Integrated Approach On Discerning Fluoride Contamination Mechanisms In The Groundwater And Formulating Remedial Strategies For Potential Health Hazards In Birbhum District, West Bengal

A thesis
submitted by

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List of Journal Publications

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Statement of Originality

I, **Riddha Chaudhuri, (Reg. No. D-7/ISLM/45/18 of 06/03/2018** do hereby declare that this thesis entitled "***Integrated approach on discerning fluoride contamination mechanisms in the groundwater and formulating remedial strategies for potential health hazards in Birbhum District, West Bengal***' contains literature survey and original research work done by the undersigned candidate as part of Doctoral studies.

All information in this thesis has been obtained and presented in accordance with existing academic rules and ethical conduct. I declare that, as required by thesis rules and conduct, I have fully cited and referred all materials and results that are not original to this work.

I also declare that I have checked this thesis as per the "Policy on Anti Plagiarism, Jadavpur University, 2019", and the level of similarity as checked by iThenticate software is **8%**.

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Certificate from Supervisors

This is to certify that the thesis entitled "***Integrated approach on discerning fluoride contamination mechanisms in the groundwater and formulating remedial strategies for potential health hazards in Birbhum District, West Bengal***' submitted by **Riddha Chaudhuri** who got registered (**Registration no. D-7/ISLM/45/18 dated 06/03/2018**) his name under the Faculty of Interdisciplinary Studies, Law & Management for the award PhD (Science) degree of Jadavpur University is absolutely based upon his own work under the supervision of Prof. Anupam Debsarkar and Dr. Satiprasad Sahoo and that neither his thesis nor any part of the thesis has been submitted for any degree/diploma or any other academic award anywhere before.

Signature of the Supervisors with date and seal:

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1. Introduction

Groundwater is a crucial resource for sustaining human life, serving as the main source of drinking water for approximately 2.5 billion people and supporting essential agricultural and industrial functions for economic growth. However, the quality of groundwater is increasingly threatened by a variety of geogenic and anthropogenic pollutants, with fluoride (F^-) identified as a particularly widespread and harmful contaminant requiring urgent attention. While low fluoride levels (0.5 to 1.5 mg/L) can help prevent dental caries, chronic exposure to higher concentrations above 1.5 mg/L can lead to fluorosis, a painful condition that negatively impacts dental and skeletal health. The World Health Organization (WHO) estimates that over 200 million people globally depend on fluoride-contaminated groundwater, particularly affecting developing countries in Asia, Africa, and Latin America, where limited access to treated water heightens public health challenges. Fluoride, a highly toxic chemical element, poses considerable health risks. Fluoride's contamination of groundwater, even at low levels, causes serious health ramifications, establishing it as a major ecological challenge for developing nations ***(Rajak et al., 2023; Chaudhuri et al., 2024)***. The regulated inclusion of fluoride in drinking water is beneficial for preventing dental caries, but excessive levels can lead to dental and skeletal fluorosis. Prolonged fluoride ingestion adversely affects the integrity and function of various bodily tissues and organs. A severe consequence of fluorosis is the development of debilitating skeletal deformities that hinder mobility and diminish quality of life. Extensive studies that critically examine the issue of contamination of fluoride have been undertaken by various researchers, including ***Mukherjee and Singh (2018), Rasool et al. (2018), Chowdhury et al. (2019), Shaji et al. (2023), and Chaudhuri et al. (2024)***, among a multitude of other scholarly works. Across the globe, five principal fluoride belts have been identified, each corresponding to distinct lithological and tectonic characteristics, along which groundwater exhibiting elevated concentrations of fluoride is exclusively found (***Fawell et al., 2006***). In India, there exists a significant challenge concerning groundwater that is contaminated with undesirably high levels of fluoride, which poses serious health risks to vast regions of the country, particularly in its arid and semi-arid zones. The Indian states that are most affected by high levels of fluoride contamination include Andhra Pradesh, Rajasthan, Gujarat, Telangana, Tamil Nadu, and West Bengal, as noted by ***Mukherjee and Singh (2018)***. A variety of natural factors significantly influence the concentration of fluoride in groundwater, including geological formations, geothermal activity, the physicochemical properties of the water, the climate as well as the specific types of soil present in the region. Nevertheless, it is crucial to recognize that certain anthropogenic factors also play a role in this issue. Correlating all of these multifaceted factors is imperative in order to enhance our understanding of fluoride contamination, particularly in relation to the specific conditions observed within the Birbhum district, West Bengal.

2. Review of Literature

Preface

Fluoride contamination in groundwater is a significant global health issue, particularly linked to dental and skeletal fluorosis. This problem affects both developed and developing nations, with severity varying due to regional geological and environmental factors. Fluoride presence in groundwater arises from natural processes and human activities, such as industrial waste disposal. Addressing fluoride contamination requires a comprehensive approach involving monitoring, risk assessment, and the development of effective remedial technologies. The following sections will review the mechanisms of fluoride contamination, potential health impacts, and technologies for fluoride removal. While fluoride can prevent dental caries in regulated amounts, excessive levels can lead to dental and skeletal fluorosis. Long-term fluoride ingestion adversely affects various bodily tissues and organs. Severe fluorosis can result in debilitating skeletal deformities, diminishing mobility and quality of life.

2.1 Sources and Controls on Mobilization of fluoride in groundwater

Li et al.,(2023) in their case study on the Cherchen River Basin, Northwestern China, found that major sources of fluoride (F^-) in desert groundwater are leaching of F^- bearing minerals, including evaporite (~58.80%), silicate (~15.89%), and carbonate (~12.94%), with river water input contributing ~12.08%. Controls on F^- mobilization include the dissolution equilibrium of CaF_2, intensive evaporation, and salinization, particularly in the alluvial plain. Under alkaline conditions, the release of F^- is enhanced by the dissolution of evaporite and fluorite, while competitive adsorption and cation exchange affect F^- adsorption capacity.

Shaji et al. (2023) propose that the origins of fluoride in groundwater are predominantly geogenic in nature, encompassing terrains characterized by high-grade metamorphism, geothermal springs, granitoid or alkaline intrusions and volcanic landscapes. Additionally, anthropogenic sources such as over-fluoridated drinking water and products for dental hygiene contribute to fluoride levels. Controls on the mobilization of fluoride are influenced by climatic conditions, geological factors, and land use practices. Effective management strategies are essential to mitigate fluoride contamination and protect public health, particularly in vulnerable regions.

Fowler et al.,(2024) point out that sources of groundwater fluoride include industrial waste streams, such as alkaline spent potliner, coal combustion byproducts, and acidic gypsum stack impoundments. The controls on fluoride mobility are primarily pH-dependent processes, with fluoride complexation occurring at low pH and carbonate stability at high pH. Elevated fluoride concentrations are typically found at pH extremes, while near-neutral conditions generally exhibit lower fluoride levels.

Gao et al.,(2024) identifies sediment lithology, particularly silt loam, as a significant source influencing fluoride mobilization in groundwater. Microbial activity enhances fluoride release from sediments, particularly affecting carbonate-bound and Fe-Al-bound fluoride fractions. The interplay of mineral dissolution and desorption processes, alongside the co-dissolution of fluoride and calcium, serves as critical controls on fluoride mobilization. The diverse mineral composition of sediments, including quartz, calcite, and illite, further contributes to the complex biogeochemical interactions governing fluoride dynamics in groundwater.

Saha et al.,(2024) are of the opinion that the sources and controls on the mobilization of fluoride (F^-) in groundwater include geogenic factors such as lithology, geomorphology, soils, and lineaments. These geological characteristics, along with climatic conditions, significantly influence fluoride contamination levels. In arid and semi-arid regions, the mobilization of fluoride is notably higher compared to humid areas. The study highlights that these controlling factors create a complex interplay that affects the spatio-temporal distribution of fluoride in groundwater across India.

2.2 Controls on mobilization of fluoride in groundwater

Nakayama et al.,(2022) found that tectonics play a vital control on fluoride mobilization in groundwater by shaping the hydrogeological structure, particularly in fractured zones. In the Tabora region, the direction of faults affects fluoride concentrations, with deeper water strikes and substantial well yield potential leading to lower fluoride levels. The flow mechanism suggests that water recharges in low fluoride concentration areas and travels through fault systems, creating preferential flow paths that mitigate fluoride contamination, highlighting the importance of tectonic features in groundwater quality.

