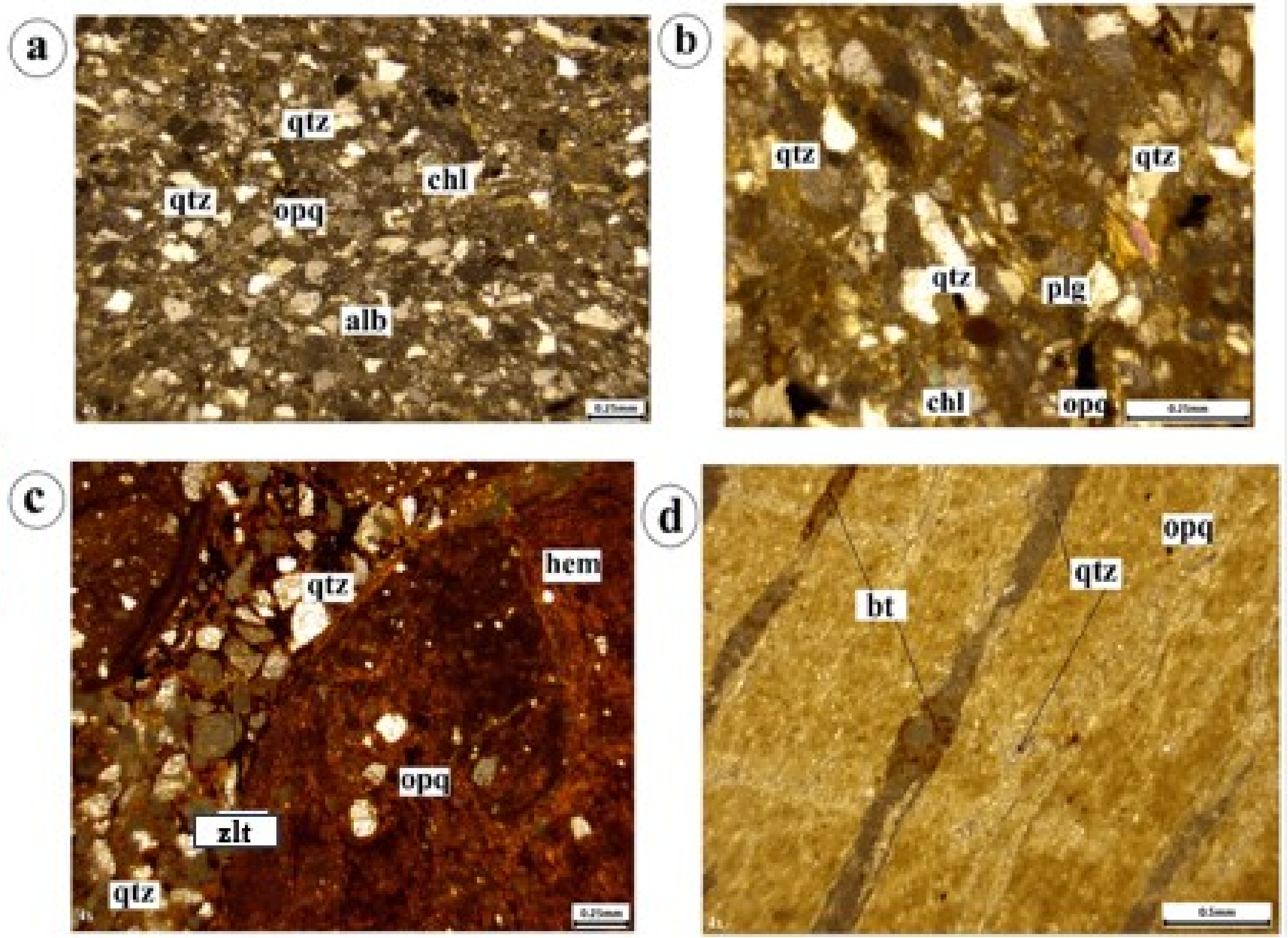
# Results and Discussion Con't….

- The mineral albite may be the possible source of excess halite dissolution.

- Fluorite minerals, especially biotite mica, form the source of fluoride ions to the percolating groundwater in respect to high pH value which favors alternation of $OH^{-}$.

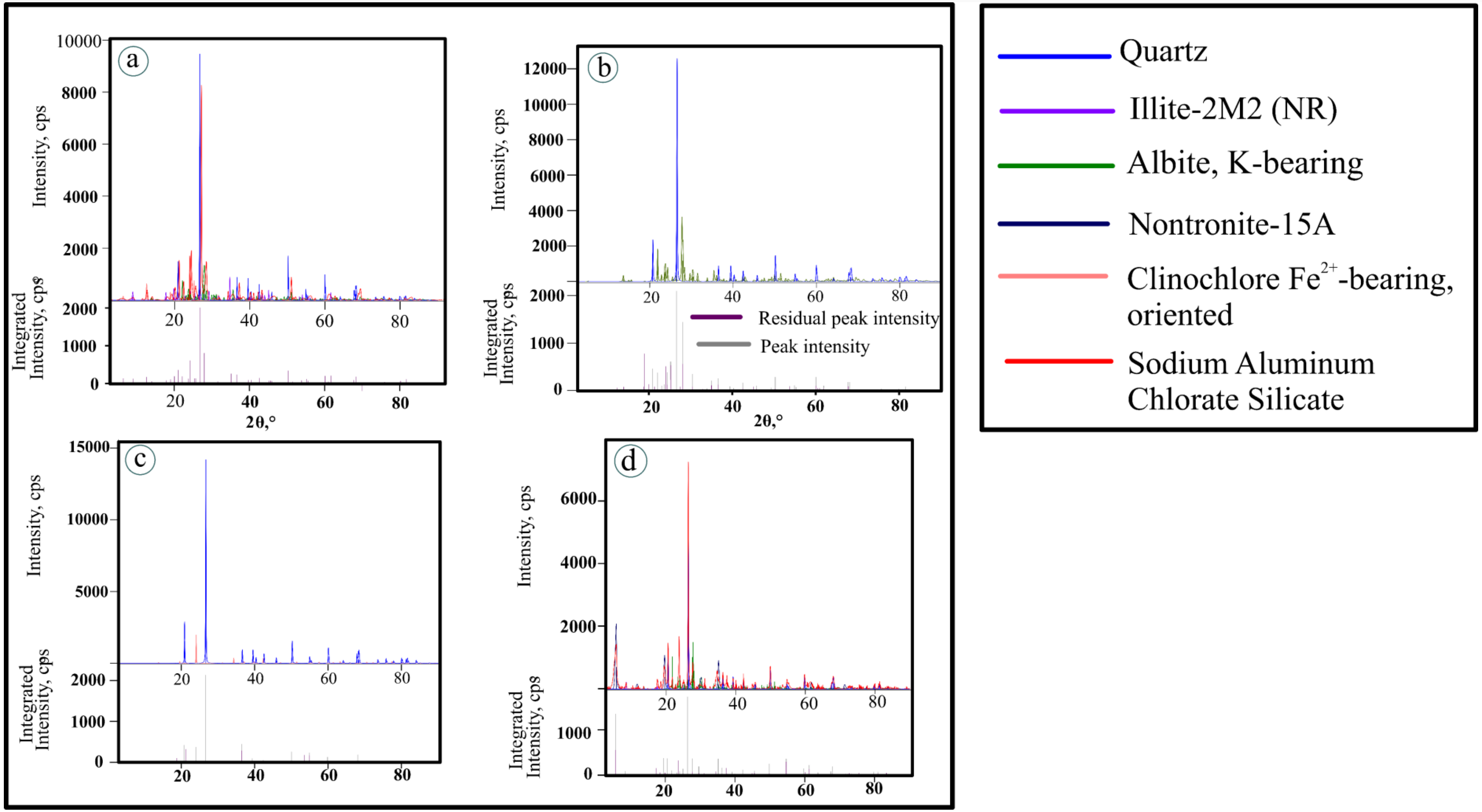
- $$\mathbf{KMg_3(AlSi_3O_{10})F_2 + 2OH \longrightarrow KMg_3(AlSi_3O_{10})(OH)_2^- + 2F^- + CO_2}$$

- Waters that are rich in sodium ($Na^+$), potassium ($K^+$), chloride ($Cl^-$), and calcium ($Ca^{2+}$) tend to have high fluoride concentrations.




Photomicrograph of studied samples (a) sandstone (b) siltstone (c) pisolite (d) mudstone. Quartz-qtz; Chlorite-chl; Plagioclase-plg; Albite-alb; Biotite-bt; Zeolite-zlt; Hematite-hem.

# X-Ray Diffraction Analysis



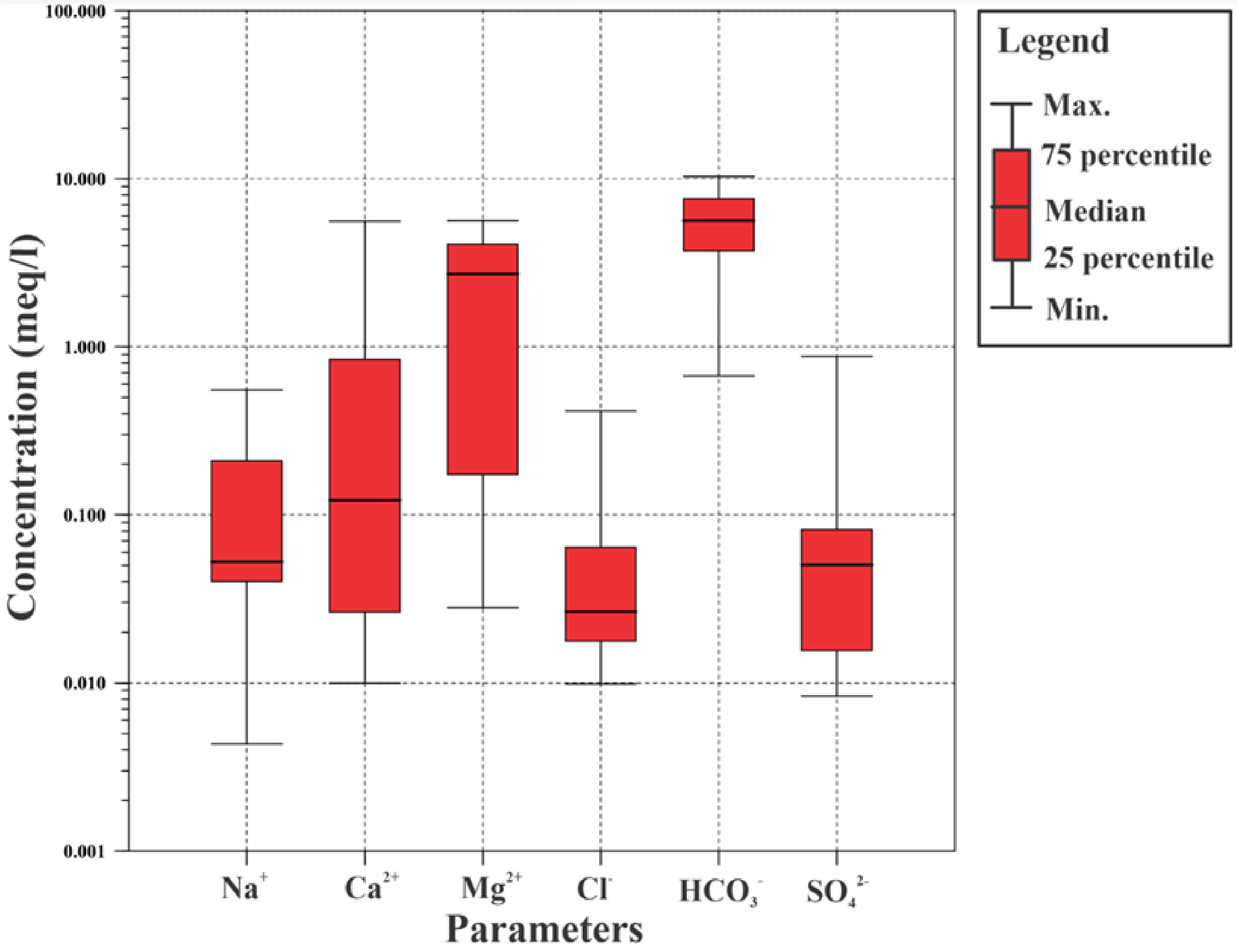

Refined Smart Lab Studio II XRD Patterns of the Studied Samples

# Results and Discussion Con’t….

Summary Statistics of the Hydrogeochemical Parameters in Groundwater of the Study Area

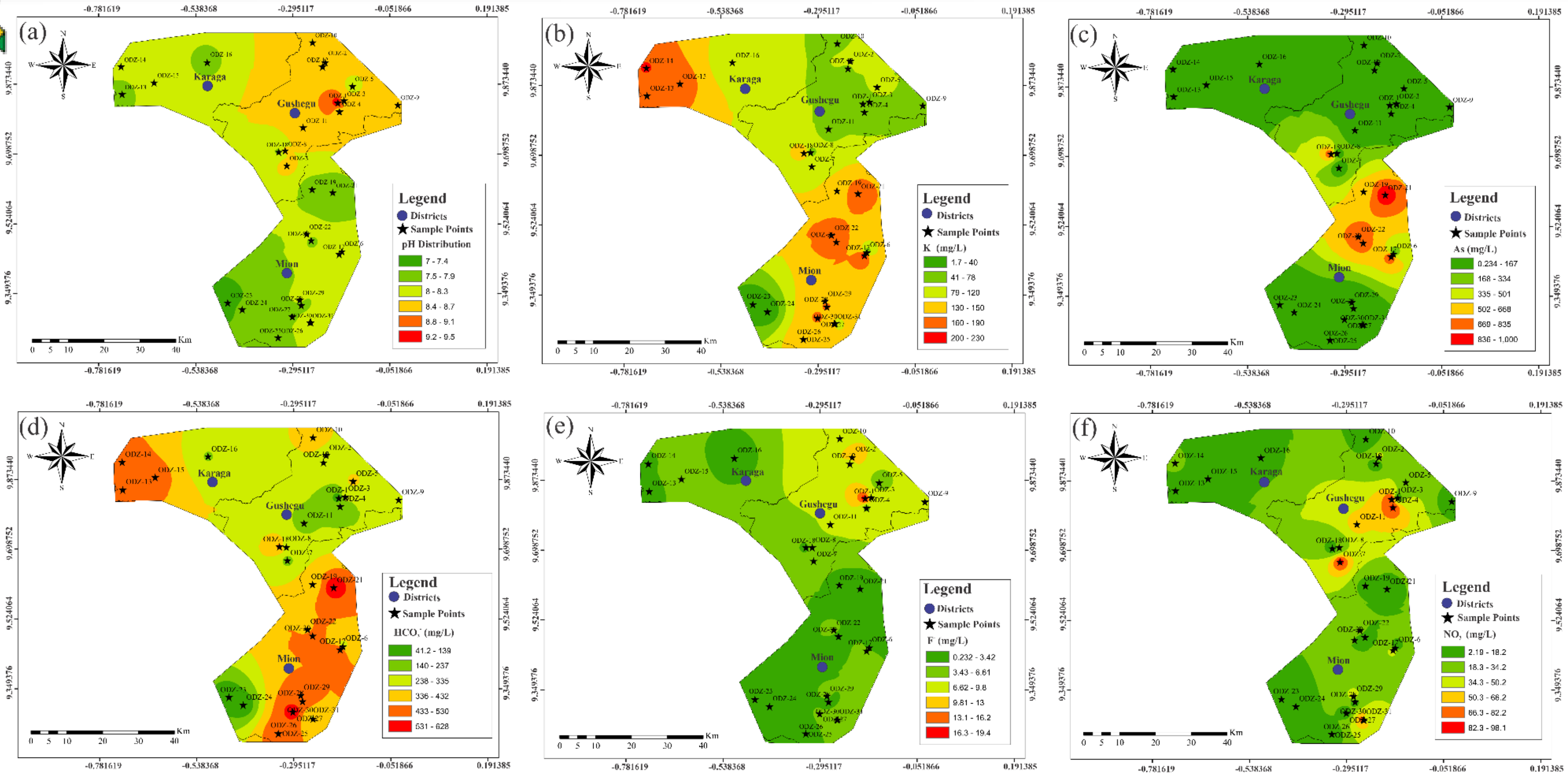
| Parameter | No. | Minimum | Maximum | Average | WHO (2022) | Samples above Threshold Value |
|---|---|---|---|---|---|---|
| pH | 31 | 7.01 | 9.55 | 8.03 | 6.5-8.5 | 4 |
| Colour | 31 | 0.00 | 170 | 19.0 | 15 | 6 |
| Temp | 31 | 25.2 | 30.5 | 28.7 | NA | 0 |
| EC | 31 | 422 | 1251 | 762 | 1000 | None |
| TDS | 31 | 221 | 638 | 390 | 1000 | None |
| Turbidity | 31 | 0.00 | 232 | 17.8 | 5 | 7 |
| $Na^{+}$ | 31 | 0.10 | 12.7 | 3.14 | 200 | None |
| $K^{+}$ | 31 | 1.60 | 234 | 108 | 200 | 2 |
| $Mg^{2+}$ | 31 | 0.34 | 68.5 | 30.5 | 150 | None |
| $Ca^{2+}$ | 31 | 0.00 | 112 | 11.3 | 200 | None |
| Alkalinity | 31 | 33.6 | 631 | 347 | - | - |
| $Cl^{-}$ | 31 | 0.35 | 14.7 | 2.09 | 250 | None |
| $SO_4^{2-}$ | 31 | 0.00 | 42.1 | 5.11 | 250 | None |
| $HCO_3^{-}$ | 31 | 40.9 | 628 | 343 | - | - |
| $NO_3^{-}$ | 31 | 2.18 | 115 | 24.7 | 50 | 5 |
| **$F^{-}$** | **31** | **0.23** | **19.5** | **4.71** | **1.5** | **27** |
| As | 31 | 0.10 | 1020 | 162 | 0.01 | 31 |
| Mn | 31 | 1.5 | 1677.87 | 147.77 | 0.08 | 31 |
| Cu | 31 | 0.25 | 618 | 96.25 | 2 | 11 |
| Fe | 31 | 0.01 | 616.4 | 106.34 | 0.3 | 22 |

# Results and Discussion Con't….




Box and Whisker Plot of the Major Ions Within the Groundwater.

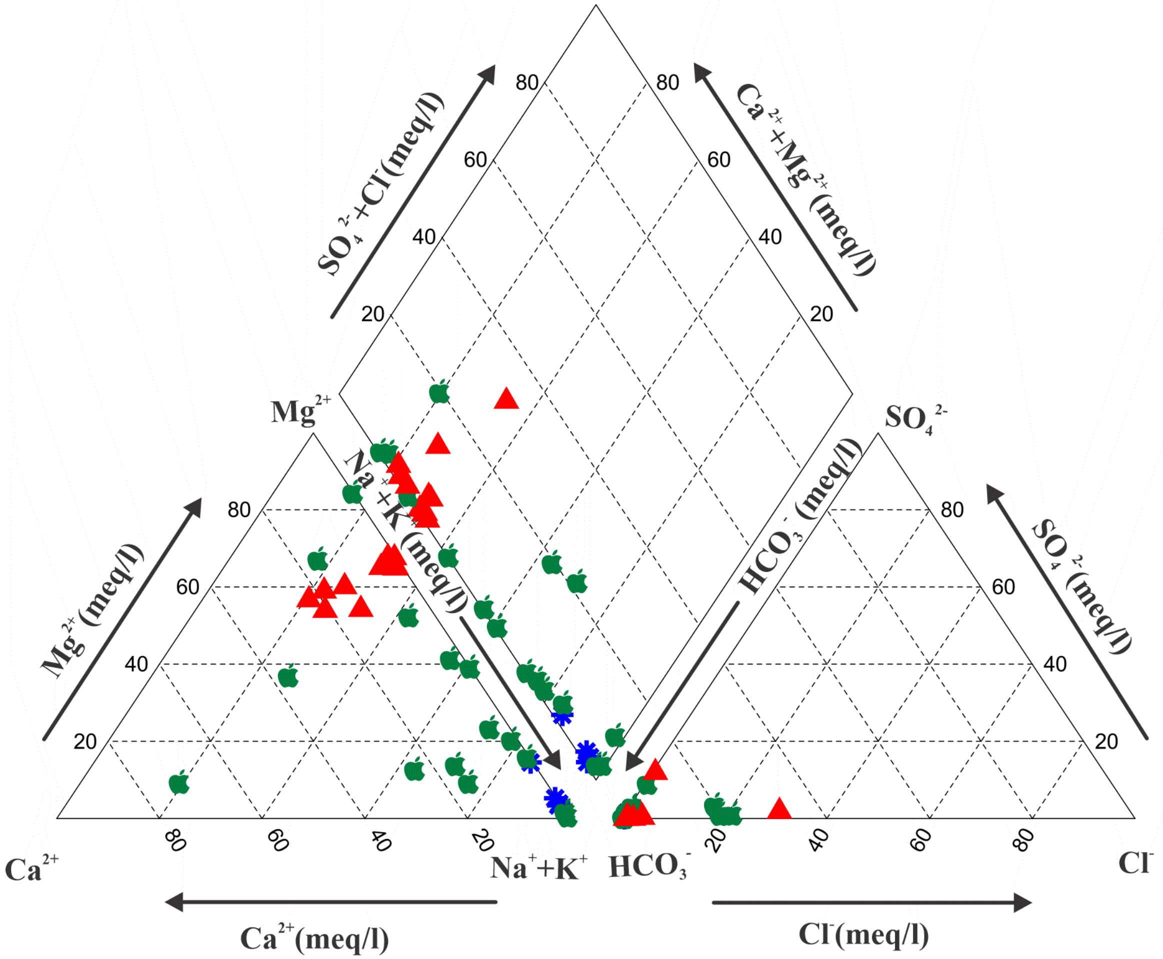
# Results and Discussion Con't….