Ou et al.,(2023) opine that fluoride mobilization in groundwater is controlled by the presence of competing anions such as hydroxide, phosphate, and carbonate, which can decrease fluoride removal efficiency due to competition for sorption sites. Additionally, the chemical adsorption mechanisms, including the formation of magnesium hydroxide and subsequent replacement of hydroxyl groups by fluoride ions, play a crucial role in fluoride mobilization and removal.

Li et al.,(2022) suggest that the mobilization of fluoride in groundwater is primarily controlled by weathering processes, which enrich the groundwater with fluoride. Additionally, the hydrogeochemical environment plays a significant role, with high fluoride concentrations observed in $Na\text{-}HCO_3\text{–}SO_4$ type groundwater. The study indicates that these high fluoride levels are influenced by palaeo-recharge and shallow leakage in closed reducing and semi-closed facultative environments, respectively, contributing to the overall fluoride dynamics in the deep aquifer system.

2.3 Global perspectives on Fluoride contamination

Kumar et al., (2023) reveal that the presence of fluoride in groundwater is a pressing global concern, especially in the arid and semiarid landscapes of India, where the issue is more pronounced compared to other Asian nations. Although fluoride serves as a vital trace element, concentrations surpassing 1.5 mg/L can lead to significant health hazards. The study explores the origins, geochemical behavior, spatial patterns, and health consequences of elevated fluoride concentrations, underscoring the immediate necessity for innovative treatment solutions to reduce exposure dangers on a global scale.

Ning et al.,(2024) focuses on geogenic fluorine-contaminated groundwater, particularly in cold Mollisol regions, highlighting that such contamination (F^- >1.0 mg/L) is prevalent in these areas globally. It emphasizes the seasonal variation of fluoride concentration in groundwater, which poses health risks, especially in economically challenged communities. While the study is centered on northeastern China, it suggests that similar issues may exist in other cold regions worldwide, indicating a broader concern regarding contamination of fluoride in the groundwater.

Chaudhuri et al., (2024) contend that the issue of fluoride contamination in groundwater constitutes a significant global environmental concern, affecting approximately 200 million people, with 62 million of those individuals located in India. Researchers have pinpointed five primary fluoride-affected regions across the globe. This contamination arises from both natural sources, such as the degradation of fluoride-laden minerals and volcanic activity, as well as human-induced factors. In India, notable areas suffering from elevated fluoride levels include Rajasthan, Tamil Nadu, Andhra Pradesh, Telangana, and West Bengal, where such concentrations present grave health hazards, including dental and skeletal fluorosis.

Saini and Gupta (2024) argue that the issue of fluoride pollution in groundwater is a major concern worldwide, impacting roughly 260 million individuals across 30 nations. India is grappling with serious difficulties, as endemic fluorosis affects around one million people in 17 states. The increased fluoride concentrations predominantly arise from fluoride-rich minerals found in local geology and soil. The World Health Organization suggests keeping fluoride levels close to 1.0 mg/L to strike a balance between dental health advantages and the prevention of fluorosis, underscoring the necessity for effective management approaches to ensure safe access to drinking water.

2.4 Indian perspectives on Fluoride contamination

De et al.,(2024) found that approximately 10% of groundwater samples within the plains of the West Bengal's lower Gangetic region exceed the recommended fluoride (F^-) levels, indicating moderate contamination. The study highlights that the groundwater is primarily saline (Na-Cl type) and identifies the leaching of fluoride from silicate minerals, particularly muscovite, as a significant factor. This contamination poses health risks, especially for infants, necessitating the implementation of safe potable water strategies in the contaminated regions.

Ambade et al., (2024) reveal that in the Indian context, the issue of groundwater fluoride contamination poses a serious threat, especially in Eastern India, notably in the East Singhbhum area of Jharkhand. The research underscores that industrial emissions, farming methods and careless waste management are key human induced factors in fluoride pollution. Throughout the investigation, fluoride concentrations varied from 0.02 to 4.7 mg/L, with 97% of samples falling within the permissible range. Nevertheless, infants were recognized as the most vulnerable group to exposure, highlighting the urgent need for raising awareness and implementing strategies to combat water contamination.

Saha et al.,(2024) opine that fluoride contamination in groundwater in India poses significant human health hazards, particularly due to geogenic and geo-environmental factors. The study identifies alarming levels of fluoride in states like Rajasthan, Telangana, and others, with 8.65% and 7.10% of pre- and post-monsoon sites above the permissible limits of 1.50 mg/L. Children are more adversely affected than adults, with potential risks of skeletal fluorosis and dental caries. Climatic conditions and geological factors significantly influence fluoride levels across the country.

Singh and Mehta (2024) believe that the presence of fluoride in groundwater poses a major challenge in India, impacting numerous states. Long-term exposure to high fluoride levels can lead to skeletal and dental fluorosis, posing serious health risks. The study employs machine learning algorithms to analyze fluoride concentrations, aiming to understand and predict contamination sources effectively. This research highlights the urgent need for monitoring and addressing fluoride levels in affected regions to safeguard public health.

Alam et al.,(2024) finds that in the Indian context, contamination of fluoride in groundwater poses a significant threat to safe drinking water, particularly in hard-rock aquifers. The study highlights that in Central India, fluoride levels exceeding 1.5 mg/L are primarily found in deeper aquifers, specifically fractured basalt and granite, while shallower aquifers remain safe. The mobilization of fluoride is linked to geochemical processes, including mineral weathering and ion exchange, emphasizing the need for targeted strategies to ensure fluoride-safe drinking water supplies in affected regions.

2.5 Health Risk Assessment

Wang et al.,(2024) observed in their study in Jiangsu Province, China that nearly all groundwater samples indicated an unacceptable risk (HQ > 1) for fluoride across all age groups, highlighting significant health concerns. The assessment helps identify the extent of risk to human health, guiding policymakers in developing strategies to mitigate fluoride exposure and ensure safe drinking water, as over 85.7% of samples exceeded the drinking water quality standard for fluoride, as per WHO.

Rajan et al.,(2024) indicated in their study in South India that 16.17% of samples exceed 4.0 mg/L, categorizing them as extreme risk according to WHO guidelines. The Comprehensive Risk Index (CRI) figures for every age category—babies, youngsters, adolescents, women, and men exceeded 1, signifying potential non-carcinogenic health hazards. Children are particularly vulnerable, highlighting the urgent need for detailed geochemical investigations and design of applicable remedial measures.

Liu and Chen (2024) indicated in their study in Suzhou city, East China, that that fluoride in shallow groundwater poses a higher non-carcinogenic risk to children compared to adults through ingestion. The investigation employed health risk evaluation frameworks to assess the prospective health effects of fluoride exposure, indicating that 26.5% of groundwater samples surpassed the Grade III quality benchmark. This highlights the necessity of tracking fluoride concentrations in groundwater to safeguard at-risk groups, especially children, from possible health hazards linked to fluoride pollution.

Yang et al.,(2024) argue that the evaluation of health risks concerning fluoride pollution in groundwater reveals that consumption through drinking water presents considerable non-carcinogenic dangers. The research discovered overall risks fluctuating between 0.22 and 3.19 for adults, and between 0.51 and 7.44 for children. Fluoride emerged as the most perilous contaminant in the groundwater, overshadowing ammonium and nitrate concentrations. This underscores the necessity for heightened scrutiny regarding fluoride exposure in drinking water, especially in agricultural landscapes such as the Guanzhong Plain, China.

2.6 Remedial Methods

Mukherjee and Roy (2023) are of the opinion that rainwater harvesting serves as a remedial method for excess fluoride in groundwater by collecting and utilizing rainwater to dilute fluoride concentrations. In the study, rainwater is harvested from a rooftop area of 5180 m^2, with an estimated annual collection of 3,951,395.22 liters. This harvested rainwater can be injected into the groundwater reserve, effectively raising the water table and reducing fluoride levels through dilution, thereby addressing the contamination issue in the aquifer.

Meng et al.,(2024) focuses on the electrochemical fixed bed system using industrial aluminum electrodes and natural bauxite (IE–BA) for fluoride removal from groundwater. This method achieved a defluorination efficiency of 98.4% after optimization, with rates exceeding 95.2% across varying fluoride concentrations. The study highlights the effectiveness of the IE–BA system in treating fluoride pollution, demonstrating its potential as a promising approach for defluorination in areas lacking municipal water systems.

Rathi et al.,(2024) discusses various remedial methods for excess fluoride in groundwater, focusing on membrane-based techniques. These include nanofiltration (NF), reverse osmosis (RO), membrane distillation (MD), electrodialysis (ED), and forward osmosis (FO). Additionally, it highlights advancements in ceramic membranes, electrodeionization, membrane capacitive deionization, and hybrid membrane techniques. Each method has its advantages and drawbacks, contributing to effective defluoridation processes aimed at achieving safe fluoride levels in water, aligning with the Sustainable Development Goals for clean water supply.

Jothimani et al., (2024) investigates column filtration as a remedial method for excess fluoride in groundwater, utilizing low-cost adsorbents such as Brick powder, Neem leaf powder, Lime, Sawdust, and Vetiver. These materials effectively reduce fluoride concentrations, with Vetiver achieving a removal efficiency of 78%, followed by Limestone at 77%. While some adsorbents are effective, they may impart color and turbidity to the water. The research emphasizes the importance of accessible and sustainable solutions for groundwater defluoridation.

2.7 Research gap

Based on the surveyed literature, the following gaps have been identified:

- Comprehension of the geological, geochemical and tectono-structural controls on fluoride contamination in the groundwater of Birbhum and identification of mechanisms of mobilization are yet to be explored. Although, present literature points out to several mechanisms for overall concentration and mobilization of fluoride in groundwater, as a whole, but it fails to shed light on the exact set of processes whose interplay leads to contamination of fluoride in the groundwater of Birbhum.
- Health Hazard Assessment of the population, segregated along ages, i.e., adult and children, that consume groundwater with fluoride above permissible limits is also to be conducted. Spatio-temporal variation of the aforementioned hazards, segregated along age, in the district of Birbhum, is also largely unexplored.
- Locally implementable remedial solutions to the population affected by consumption of groundwater contaminated with fluoride are to be investigated. Although several such remedies have been surveyed, many are either expensive or require technical knowledge for on-ground implementation. Therefore, development of affordable and locally executable remedial technologies, technologies that require little strategic interventions and or technical knowledge, are a major gap of the research.

Chapter 3: Objectives and Scopes of Study

Objectives of the study:

The present research has been conducted with the objective to *understand geological and geochemical controls on fluoride contamination and mobilization in the groundwater of Birbhum, assess and delineate potential health risks thereof and to formulate locally implementable strategies to ameliorate the said risks.*

Scopes of the study:

The scopes of the present work considered for achieving the stated objectives are mentioned hereunder :

- Identification of the study area;
- Conduction of geochemical analysis of ground water samples;
- Conduction of petrological analysis of rock samples to understand the mineralogical control on fluoride contamination in the groundwater;
- Conduction of lineament analysis to understand the mobilization pathways of fluoride in groundwater;
- Conduction of statistical analysis of major cations and anions in groundwater to understand the correlations, if any, between fluoride and other ions;
- GIS mapping of regions affected by high fluoride in the groundwater to analyse the spatio-temporal variations;
- Conduction of risk analysis to delineate health hazards arising out of consumption of water contaminated with fluoride above the safe level in spatio-temporal dimensions
- Delineation of appropriate remedial strategies for abatement of the health hazards associated with fluoride contamination; and
- Recommendation of a proper methodology for localized implementation of the said remedial methods.

Phases of Research

The research work was further segregated to four different phases for better execution as mentioned below:

- **PHASE I:** Establishment of geological and geochemical controls on contamination and mobilization of fluoride in the groundwater
- **PHASE II:** Spatio-temporal mapping and analysis of fluoride contamination in the groundwater and that of health hazards arising out of consumption of groundwater with high fluoride content
- **PHASE III:** Presentation of a locally implementable ameliorative strategy in the form of Rainwater Harvesting, using Analytical Hierarchy Process (AHP)

4. Geogenic controls on fluoride contamination in the groundwater

4.1 Preface

Fluoride ions in drinking water arise from various geogenic processes ***(Chowdhury et al., 2019)***. Key contributors to fluoride contamination include mineral weathering, volcanic eruptions, hydrothermal activities, and marine aerosols ***(Edmunds and Smedley, 2005; Vithanage and Bhattacharya, 2015)***. Significant geological sources of fluoride include fluoride-rich rocks such as alkali rhyolites, granitic rocks, and mafic formations. Critical minerals in the environmental fluoride cycle include fluorite, fluorspar, cryolite, apatite, fluorapatite, and mica ***(Jha and Tripathi, 2021)***. Fluoride concentrations vary based on lithological composition, with measured concentrations of 1300 mg/kg in marine shale, 1000 mg/kg in alkaline igneous rocks, and 100 mg/kg in ultramafic rocks, reflecting diverse geochemical environments ***(Nagudi et al., 2003; Scaillet and Macdonald, 2004; Ozsvath, 2006)***. Fluoride-bearing minerals are often linked to pegmatitic intrusions, hydrothermal veins, and differentiated magmas, facilitating fluoride ion release through leaching, hydrolysis, and ion-exchange processes ***(Aind et al., 2022; Rashid et al., 2024)***. Groundwater fluoride contamination is significantly influenced by the lithology of aquifer host rocks, especially those underlain by granitic formations known for their geochemical traits. These rocks, common in cratonic shields and Precambrian complexes, are notable geogenic fluoride sources due to their mineral composition. Granitic formations contain various fluoride-bearing minerals, both primary and accessory, such as fluorite and mica, which release fluoride during weathering ***(Chakrabarti et al., 2013; Dubey et al., 2021)***. Furthermore, hornblende and other iron-magnesium silicate minerals can also release fluoride ions due to oxidative weathering, particularly in fractured geological areas ***(Mukherjee and Singh, 2020)***.

The tectonic characteristics of a region significantly influence groundwater fluoride concentrations. Studies show high fluoride levels in groundwater correlate with specific tectonic zones. Regions with intra-continental hotspots and magmatic belts report the highest fluorosis incidences and fluoride concentrations ***(Chowdhury et al., 2019)***. Calc-alkaline volcanoes in the East African Rift System produce fluorine-rich lavas, akin to those in the Andes and Japan ***(Rosi et al., 2003)***. Regional thermal fields and felsic volcanic rocks in geothermal areas significantly contribute to groundwater fluoride contamination ***(Alemayehu et al., 2006; Furi et al., 2011)***. Geothermal spring waters often exceed WHO fluoride safety standards, raising public health concerns. Thermal springs play a vital role in the hydrological cycle of volcanic areas. Their thermal energy partly originates from the radioactive decay of uranium, thorium, and potassium in granitic rocks that generate heat (Karakus, 2015). Thermal waters in the Chotanagpur Granite Gneiss Complex show fluoride levels surpassing health authority limits ***(Minissale et al., 2000; Chandrasekhar and Chandrasekharam, 2011; Singh et al., 2015)***. Taptapani hot springs in Odhisa and Bakreshwar hot springs in West Bengal exhibit fluoride levels reaching 16 mg/L within the SONATA geothermal province. Similarly, prominent hot springs in the Cambay Geothermal

Province, particularly in Tuwa of the Godhra granitic formation, display fluoride content ranging from 2.5 to 4 mg/L.

The enrichment of fluoride in groundwater is influenced by various factors including temperature, pH, anion exchange, geological contact time, mineral solubility, geological formations, and the absence of precipitating ions ***(Liu et al., 2023; Wei et al., 2024)***. In arid and semiarid areas, low annual precipitation and high evaporation lead to reduced groundwater hydraulic conductivity ***(Su et al. 2006)***. This low conductivity results in minimal groundwater recharge and prolonged interaction with rock formations, increasing fluoride concentrations. Empirical evidence shows that low-lying plains have higher fluoride concentrations due to longer water contact with aquifers, while higher elevations report lower levels ***(Ali et al., 2023)***. The retention time of water in an aquifer is critical for interaction with geological materials, correlating fluoride concentration with retention time ***(Saxena and Ahmed, 2003)***. Additionally, pH significantly influences fluoride ion solubility and mobility, with increased sodium and bicarbonate concentrations raising pH and promoting fluoride mineral dissolution ***(Rango et al. 2009)***. At low pH, fluoride ions form complexes with aluminum and iron, and below pH 4.0, they are adsorbed by clay minerals, while above pH 6.5, adsorption decreases significantly. In alkaline conditions, specifically at pH levels exceeding 7, hydroxide ions replace fluoride ions in certain minerals through anion exchange reactions ***(Li et al. 2014)***.