Spatial Distribution Maps of Parameters with Concentrations Exceeding their Guideline Values provided by WHO (2017).

# Results and Discussion Con't….

## Geochemical Evolution of Groundwater




**Legend**

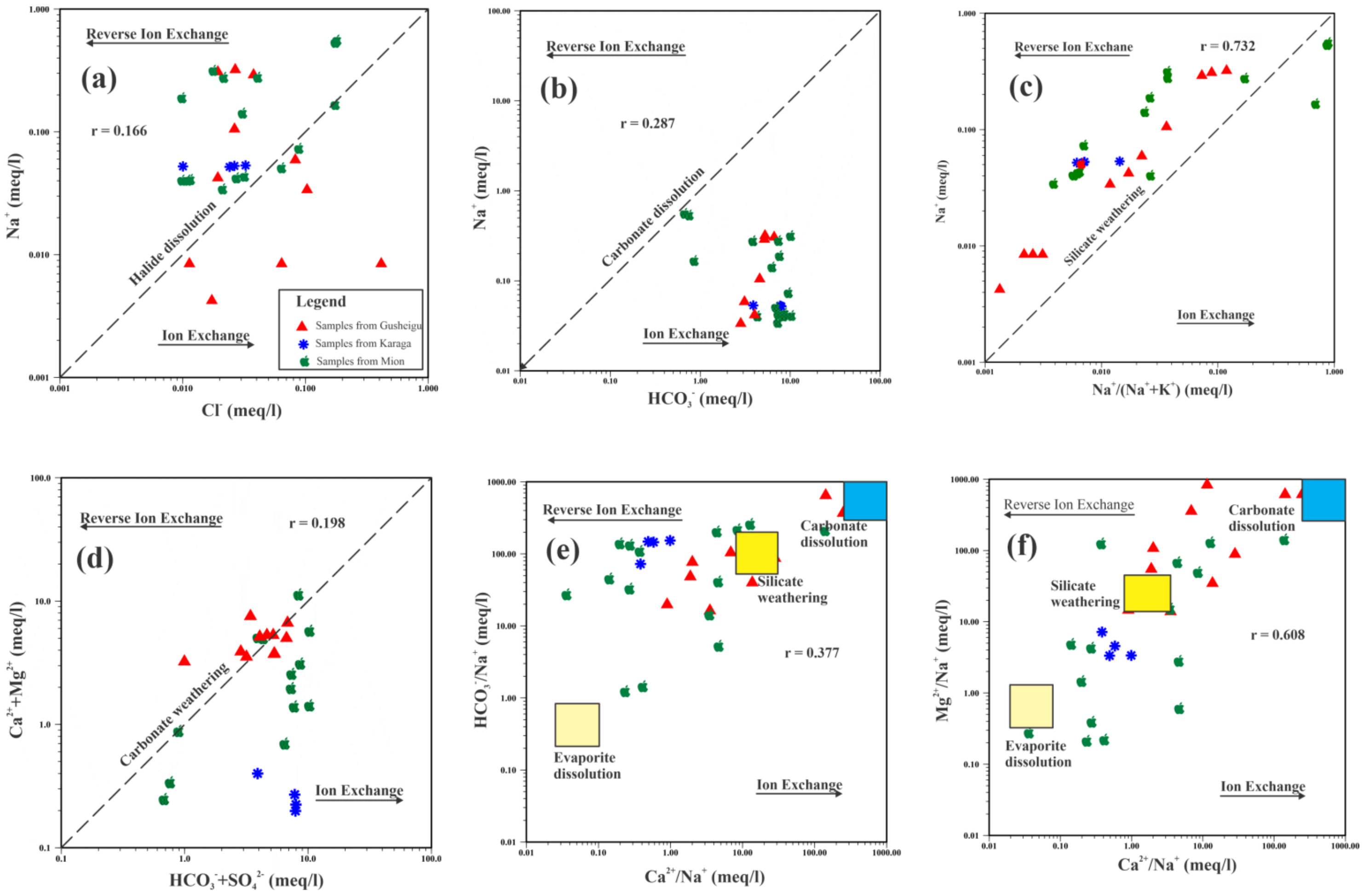
- ▲ Samples from Gusheigu
- ✱ Samples from Karaga
- Samples from Mion

**Water Types/Hydrochemical Facies**

| | |
|---|---|
| $K^+ - HCO_3^-$ | 32.25% |
| $Mg^{2+} - K^+ - HCO_3^-$ | 29.03% |
| $K^+ - Mg^{2+} - HCO_3^-$ | 9.68% |
| $Mg^{2+} - Ca^{2+} - K^+ - HCO_3^-$ | 6.45% |
| $Mg^{2+} - K^+ - Ca^{2+} - HCO_3^-$ | 6.45% |
| $Mg^{2+} - HCO_3^-$ | 6.45% |
| $Na^+ - Ca^{2+} - HCO_3^-$ | 3.23% |
| $Ca^{2+} - HCO_3^-$ | 3.23% |
| $Na^+ - HCO_3^- - Cl^-$ | 3.23% |

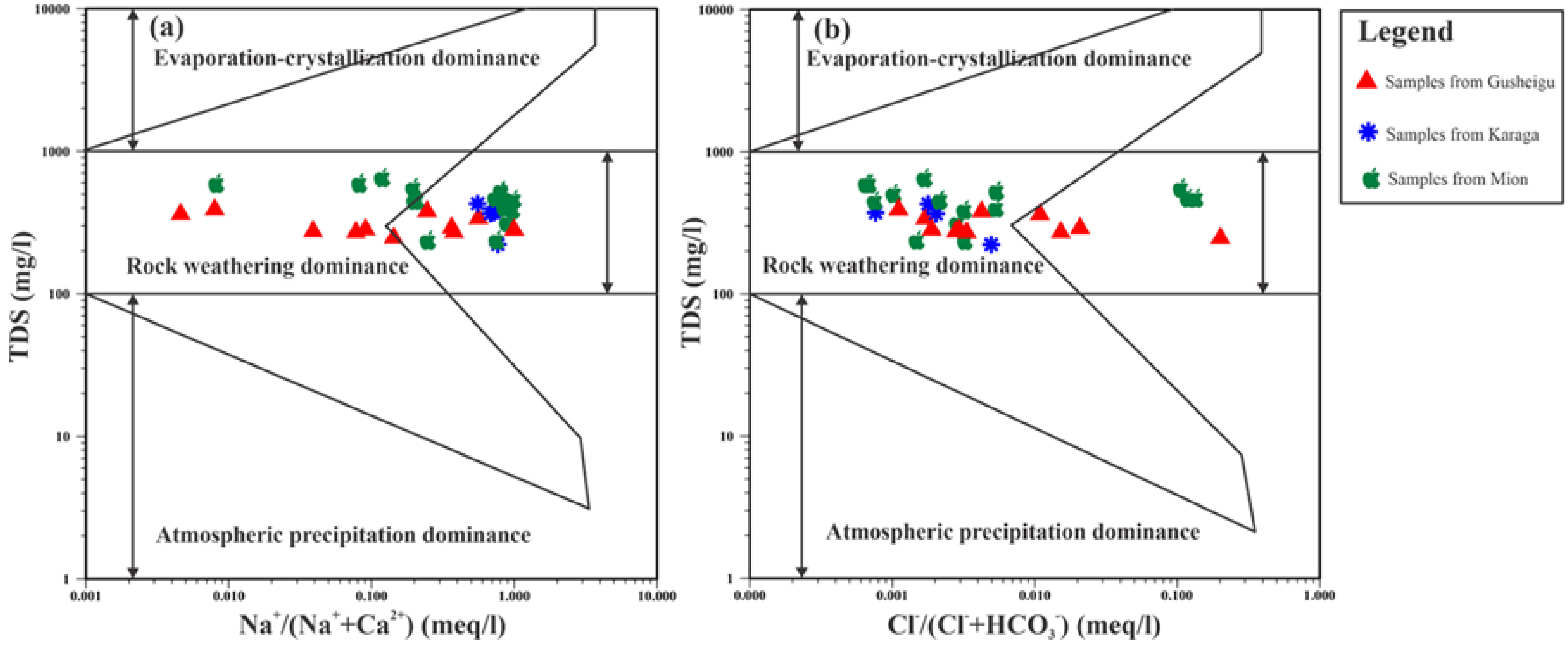
Trilinear Piper Diagram Showing the Hydrogeochemical Facies of Study Area's Groundwater