4.2 Methodology

4.2.1 Study Area

The district of Birbhum is the northernmost administrative division in Burdwan, West Bengal. It is geographically located between specific latitude and longitude coordinates. Known as the "Land of the Red Soil," Birbhum is culturally and historically significant within West Bengal's heritage. The district spans approximately 4545 square kilometers and has an isosceles triangular shape, with the river Ajay marking its geographical boundaries. To the west, it borders Jharkhand, while to the east, it is adjacent to Murshidabad and Burdwan, underscoring its strategic importance. Birbhum is classified within the lower Gangetic plain, featuring red laterite soils mixed with alluvial deposits, enhancing its agricultural potential and ecological diversity. These geographical and climatic factors are pivotal in influencing the socio-economic conditions and cultural practices of Birbhum's residents.

The Birbhum landscape is shaped by lateritic soil, creating the unique "khoai" region characterized by its undulating topography and erosion features like rills and gullies. The district also showcases micro-relief forms, including ravines, waterfalls, and terraces, akin to African and Brazilian highlands, highlighting its global geological relevance. Birbhum experiences "dry sub-humid mega thermal" climatic conditions, with extreme temperature fluctuations ranging from 44°C-46°C in summer to 6°C-7°C in winter, emphasizing its climatic diversity. Moderate precipitation, peaking in July at 350 mm, contributes to the region's drought-prone status, impacting agriculture and water availability. The district faces significant groundwater quality issues, particularly fluoride contamination, which poses health risks and affects water quality in areas like Rampurhat-II block.

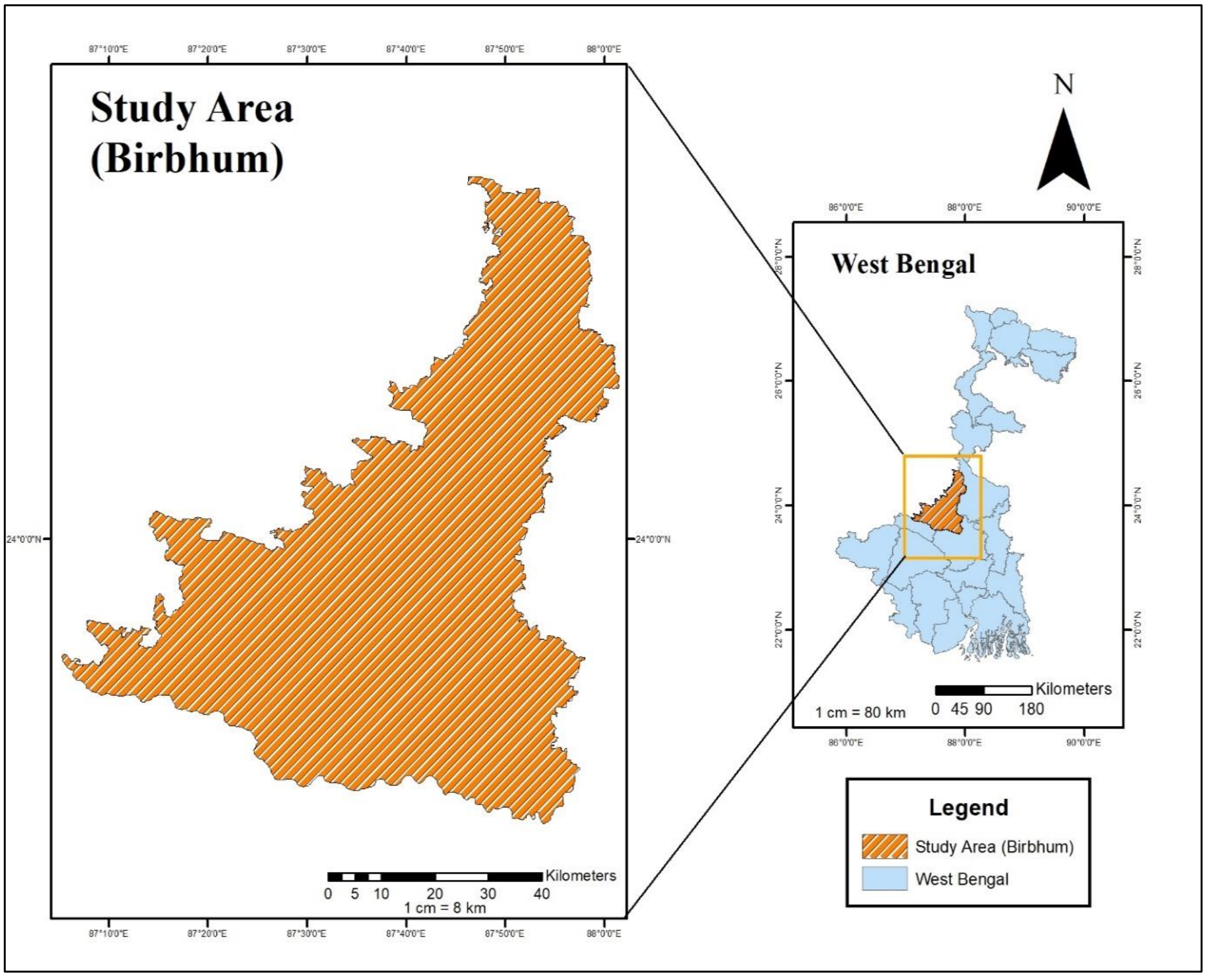


Figure 4.1: Study Area Map

4.2.1.1 Geology of Birbhum

Birbhum demonstrates significant geological diversity. It features Archean granitic rocks, Rajmahal basaltic traps, Gondwana coal deposits, and varied alluvial deposits, creating a complex geological framework. The Archean rocks, mainly the Chotanagpur Granite Gneiss, are predominantly found in the district's southwest, forming a key geological component. Gondwana formations are dispersed in the southern and southwestern regions, particularly along the Ajoy River banks (CGWB). The Rajmahal basaltic traps are prominently located in the northern and northwestern parts of the district. Furthermore, Tertiary formations consist largely of clay beds and ferruginous and feldspathic sandstones, adding to the area's intricate stratigraphy (Mukherjee et al., 1969). The alluvial deposits show a notable thickness gradient, increasing from the west to the east, ranging from below 20 meters to 80 meters below ground level (bgl), indicating significant sediment accumulation over time (CGWB). Older alluvial deposits, from the Upper Tertiary to Lower Quaternary, significantly influence the geomorphology in the eastern and southeastern areas. Additionally, these older alluvium layers are often covered by laterite and lateritic soils in upland regions. Recent alluvium, comprising alternating sand, silt, and clay strata from the Upper Quaternary epoch, is particularly present in the eastern sectors and along major river courses.

Birbhum is geographically positioned at the western edge of the Bengal Basin, separated from the ancient Precambrian Indian Shield by a fault zone indicative of dislocation and cataclasis. Extensional tectonics have led to a complex graben system characterized by tilted and downthrown blocks formed during the Gondwana rifting events, further complicated by intersecting normal faults. The geological structure of Birbhum is chiefly defined by the Rajmahal Trap, an extensive formation of tholeiitic basalt flows from the Late Cretaceous period, resulting from significant igneous activity linked to the Kerguelen hotspot.