# Results and Discussion Con't….



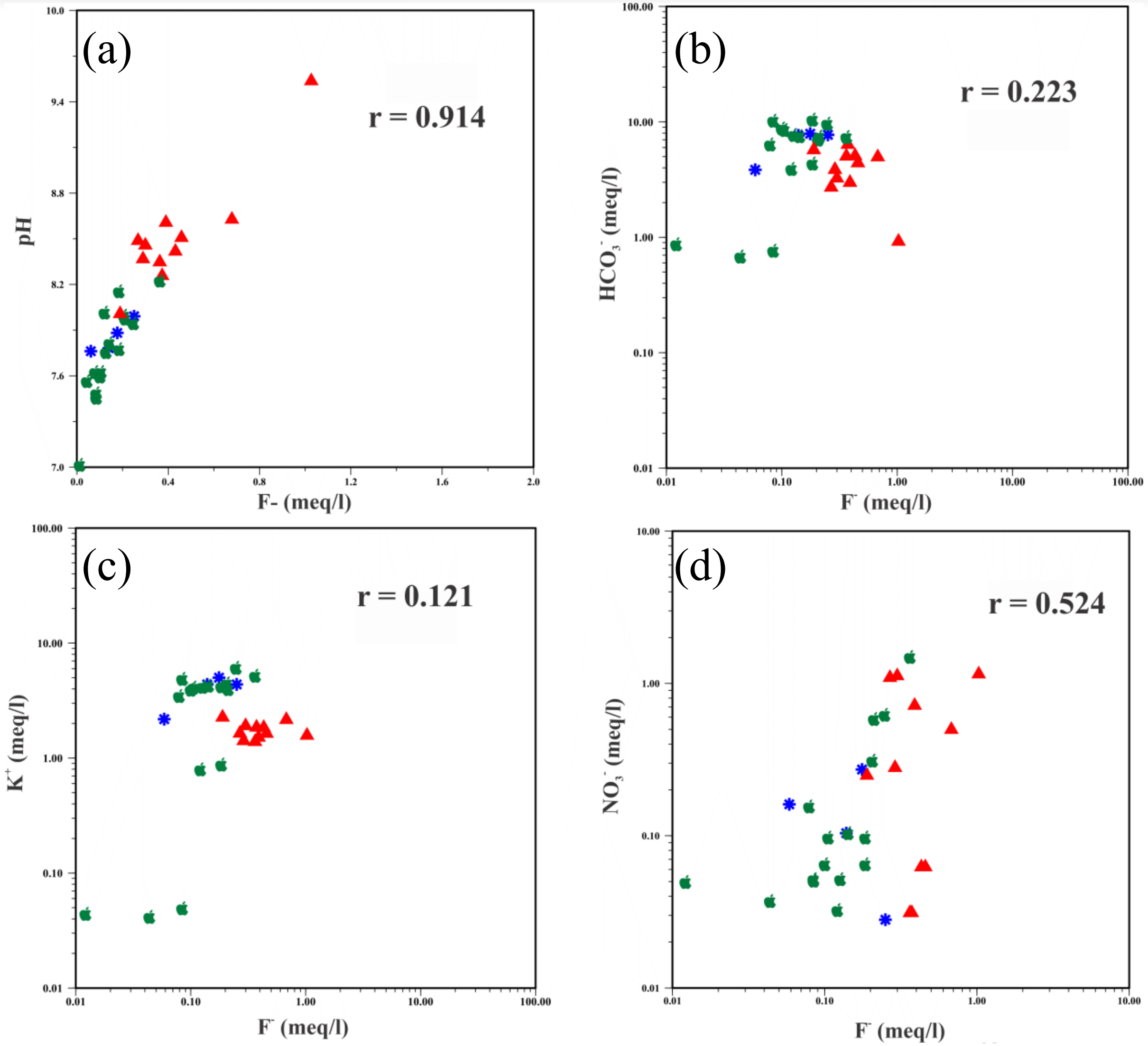

Bivariate Scatter Plot Showing Evolution Processes in Groundwater Chemistry

# Results and Discussion Con't….



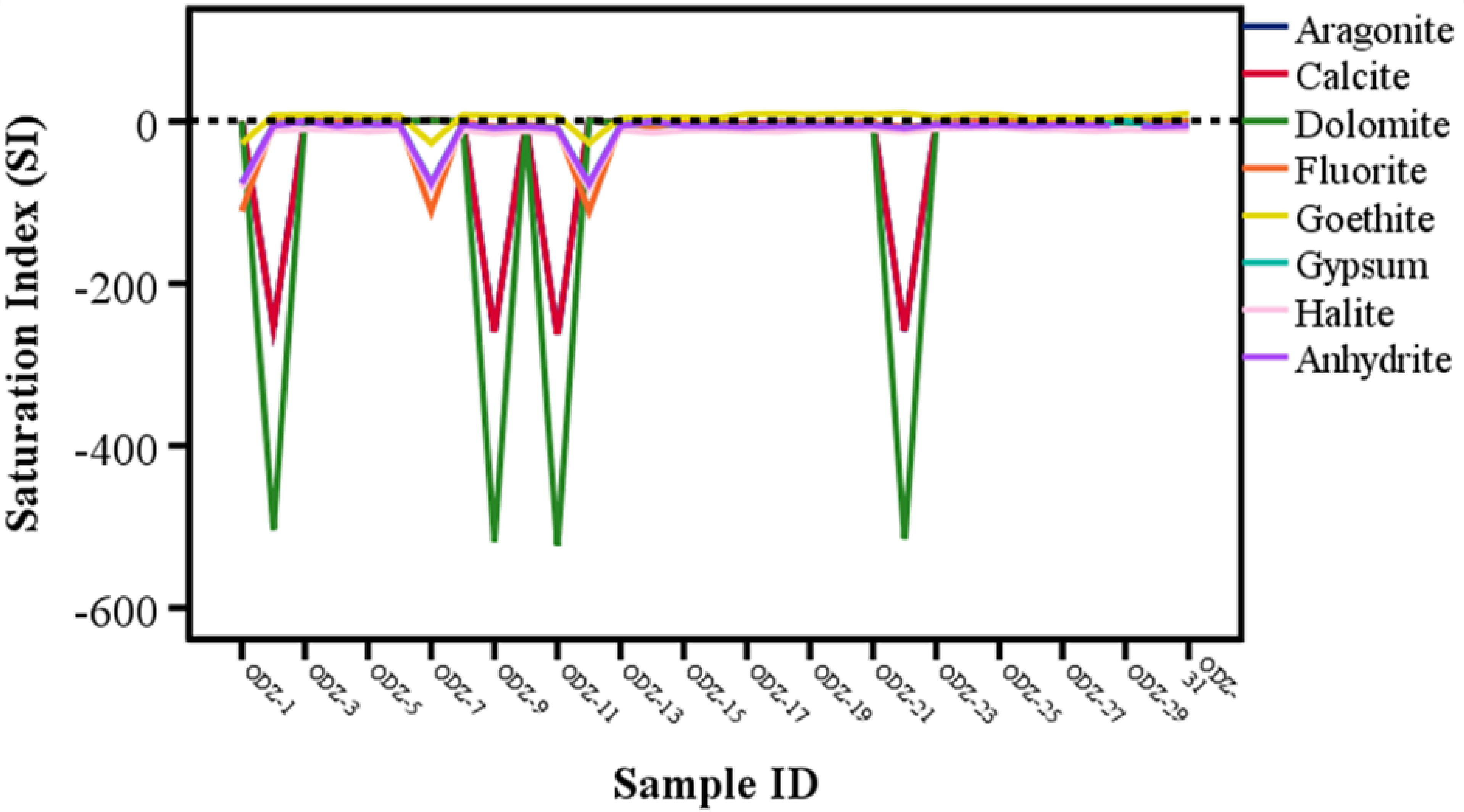

Gibbs Diagram Showing the Major Hydrogeochemical Mechanisms Affecting Groundwater in the Study Area

# Results and Discussion Con’t….




Sources of Groundwater Fluoride Enrichment

# Results and Discussion Con't….




Saturation Index (SI) for Various Mineral Phases Across Different Water Samples

# Results and Discussion Con't….

Pearson Correlation Matrices of the Hydrochemical Parameters (Values in Bold Indicate correlation Coefficients ≥ 0.7)