4.2.2 Petrographic analysis

Microscopic analyses were performed on rock samples collected from diverse locations in the district. The samples were specifically sourced from areas with elevated fluoride levels in groundwater, facilitating a focused investigation of fluoride behavior. The objective was to attain a clear understanding of the geological context, with a focus on mineral assemblages and their roles in geo-genic fluoride contamination in groundwater. The coordinates of the sampled locations are listed in **Table 4.1.**

Table 4.1: Locations of rock sample collection

Name of the location	Latitude	Longitude
Tantipara Granite	23.8960°N	87.3774°E
Dubrajpur Granodiorite	23.7877°N	87.3744°E
Bakreshwar River Gneiss	23.8870°N	87.3793°E
Jhapartala Granite Gneiss	23.8715°N	87.3682°E
Sukna Pegmatite	23.9835°N	87.5184°E

4.2.3 Geochemical analysis of groundwater

Groundwater quality data from 2016 to 2019 were sourced from PHED, WB. Primary data from approximately 50 wells in fluoride-affected blocks of Birbhum were analyzed. Various analyses were performed to elucidate the ionic characteristics and dominant geochemical processes in the region's groundwater. The following analyses were conducted:

- Gibbs Diagram: Gibbs diagrams serve as an essential geochemical analysis tool for understanding water-geological interactions. They identify dominant processes affecting groundwater chemistry, such as rock-water interaction, evaporation, and precipitation. By plotting major ion ratios, Gibbs diagrams elucidate the sources and mechanisms governing groundwater composition ***(Makri et al., 2019; Changsheng et al., 2022)***. Consequently, they are crucial for water quality assessment and hydrogeochemical evolution insights.
- Piper Trilinear Diagrams: The Piper diagram serves as a key instrument in groundwater geochemical analysis, enabling visualization and interpretation of water sample chemistry. It graphically represents major ionic species, facilitating water type classification and hydrochemical process understanding. The applications of Piper diagrams encompass water quality assessment for domestic and irrigation purposes, geochemical process identification, and large dataset visualization. Furthermore, they are vital for classifying groundwater into hydrochemical facies based on major cation and anion concentrations, aiding in the comprehension of groundwater sample chemistry and origins (***Darwesh et al., 2019; Arulnangai, 2020)***. These diagrams also enable the identification of dominant water types, which may indicate specific geochemical processes or contamination sources ***(Karmegam et al., 2011)***.

The term lineament refers to geological features with linear or curvilinear patterns observable on the Earth's surface through advanced methodologies, which are crucial in structural geology and tectonic analysis. These features often indicate underlying geological structures such as faults and fractures, providing insights into crustal deformation and tectonic evolution ***(Gabrielsen et al., 2024)***. Additionally, lineaments are vital for understanding the Earth's crust's structural characteristics and serve as pathways for hydrothermal fluids and groundwater movement ***(Meles et al., 2024)***. Consequently, studying lineaments is essential for geoscientists to enhance comprehension of the Earth's physical properties and fluid dynamics, aiding in geological processes and resource management. Lineament maps and density maps were created for Birbhum district to assess the presence, orientation, and spatial extent of lineaments for understanding fluoride-contaminated groundwater pathways. GIS platforms facilitated the generation of these maps. The created maps were compared with existing lineament maps from the Bhuvan portal for accurate delineation.

Table 4.2 Generalized stratigraphic succession for the district of Birbhum ***(Mukherjee et al., 1969; Sen et al., 1987)***

Horizon	**Formation**	**Lithology**
Recent		Alluvium
Quarternary/Palaeogene-Neogene	Undifferentiated Quaternary and Paleogene-Neogene deposits	Laterites, lateritic soil, lateritic gravel with petrified wood and china clay
	Unconformity	
Lower Cretaceous/Middle Jurassic	Rajmahal Formation	Rajmahal volcanics (traps) with intercalated sedimentary rocks
	Unconformity	
Lower Jurassic/Upper Triassic	Dubrajpur Formation	Conglomerates, coarse- to medium-grained feldspathic sandstone (occasionally mottled), gray siltstone, mottled shale, and thin coal bands
	Disconformity	
Lower Permian	Barakar Formation	Infraformational conglomerate, fine- to medium-grained sandstone, carbonaceous sandstone with clasts, gray shale fireclay, carbonaceous shale, and coal seams
Lower Permian	Talchir Formation	Greenish sandstone, silt stone, varvites, mottled clay and conglomerates
	Unconformity	
Precambrian	Chotanagpur Granite Gneiss	Granites and granitoid gneisses with pegmatite, quartz veins, and metabasic dykes

4.2.5 Statistical analysis

Statistical analysis is essential for comprehending groundwater hydro-chemical dynamics. It elucidates groundwater geochemistry, revealing chemical characteristics, contamination sources, and hydro-geochemical processes influencing quality. Researchers utilize statistical techniques to analyze complex datasets, identify patterns, and enhance groundwater management decisions. These methods quantify ionic concentration relationships, aiding in the identification of contamination sources, natural processes, and anthropogenic impacts.

Hydro-geochemical studies investigate the complex interactions among water, geological materials, and human activities affecting aquatic chemical composition. These interactions involve multiple processes, such as mineral weathering, ion exchange, redox reactions, and contamination, which collectively influence water quality and ecosystem health. Researchers employ robust statistical tools to quantify variable associations in these relationships. Pearson's correlation coefficient (r) is a fundamental method for revealing linear relationships and understanding hydro-geochemical dynamics.

The Pearson correlation analysis conducted on various geochemical parameters sought to establish a significant relationship between fluoride concentration and other groundwater quality indicators. The correlation coefficient, represented as r and developed by Karl Pearson, quantitatively measures the strength and direction of relationships between two variables, denoted as λ and ξ, and is mathematically expressed as per ***Suleiman et al. (2022).***

$$r = \frac{n(\sum_{i=1}^{n} \xi_i \lambda_i) - (\sum_{i=1}^{n} \xi_i)(\sum_{i=1}^{n} \lambda_i)}{\sqrt{\left[n \sum_{i=1}^{n} {\xi_i}^2 - (\sum_{i=1}^{n} \xi_i)^2\right]}\left[n \sum_{i=1}^{n} {\lambda_i}^2 - (\sum_{i=1}^{n} \lambda_i)^2\right]}$$

Pearson's correlation was conducted with four sets of samples:

- Water samples having Fluoride (F^-) content less than 1.0 mg/L.
- Water samples having F^- content between 1.0 mg/L and 3.0 mg/L
- Water samples having $F^- > 3.0$ mg/L
- With the entire dataset

4.3 Results and Discussions

4.3.1 Petrographic analysis

The microscopic analysis of granite-gneiss samples indicates a mineral assemblage including Quartz, Microcline, Biotite, Apatite, sphene, and minor Chlorite, with Biotite and Apatite being notable Fluorine contributors under alkaline conditions. The mineralogical assessment of Birbhum surface exposures identifies apatite and biotite as the primary fluoride-bearing minerals, while hornblende is of lesser significance. Modal analysis data reveals that the granitic samples consist of approximately 20–30% quartz, 40–45% feldspar, 5–10% apatite, and 20–25% biotite, with trace amounts of chlorite and sphene, indicating a complex mineralogical diversity. Apatite grains display euhedral to subhedral morphologies with variable sizes, some extending up to 200 µm, often located near hydrous minerals at feldspar and quartz interfaces. The apatite grains demonstrate strong associations with biotite and, in some areas, with chlorite, highlighting intricate interactions among these mineral phases.

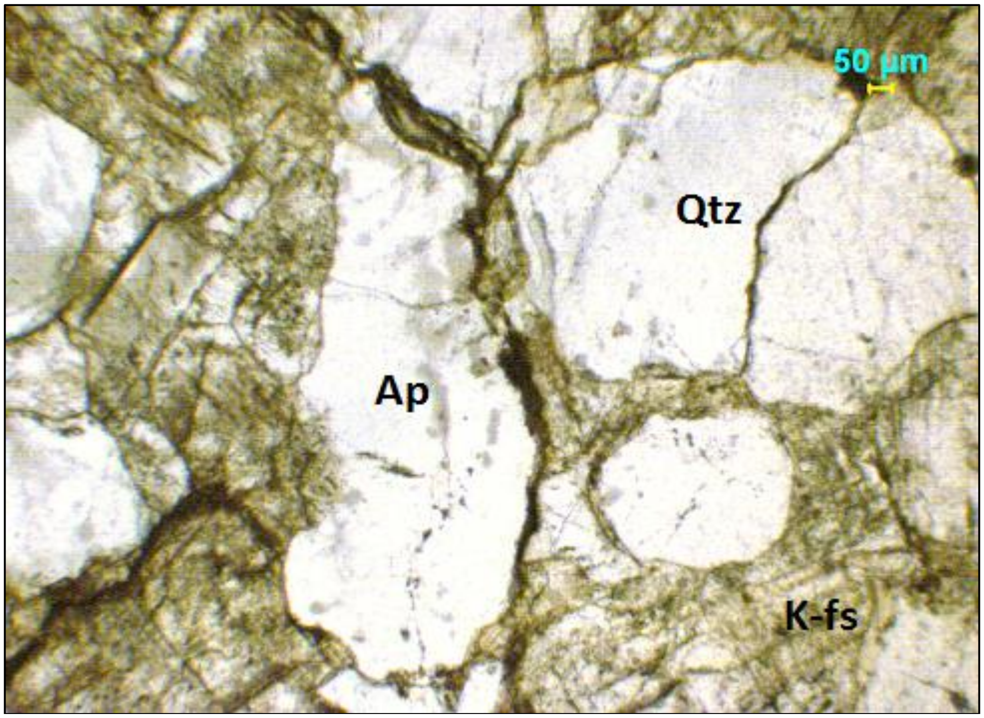


Figure 4.2 Tantipara granite showing an assemblage of Apatite, K-feldspar and Quartz under Plain Polarized Light (PPL).