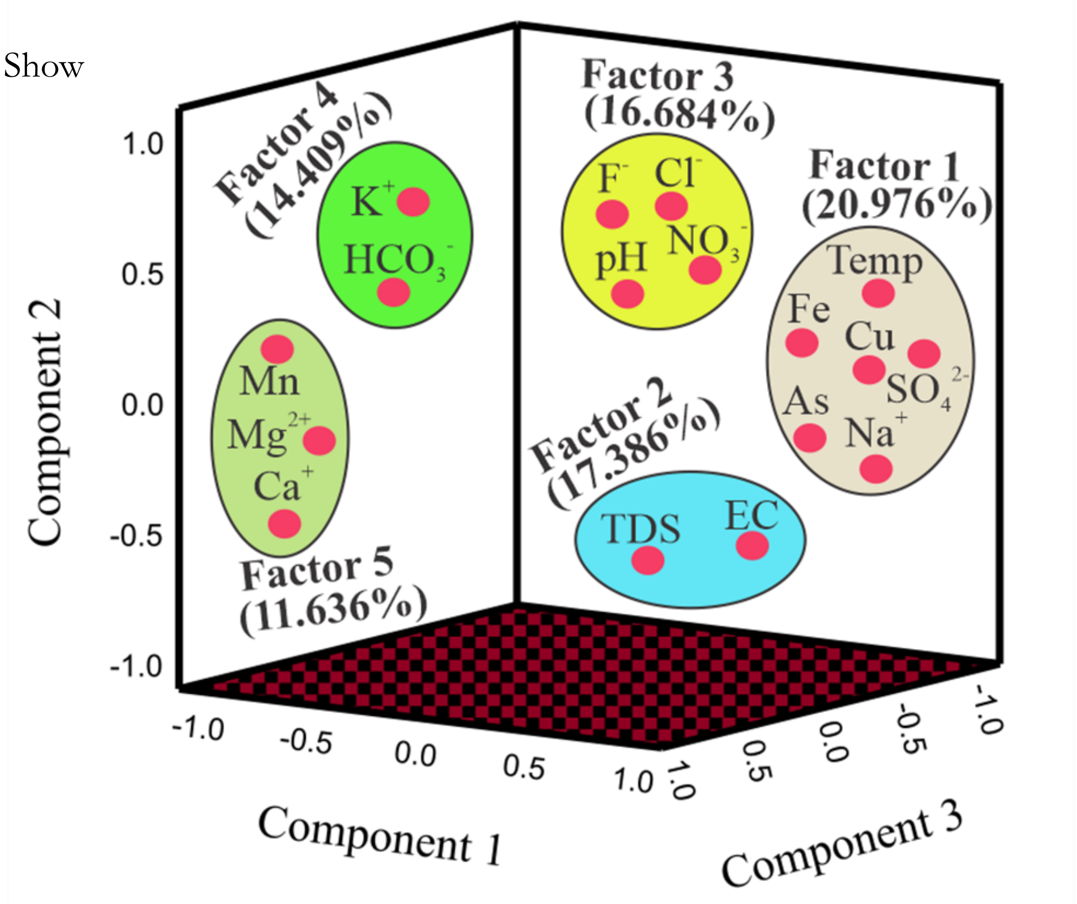
| | pH | Temp | EC | TDS | $Na^+$ | $K^+$ | $Mg^{2+}$ | $Ca^{2+}$ | $Cl^-$ | $SO_4^{2-}$ | $HCO_3^-$ | $NO_3^-$ | $F^-$ | As | Mn | Cu | Fe |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| pH | 1.00 | | | | | | | | | | | | | | | | |
| Temp | 0.39 | 1.00 | | | | | | | | | | | | | | | |
| EC | -0.51 | -0.22 | 1.00 | | | | | | | | | | | | | | |
| TDS | -0.52 | -0.23 | **0.99** | 1.00 | | | | | | | | | | | | | |
| $Na^+$ | -0.31 | 0.21 | 0.07 | 0.09 | 1.00 | | | | | | | | | | | | |
| $K^+$ | -0.18 | -0.29 | 0.49 | 0.47 | -0.39 | 1.00 | | | | | | | | | | | |
| $Mg^{2+}$ | 0.50 | 0.29 | -0.19 | -0.20 | -0.27 | -0.30 | 1.00 | | | | | | | | | | |
| $Ca^{2+}$ | -0.05 | 0.00 | 0.27 | 0.27 | -0.14 | -0.02 | 0.48 | 1.00 | | | | | | | | | |
| $Cl^-$ | 0.31 | 0.23 | -0.07 | -0.06 | 0.17 | -0.39 | -0.18 | -0.16 | 1.00 | | | | | | | | |
| $SO_4^{2-}$ | -0.08 | 0.27 | 0.01 | 0.00 | -0.01 | 0.18 | -0.01 | -0.02 | -0.14 | 1.00 | | | | | | | |
| $HCO_3^-$ | -0.27 | -0.25 | 0.45 | 0.43 | -0.29 | **0.89** | -0.05 | 0.06 | -0.64 | 0.19 | 1.00 | | | | | | |
| $NO_3^-$ | 0.59 | 0.17 | 0.08 | 0.08 | -0.39 | 0.11 | 0.17 | -0.02 | 0.37 | -0.11 | -0.19 | 1.00 | | | | | |
| $F^-$ | **0.91** | 0.38 | -0.30 | -0.31 | -0.20 | -0.12 | 0.38 | -0.05 | 0.45 | -0.11 | -0.22 | 0.52 | 1.00 | | | | |
| As | -0.28 | 0.24 | 0.20 | 0.20 | 0.13 | 0.54 | -0.48 | -0.18 | -0.10 | 0.34 | 0.46 | -0.11 | -0.23 | 1.00 | | | |
| Mn | 0.37 | 0.26 | -0.32 | -0.32 | -0.08 | -0.26 | 0.24 | 0.09 | 0.01 | -0.06 | -0.23 | 0.04 | 0.31 | -0.21 | 1.00 | | |
| Cu | -0.29 | 0.23 | 0.20 | 0.20 | 0.14 | 0.54 | -0.48 | -0.18 | -0.10 | 0.35 | 0.46 | -0.11 | -0.23 | **0.99** | -0.19 | 1.00 | |
| Fe | -0.35 | 0.22 | 0.28 | 0.28 | 0.21 | 0.49 | -0.54 | -0.20 | -0.04 | 0.32 | 0.40 | -0.10 | -0.27 | **0.99** | -0.22 | **0.99** | 1.00 |

# Results and Discussion Con't….

## Factor Analysis

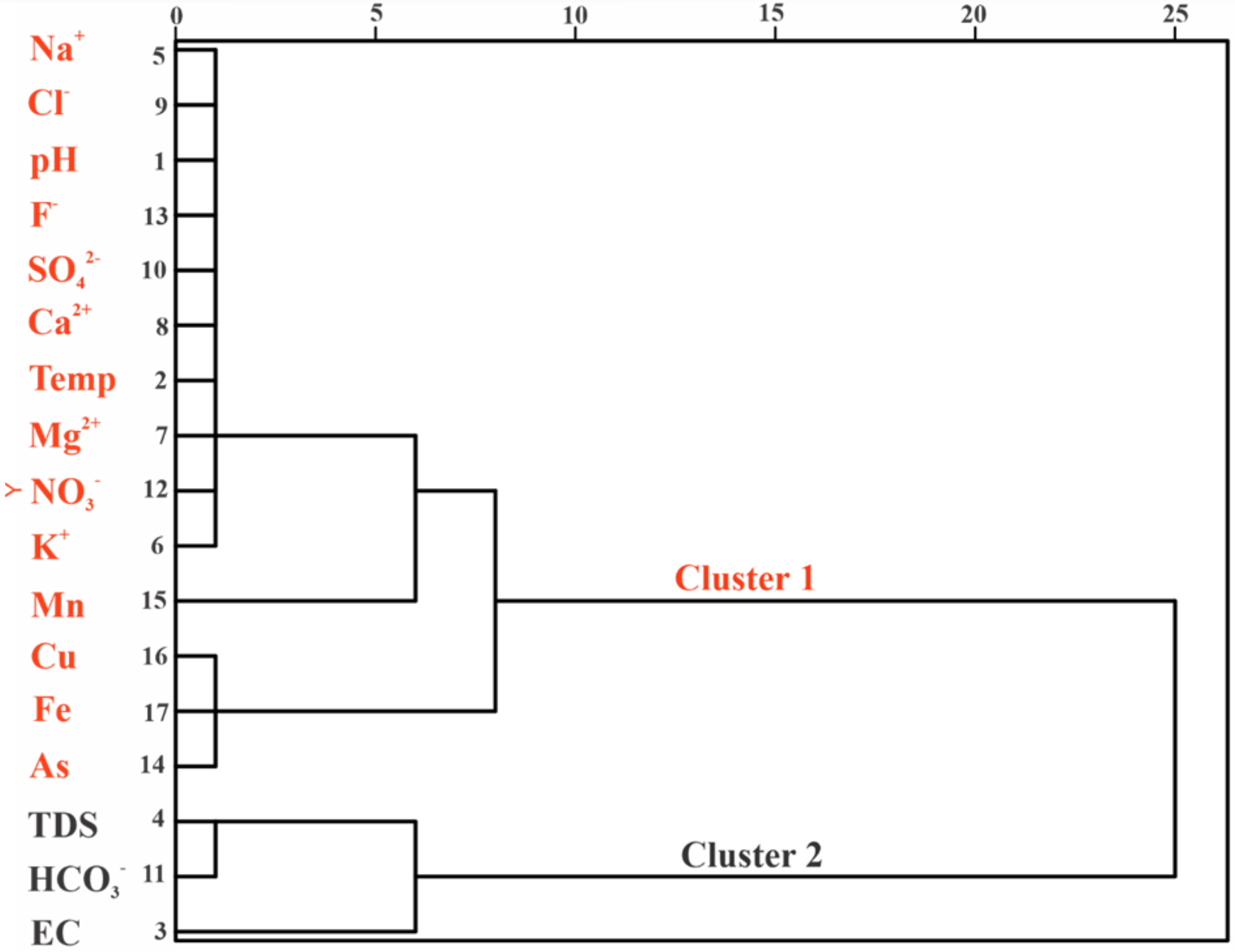
Principal Components Analysis for the Groundwater Samples (Values in Red Show the Various Parameters and their Suitable PC's)

| Component | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| pH | -0.111 | -0.484 | 0.809 | 0.028 | 0.205 |
| Temp | **0.528** | -0.263 | 0.342 | -0.440 | 0.413 |
| EC | 0.097 | **0.960** | -0.065 | 0.113 | 0.072 |
| TDS | 0.094 | **0.962** | -0.072 | 0.095 | 0.060 |
| $Na^+$ | **0.195** | 0.098 | -0.375 | -0.718 | -0.084 |
| $K^+$ | 0.391 | 0.393 | 0.067 | **0.774** | -0.192 |
| $Mg^{2+}$ | -0.277 | -0.215 | 0.226 | 0.098 | **0.813** |
| $Ca^{2+}$ | -0.134 | 0.332 | -0.076 | 0.046 | **0.747** |
| $Cl^-$ | -0.078 | 0.091 | **0.554** | -0.647 | -0.287 |
| $SO_4^{2-}$ | **0.550** | -0.112 | -0.123 | 0.075 | 0.232 |
| $HCO_3^-$ | 0.364 | 0.293 | -0.191 | **0.797** | 0.049 |
| $NO_3^-$ | -0.092 | 0.170 | 0.858 | 0.069 | -0.030 |
| $F^-$ | -0.072 | -0.278 | 0.844 | -0.063 | 0.154 |
| As | **0.921** | 0.144 | -0.072 | 0.122 | -0.254 |
| Mn | -0.046 | -0.426 | 0.159 | -0.086 | **0.343** |
| Cu | **0.923** | 0.139 | -0.080 | 0.122 | -0.252 |
| Fe | **0.902** | 0.225 | -0.094 | 0.030 | -0.292 |
| Extraction Method: Principal Component Analysis | | | | | |




Rotation Plot Showing the Associations Between Ions in R-Mode Factor Analysis

# Results and Discussion Con't….




Hierarchical Cluster Analysis Performed Using the Within-Group Linkage Extraction Criterion with Results Shown Through a Dendrogram

# Results and Discussion Con't....

## Probabilistic Human Risk Assessment

- The study categorized the population into four groups according to physiological and behavioral distinctions: infants (< 2 years), children (2 to < 8 years), teenagers (8 to < 18 years), and adults (≥ 18 years).