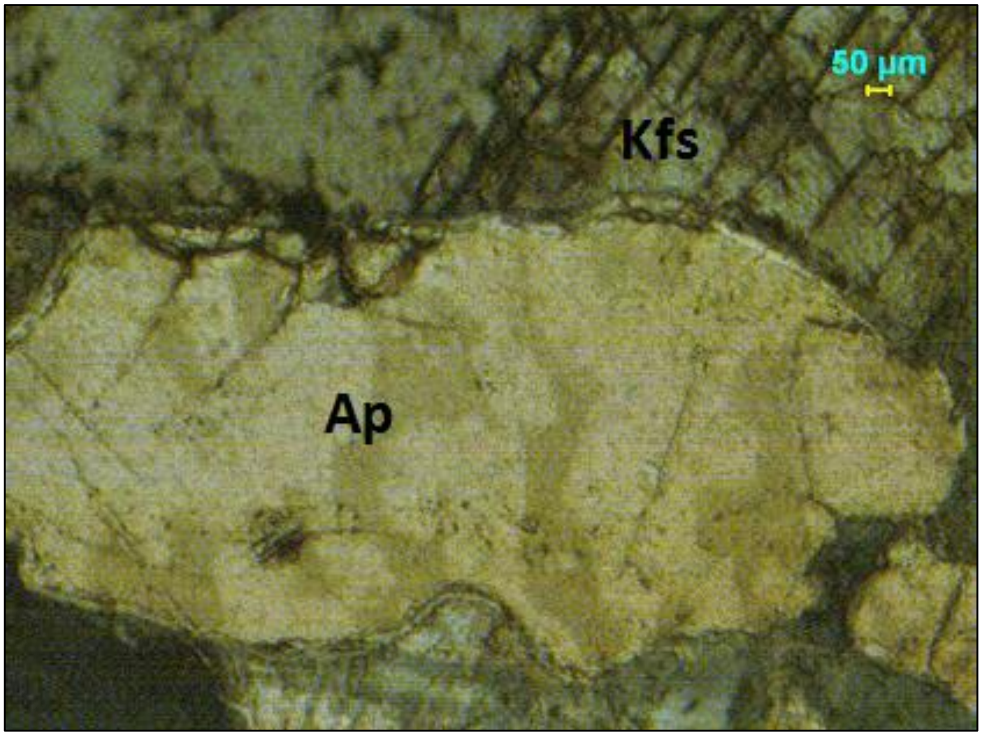


Figure 4.3 Same sample under Cross-Polarised Light (CPL)

4.3.2 Geochemical analysis

The pH values in the study area range from 7.0 to 7.7, with occasional readings below 7 or above 8 under specific conditions. A significant 88% of electrical conductivity (EC) values are below 1000 mg/L, indicating low ionic content in the water. The total dissolved solids (TDS), indicative of salinity, vary from 270 to 714 mg/L. The bicarbonate (HCO_3^-) content is notably high, ranging from 152 to 396 mg/L, indicating an abundance of this anion. Additionally, calcium (Ca^{2+}) levels are consistently lower than sodium (Na^+) in most samples, particularly in those contaminated with fluoride.

4.3.2.1 Gibbs Diagram

Data from PHED were organized by ascending fluoride content for the Gibbs diagram. Points representing fluoride concentrations above 1.5 mg/L were marked in red, while those below this threshold were indicated in green.

The diagram **(Figure 4.3)** illustrates that the primary geochemical influence on groundwater chemistry stems mainly from the interaction of rocks and water, with evaporation playing a minor role. At fluoride concentrations around 1.5 mg/L, most samples reflect the rock-water interaction as the key geochemical influencer, with some exceptions. For samples with fluoride levels under 1.5 mg/L, a predominant influence of rock interaction is observed, though evaporation is noted as a significant factor in some cases, indicating its relevance to

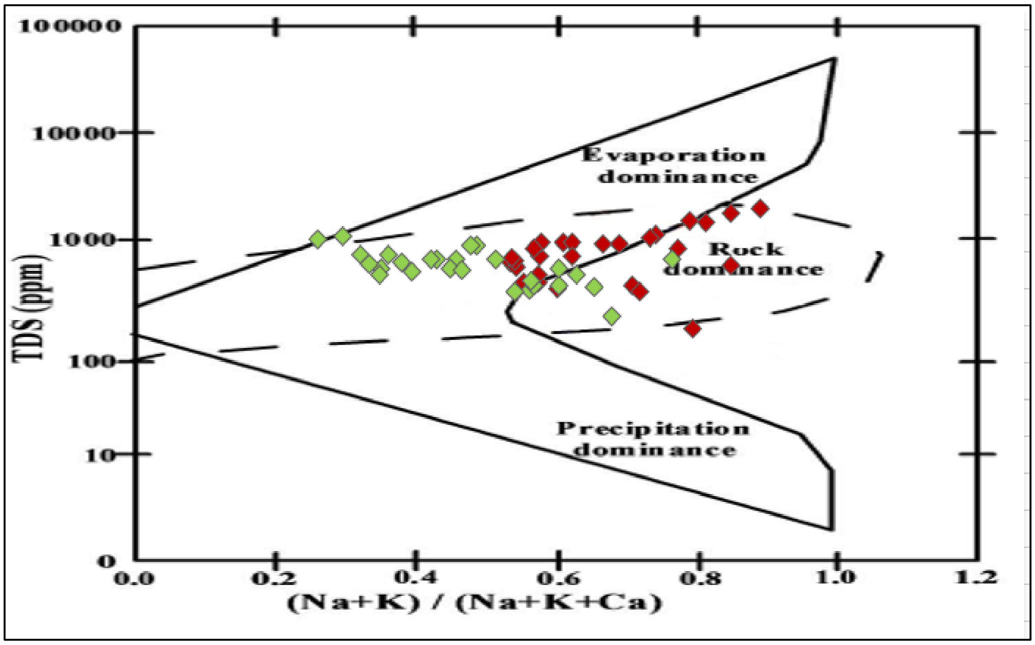


Figure 4.4 Gibbs diagram denoting major geochemical controls on groundwater chemistry. Green colour depict points with F$^-$<1.5 mg/L, red depicting F$^-$>1.5 mg/L