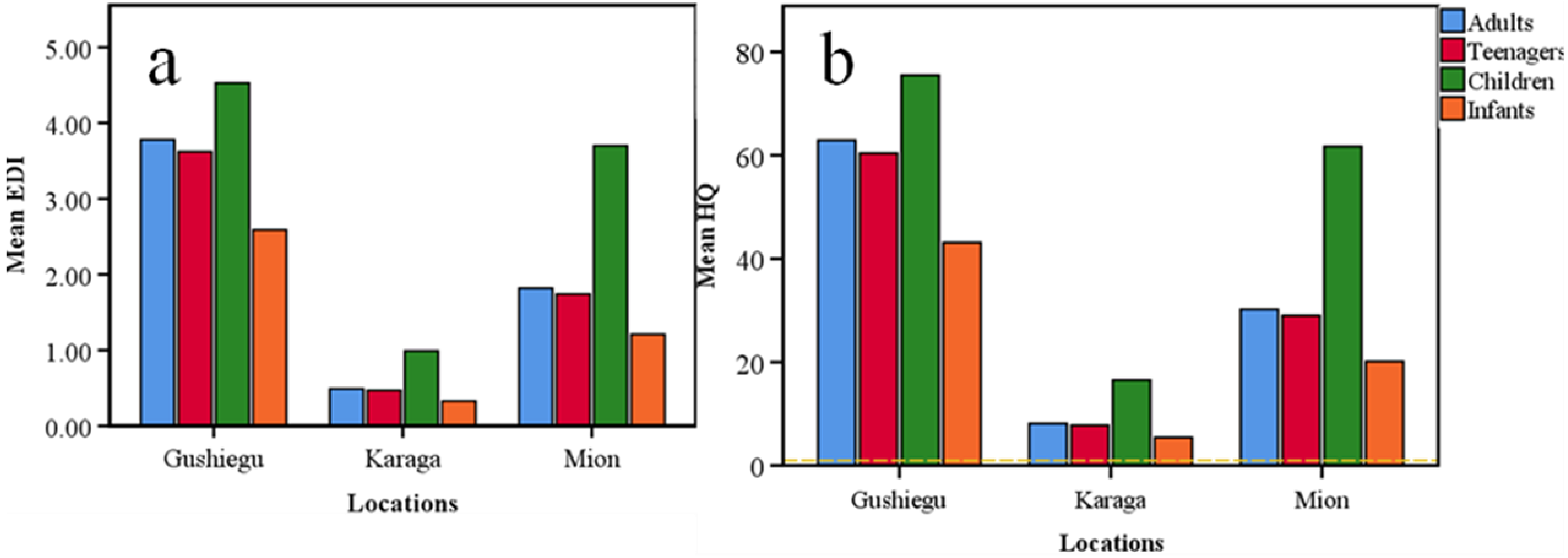
$$EDI = \frac{C_f \times C_d}{B_w}$$

**Average body weight (Bw) and daily average consumption of drinking water (Cd) of the varying age groups**

| | $B_w$ (kg) | | |
|---|---|---|---|
| **Age Group** | **Karaga and Mion** | **Gushiegu** | **$C_d$ (L/day)** |
| Adults | 60.0 | 60.0 | 2.50 |
| Teenagers | 50.0 | 50.0 | 2.00 |
| Children | 10.0 | 17.0 | 0.85 |
| Infants | 3.6 | 3.5 | 0.10 |

# Results and Discussion Con't….

## Probabilistic Human Risk Assessment

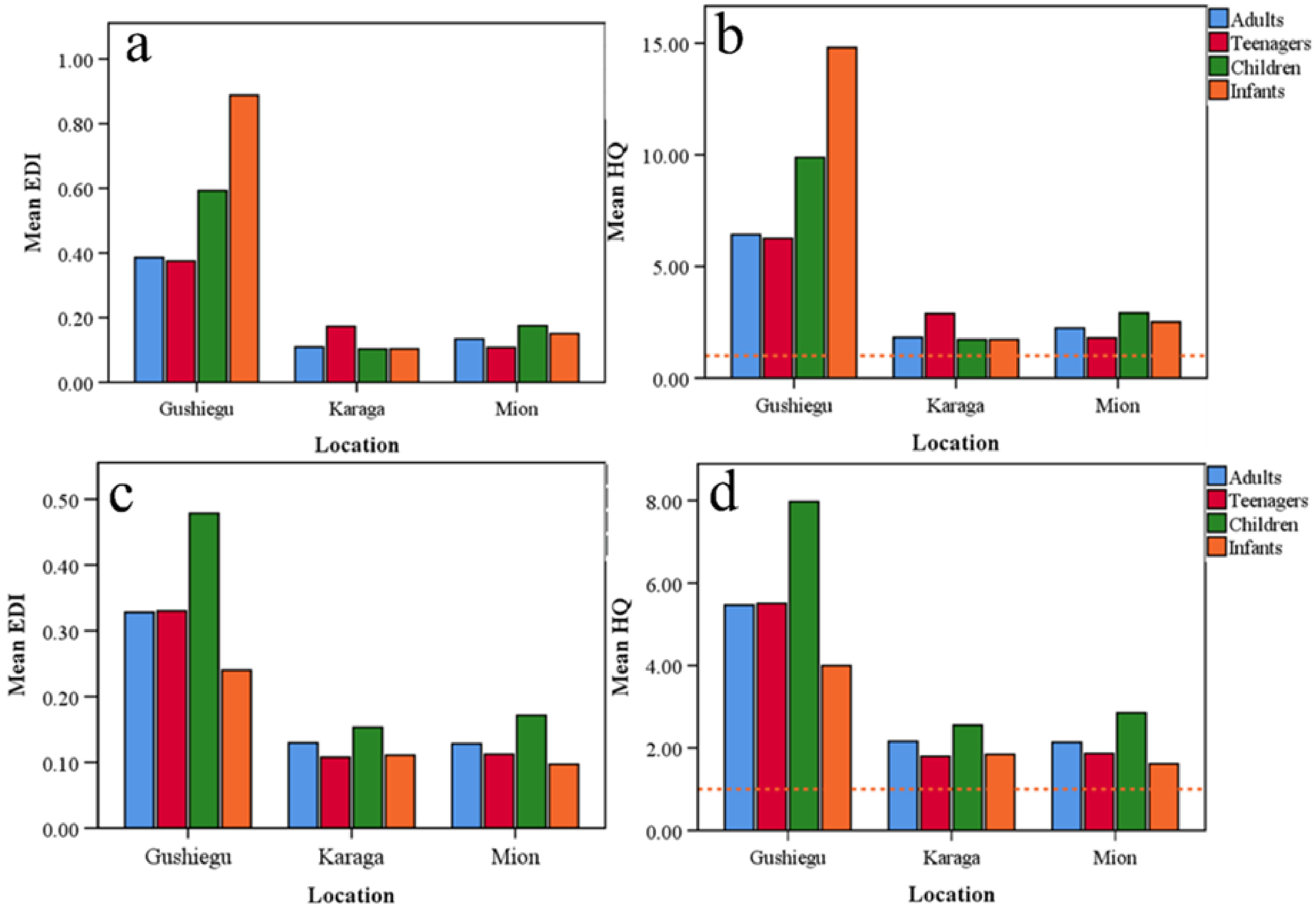



Calculated EDI and Hazard Quotient (HQ) values among different age groups

# Results and Discussion Con't....

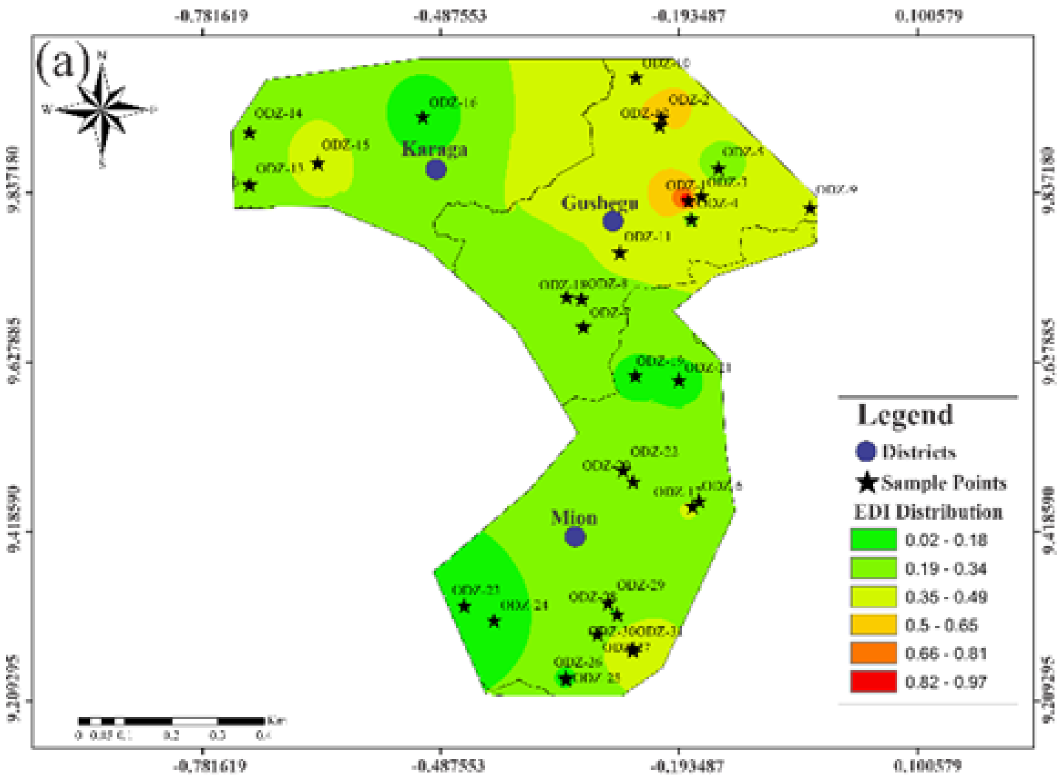
## Probabilistic Human Risk Assessment

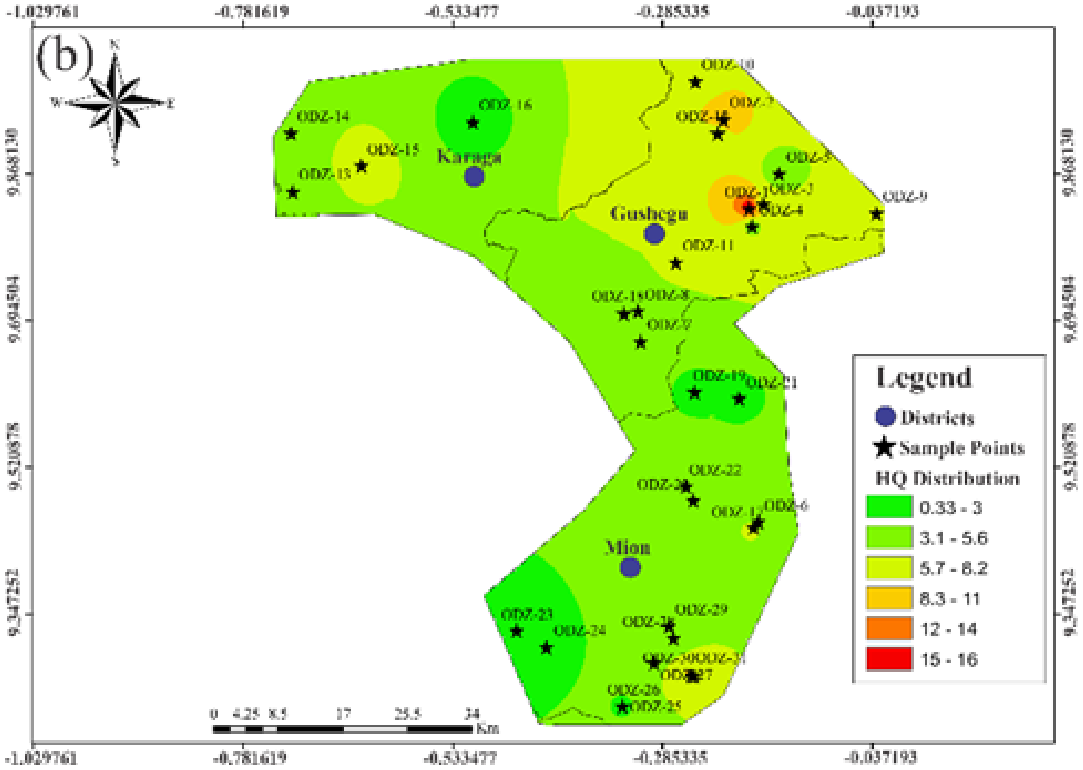
a-b and c-d are plotted data from the 100th and 500th iterations in the Monte Carlo Simulation, respectively.




Predictive Monte Carlo Analysis

# Results and Discussion Con't….




Spatial Distribution Maps of (a) EDI and (b) HQ of Children in the Study Area

# Results and Discussion Con't….

## Community-based Health Surveillance

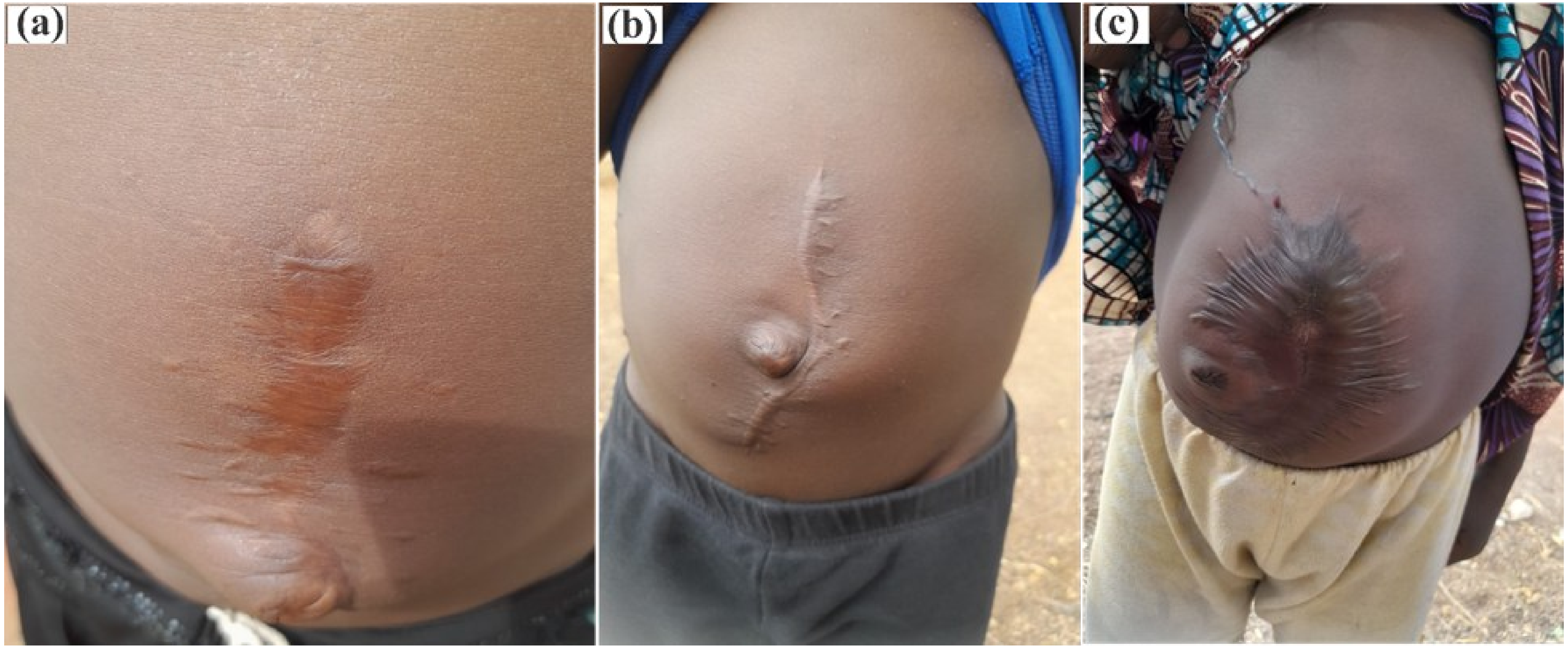

(a) Community-based Health Surveillance (b) Dental Fluorosis in Yishei (c) Dental Fluorosis in Wantugu (d) Teeth Appearance in Karaga (e) Skeletal Fluorosis? in Wantugu

# Results and Discussion Con't….


Surgically Operated Children in Yishei

# Results and Discussion Con't….

## Community-based Health Surveillance




Surgically Operated Children in Yishei

# Challenges and Opportunities

## Challenges

- **Data Availability and Quality**: Reliable and comprehensive data on geological factors and their health impacts are often lacking, making it difficult to assess risks accurately.

- **Interdisciplinary Collaboration**: Effective medical geology requires collaboration between geologists, medical professionals, and policymakers, which can be challenging due to differing terminologies, methodologies, and priorities.

- **Public Awareness**: There is a general lack of awareness about the importance of geological factors in health, which can hinder public support and funding for related initiatives.

- **Resource Allocation**: Limited financial and human resources can restrict the scope and impact of medical geology projects.

# Challenges and Opportunities

## Opportunities

- **Improved Public Health**: By identifying and mitigating geological health risks, medical geology can contribute to better health outcomes and reduce healthcare costs.

- **Sustainable Resource Management**: Understanding the health impacts of geological materials can lead to more sustainable mining and resource management practices.

- **Policy Development**: Insights from medical geology can inform policies aimed at reducing health risks associated with geological factors, supporting SDGs related to health, clean water, and sustainable cities.

- **Innovation and Research**: The field offers opportunities for innovative research and technological advancements, particularly in areas like water purification, soil remediation, and environmental monitoring.

# Students Trained So Far

Topic: **Hydrogeochemistry and Human Health Risk Assessment of Fluoridated Groundwater in Some Parts of the Voltaian Supergroup, Northern Ghana**

Name: Onesimus D. Zeon (International Student from Liberia)

Level: MSc (2024)

Topic: **Hydrogeochemical Characterisation of Groundwater in the Fanteakwa District Using Geochemical Modelling and Multivariate Statistical Approaches**

Name: Raphael Kobena Nuamah

Level: MSc (2023)

# Students Trained So Far

Topic: **Hydrogeochemical Appraisal of the Co- Occurrence of Fluoride and Nitrate in Groundwater f Gushegu Municipality in the Northen Region, Ghana: Implication for Human Health Risk Assessment**

Name: Yvonne Otoo Benyiwah

Level: BSc (2024)

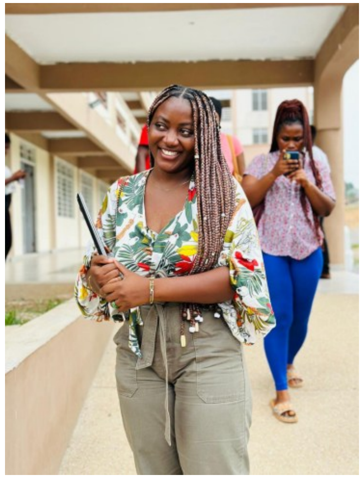
Topic: **Hydrogeochemical Characterisation and Quality Assessment of Groundwater in the Nkwanta District**

Level: BSc

Name: Osman Kamal Deen

Level: BSc (2024)

# Students Trained So Far



Topic: **Hydrogeochemical Processes and Evolution of Groundwater in the Voltaian Aquifer of Krachi East Municipality, Oti Region**

Name: Harriet Naa Larteley Yeboah

Level: BSc (2024)

Topic: **Hydrogeochemistry, Enrichment Mechanism and Health Risk Assessment of Groundwater Fluoride in the Karaga District, Northern Region**

Name: Celestina Yalley Akasi

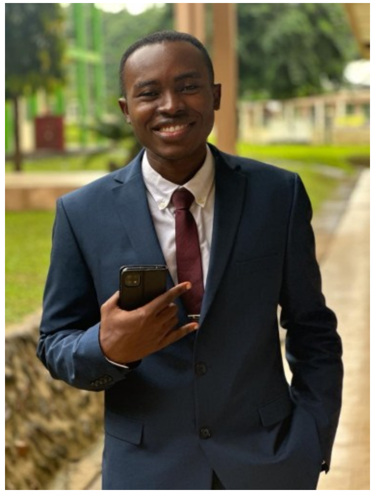
Level: BSc (2024)

# Students Trained So Far

Topic: **Assessment of Concentrations of Heavy Metals and Pollution Levels in Soils Within the Ewoyaa Lithium Project, Southern Ghana**

Name: Nathaniel Nyameboam

Level: BSc (2024)



Topic: **Assessment of the Geochemical Evolution of Fluoridated Groundwater in the Zabzugu District: An Integrated Hydrogeochemical and Multivariate Statistical Approach**