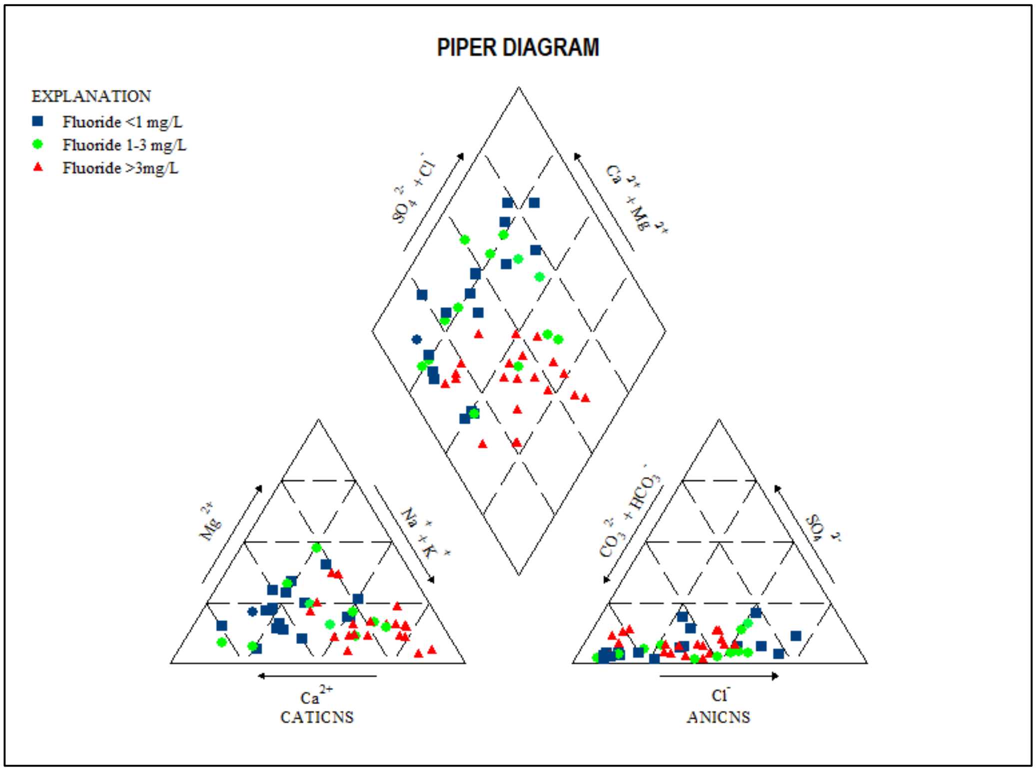


Figure 4.5 Piper trilinear diagram depicting ionic concentrations

groundwater chemistry.

4.3.2.2 Piper Trilinear Diagram

Data was systematically categorized into three groups based on fluoride concentration: less than 1 mg/L, 1 to 3 mg/L, and greater than 3 mg/L. The Piper diagram was created using USGS's GW chart software.

Analysis of the diagram reveals that groundwater samples primarily exhibit Na-HCO3 characteristics, with Sodium (Na^+) as the main cation and bicarbonate (HCO_3^-) as the main anion, especially in samples with fluoride over 3 mg/L. For samples with fluoride between 1 and 3 mg/L, $Na\text{-}HCO_3$ type predominates, while some samples with lower fluoride concentrations exhibit a Ca-HCO3 type profile, with Calcium (Ca^{2+}) as the main cation. Although many samples with fluoride below 1 mg/L show Ca2+ dominance, Sodium (Na^+) and Calcium (Ca^{2+}) are often found in similar amounts. Throughout the fluoride contamination spectrum, bicarbonate (HCO_3^-) is the most prevalent anion.

4.3.3 Lineament Analysis

The analysis of lineaments in the district indicates a significant concentration in the western and northwestern areas, as shown in **Figure 4.5**. Most lineaments trend Northwest to Southeast, with other orientations also recorded. Notably, North-South and Northwest-Southeast lineaments converge near Dubrajpur, close to the Bakreshwar hot springs in the SONATA geothermal province. Clusters of major lineaments are present in key localities such as Nalhati, Rampurhat, Md Bazar, Rajnagar, Suri, and Dubrajpur. The study reveals a complex network of lineaments correlating with well locations affected by high fluoride levels. Major lineaments are primarily found in Granite and Granite Gneiss regions, with few in Basaltic areas. There is a marked absence of major lineaments in the Eastern and Southeastern regions, which are characterized by alluvial deposits.

Lineament density maps represent spatial patterns indicative of geological lineament concentrations. The map indicates dense lineament groupings in geological blocks such as Khoyrasole, Dubrajpur, Suri I, Rajnagar, Md Bazar, Nalhati I, and parts of Rampurhat I, as shown in **Figure 4.6**. Elevated lineament density near the Bakreshwar hot springs underscores its role as a junction for various geological trends. Generally, higher lineament densities correlate with western blocks, which also show increased fluoride concentrations in groundwater, contrasting with lower densities in the eastern blocks. Thus, lineament presence and arrangement are crucial for the mobilization of fluoride-contaminated groundwater.

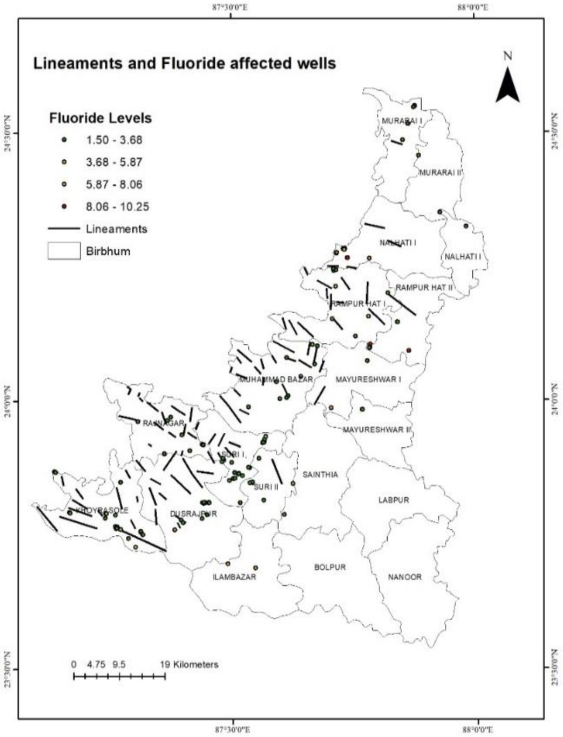


Figure 4.6 Spatial disposition map of lineaments along with fluoride affected wells