Name: Matthew Cobbiah Owusu

Level: BSc (2023)

# Students Trained So Far

Topic: **Application of Moringa oleifera as Coagulant for Defluoridation of Groundwater in Vea Community, Upper East Region**

Name: Kubi Grace Kabuki

Level: BSc (2023)

Topic: **Hydrogeochemical Assessment of Groundwater Quality in the Kintampo South District, Bono East Region, Ghana**

Name: Iddrisu Rafiatu

Level: BSc (2022)

# Students Trained So Far

Topic: **Occurrence, controlling factors and health hazards of nitrate-enriched groundwater in some Birimian aquifers in the Upper West Region, Ghana**

Name: Nyamekye Samuel

Level: BSc (2022)

Topic: **Hydrochemical assessment of nitrate contamination in groundwater of the Maluwe Basin, Savannah Region, Ghana: Implications for human health risk assessment**

Name: Okai Caleb Okaitei

Level: BSc (2022)

# Students Trained So Far

Topic: **Development of a low-cost household defluoridation unit using thermally activated cow bone: A case study at North East Region**

Name: Charles Mensah

Level: BSc (2022)

Topic: **Assessment of the Quality of Groundwater for Drinking and Irrigation Purposes in the Bono East Region**

Name: Emmanuel Prince Addo

Level: BSc (2021)

# Students Trained So Far


Topic: **Geochemical Controls on High Groundwater Fluoride in the Bongo District and its Environs, Upper East Region: Implications for Human Health Risk Assessment**

Name: Moses Boakye Okyere

Level: BSc (2021)

Topic: **Hydrogeochemical Evolution and Assessment of Groundwater Quality for Drinking and Irrigation Purposes in the Gushegu District and Some Parts of the North East Region of Ghana**

Name: Timothy Abangba

Level: BSc (2021)

# Future Directions

## 1. Enhanced Data Integration and Analysis

•**Big Data and AI**: Leveraging big data and artificial intelligence to analyze complex interactions between geological factors and health outcomes can lead to more precise risk assessments and targeted interventions.

•**Geospatial Technologies**: Utilizing advanced geospatial technologies for mapping and monitoring geological health risks can improve early warning systems and response strategies.

## 2. Interdisciplinary Collaboration

•**Cross-Sector Partnerships**: Strengthening collaborations between geologists, medical professionals, environmental scientists, and policymakers to develop holistic solutions to health challenges.

•**Community Engagement**: Involving local communities in research and decision-making processes to ensure that interventions are culturally appropriate and sustainable.

# Future Directions

## 3. Policy and Regulation

•**Evidence-Based Policies**: Developing and implementing policies based on robust scientific evidence to mitigate health risks associated with geological factors.

•**International Standards**: Establishing international standards and guidelines for monitoring and managing geogenic contaminants.

## 4. Education and Capacity Building

•**Training Programs**: Creating specialized training programs for professionals in both geology and health sectors to build capacity and expertise in medical geology.

•**Public Awareness Campaigns**: Increasing public awareness about the health impacts of geological factors through education and outreach initiatives.

# Future Directions

**5. Technological Innovations**

•**Water and Soil Remediation**: Advancing technologies for the remediation of contaminated water and soil to reduce exposure to harmful geogenic substances.

•**Health Monitoring Devices**: Developing portable and affordable health monitoring devices to detect and measure exposure to geological hazards.

**6. Research and Development**

•**Disease Etiology**: Investigating the role of geological factors in the etiology of diseases with unknown causes to uncover new health risks and preventive measures.

•**Sustainable Practices**: Promoting sustainable mining and resource management practices to minimize environmental and health impacts.

# Conclusion

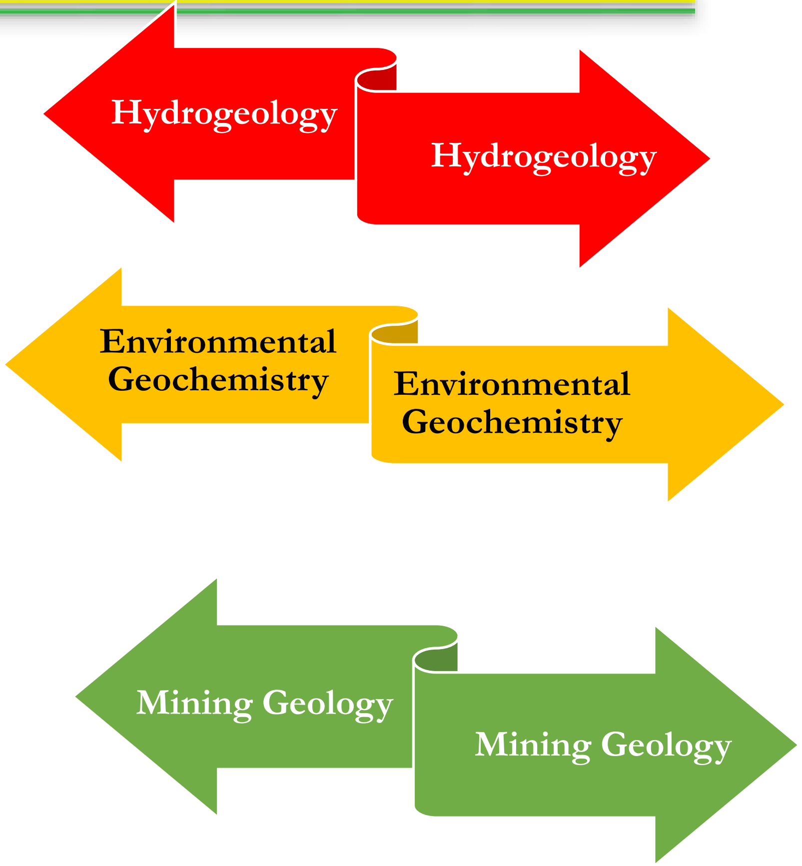
In conclusion, medical geology plays a pivotal role in achieving the Sustainable Development Goals (SDGs) by addressing the complex interactions between geological factors and human health. By leveraging interdisciplinary collaboration, advanced technologies, and innovative research, we can:

- ❖ **Enhance Public Health**: Identify and mitigate health risks associated with geological factors, leading to improved health outcomes and reduced healthcare costs.
- ❖ **Promote Sustainable Practices**: Foster sustainable resource management and mining practices that minimize environmental and health impacts.
- ❖ **Inform Policy Development**: Provide robust scientific evidence to inform policies aimed at reducing health risks and promoting sustainable development.
- ❖ **Advance Education and Awareness**: Increase public awareness and build capacity through education and training programs, ensuring that communities are well-informed and equipped to address geological health risks.

By focusing on these areas, medical geology can significantly contribute to the global effort to achieve the SDGs, particularly those related to health, clean water, and sustainable cities. As we move forward, continued investment in research, technology, and interdisciplinary collaboration will be essential to fully realize the potential of medical geology in creating a healthier and more sustainable future.

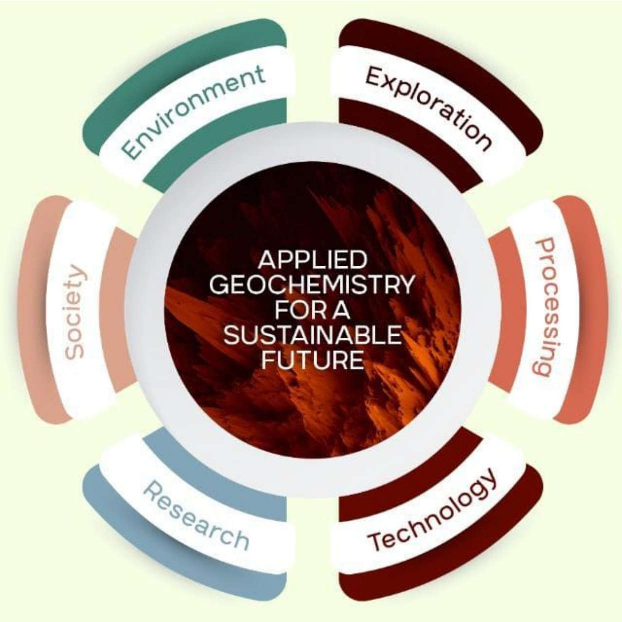
# Ongoing Research for Collaboration

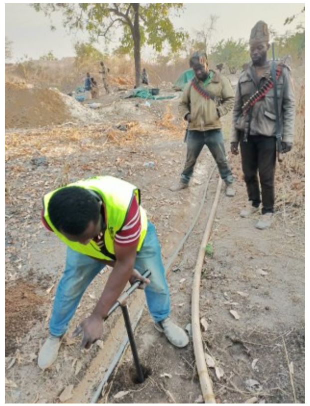
- Groundwater-surface water interaction
- Hydrogeochemistry and groundwater exploration
- Application of groundwater geochemistry in mineral exploration
- Speciation mechanisms of PTEs in environmental media i.e. soil, water, and plants
- Medical geology
- Impact of mining activities on water quality in mining and post-mining areas
- Fluid inclusion studies and isotope geochemistry of metallic ore deposits
- Ore textures, mineral paragenesis, and whole-rock geochemistry
- Geochemical exploration for critical mineral resources
- Petrogenesis of auriferous granitoids in diverse geological terranes
- Application of AI and multivariate statistical techniques in mineral exploration geochemistry

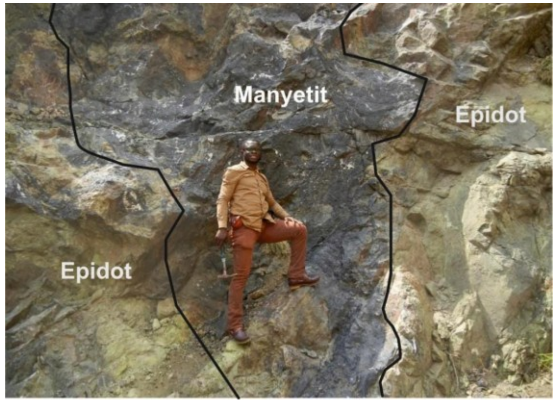


# Research Group Established

- Applied Geochemistry Research Group (AGReG), University of Mines and Technology, Ghana, 2021






# Acknowledgements

Special thanks go to the University College of Water Science and Engineering for the invitation to this webinar as the Guest Speaker.

I am looking forward to collaborating with you on similar endeavors!!

I also thank all my research team members.

# THANK YOU