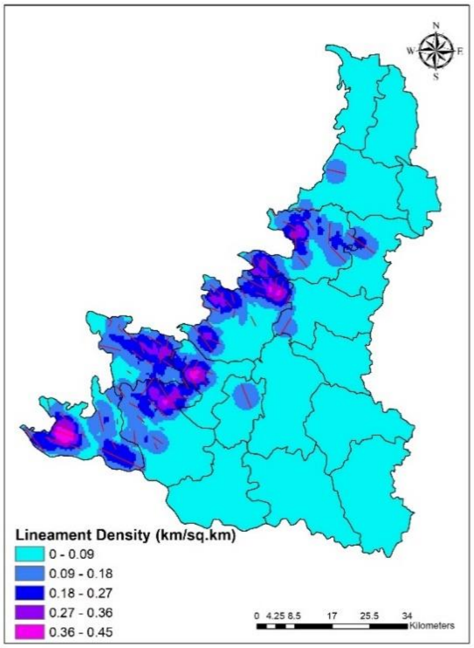


Figure 4.7 Lineament Density Map

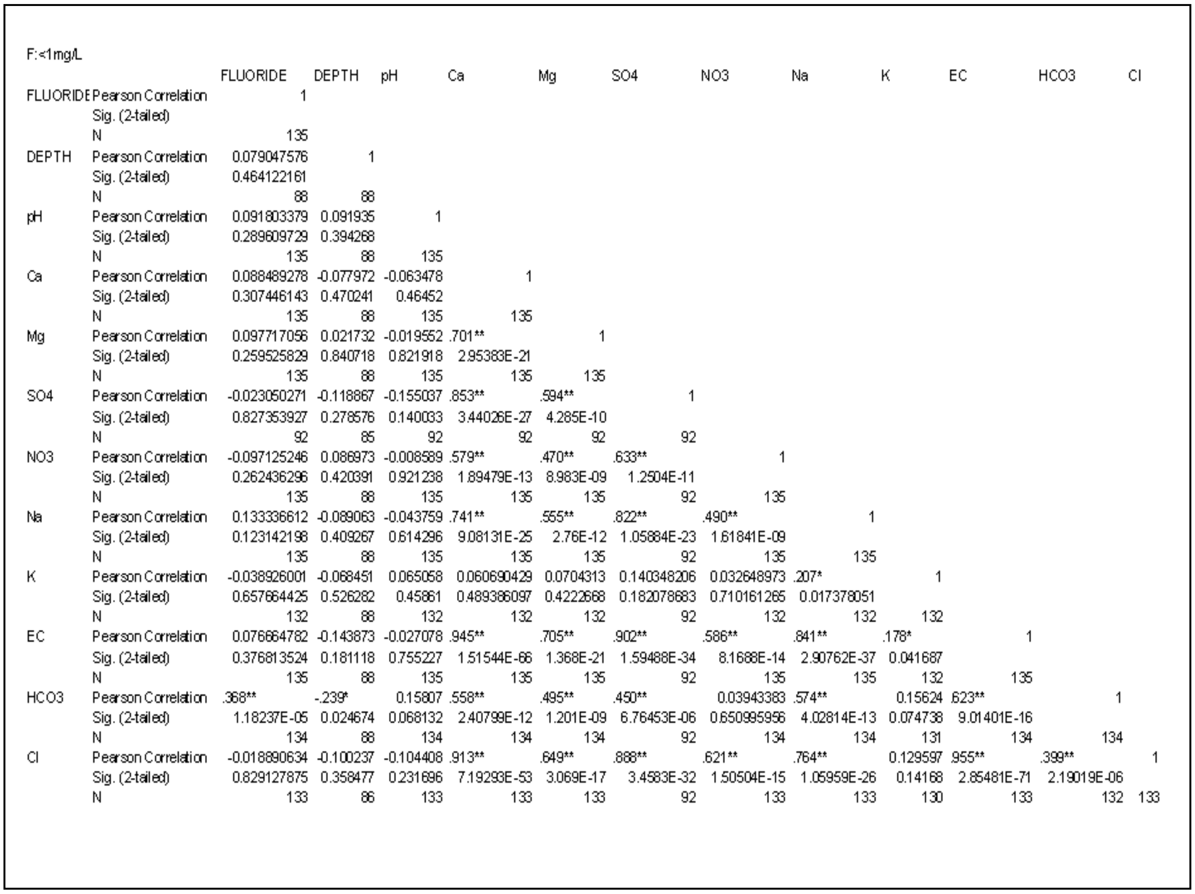
4.3.4 Statistical Analysis

In the tables below, correlations between fluoride and various anions and cations are presented with Pearson Correlation Coefficients, enhancing the understanding of statistical significance in these relationships. Fluoride concentrations below 1 mg/L show a positive correlation with Bicarbonate (HCO_3^-), with a correlation coefficient of 0.368, significant at the 1% confidence level. For fluoride concentrations between 1 and 3 mg/L, a positive correlation with Sulphate (SO_4^{2-}) is observed, with a correlation coefficient of 0.512, significant at the 1% confidence level; negative correlations with Calcium (Ca^{2+}) and Chloride (Cl^-) are also identified, with coefficients of -0.363 and -0.441, significant at the 5% and 1% confidence levels, respectively.

At fluoride concentrations exceeding 3.0 mg/L, no statistically significant correlations are found between fluoride and other variables.

A thorough analysis of the dataset indicates that Fluoride positively correlates with both pH and Sodium (Na^+), with correlation coefficients of 0.272 and 0.536, respectively, both significant at the 1% confidence level, emphasizing the relevance of these associations in the study.

Table 4.3 : Correlation matrix (Pearson correlation) when the value of Fluoride is < 1mg/L



F:<1mg/L

		FLUORIDE	DEPTH	pH	Ca	Mg	SO4	NO3	Na	K	EC	HCO3	Cl
FLUORIDE	Pearson Correlation	1											
	Sig. (2-tailed)												
	N	135											
DEPTH	Pearson Correlation	0.079047576	1										
	Sig. (2-tailed)	0.464122161											
	N	88	88										
pH	Pearson Correlation	0.091803379	0.091935	1									
	Sig. (2-tailed)	0.289609729	0.394268										
	N	135	88	135									
Ca	Pearson Correlation	0.088489278	-0.077972	-0.063478	1								
	Sig. (2-tailed)	0.307446143	0.470241	0.46452									
	N	135	88	135	135								
Mg	Pearson Correlation	0.097717056	0.021732	-0.019552	.701**	1							
	Sig. (2-tailed)	0.259525829	0.840718	0.821918	2.95383E-21								
	N	135	88	135	135	135							
SO4	Pearson Correlation	-0.023050271	-0.118867	-0.155037	.853**	.594**	1						
	Sig. (2-tailed)	0.827353927	0.278576	0.140033	3.44026E-27	4.285E-10							
	N	92	85	92	92	92	92						
NO3	Pearson Correlation	-0.097125246	0.086973	-0.008589	.579**	.470**	.633**	1					
	Sig. (2-tailed)	0.262436296	0.420391	0.921238	1.89479E-13	8.983E-09	1.2504E-11						
	N	135	88	135	135	135	92	135					
Na	Pearson Correlation	0.133336612	-0.089063	-0.043759	.741**	.555**	.822**	.490**	1				
	Sig. (2-tailed)	0.123142198	0.409267	0.614296	9.08131E-25	2.76E-12	1.05884E-23	1.61841E-09					
	N	135	88	135	135	135	92	135	135				
K	Pearson Correlation	-0.038926001	-0.068451	0.065058	0.060690429	0.0704313	0.140348206	0.032648973	.207*	1			
	Sig. (2-tailed)	0.657664425	0.526282	0.45861	0.489386097	0.4222668	0.182078683	0.710161265	0.017378051				
	N	132	88	132	132	132	92	132	132	132			
EC	Pearson Correlation	0.076664782	-0.143873	-0.027078	.945**	.705**	.902**	.586**	.841**	.178*	1		
	Sig. (2-tailed)	0.376813524	0.181118	0.755227	1.51544E-66	1.368E-21	1.59488E-34	8.1688E-14	2.90762E-37	0.041687			
	N	135	88	135	135	135	92	135	135	132	135		
HCO3	Pearson Correlation	.368**	-.239*	0.15807	.558**	.495**	.450**	0.03943383	.574**	0.15624	.623**	1	
	Sig. (2-tailed)	1.18237E-05	0.024674	0.068132	2.40799E-12	1.201E-09	6.76453E-06	0.650995956	4.02814E-13	0.074738	9.01401E-16		
	N	134	88	134	134	134	92	134	134	131	134	134	
Cl	Pearson Correlation	-0.018890634	-0.100237	-0.104408	.913**	.649**	.888**	.621**	.764**	0.129597	.955**	.399**	1
	Sig. (2-tailed)	0.829127875	0.358477	0.231696	7.19293E-53	3.069E-17	3.4583E-32	1.50504E-15	1.05959E-26	0.14168	2.85481E-71	2.19019E-06	
	N	133	86	133	133	133	92	133	133	130	133	132	133

Microscopic analysis of rock samples indicates an assemblage of minerals, notably Quartz, Microcline, Biotite, Apatite, sphene, and minor Chlorite, with Biotite and Apatite being key Fluorine sources under alkaline conditions. Biotite may contain up to 0.91% Fluorine, while Hornblende has about 0.17%, and Fluorapatite can reach 3.72% Fluorine concentrations. Apatite grains exhibit significant associations with Biotite and Chlorite, suggesting potential geochemical interactions among these minerals. The close relationships of hydrous phases with Apatite and myrmekitic textures at feldspar megacryst boundaries are influenced by late-stage fluid activity related to crystallization and pegmatitic intrusions. This fluid activity is pivotal in the distribution and concentration of Fluorine within mineral assemblages (Demartis et al., 2014). Hornblende and Biotite are more susceptible to chemical degradation and leaching by groundwater than the more durable Fluorite. In hydrothermal systems (100–400°C), F^- partitions into fluids due to temperature-related mineral-fluid equilibria. The reaction of biotite demonstrates that HF dissociates, contributing fluoride to the system ***(Zhu & Sverjensky, 1991)***. The studied region, characterized by high evapo-transpiration and a humid subtropical climate with dry spells, anticipates significant weathering and resultant ion influx into circulating water. The consistent chemical composition of water pre and post-monsoon suggests these aquifers lack regular flushing, essential for water quality maintenance. This hydrological condition has led to prolonged water residence times within fluoride-associated aquifers, increasing Fluoride ionic concentrations in the groundwater system.

The groundwater pH ranges from 7.0 to 7.7, indicating an alkaline environment conducive to the solubility of fluoride minerals. This environment enhances the dissolution of fluoride from minerals such as fluorite, biotite, and silicate clays. The release of fluoride ions into the water is intensified by the higher pH ***(Younas et al., 2019; Ali et al., 2023)***. Analysis via the piper diagram (Fig 4.13) reveals that sodium (Na^+) and bicarbonate (HCO_3^-) are the principal ions in Birbhum's groundwater. Groundwater samples exceeding fluoride limits predominantly belong to the Na-HCO_3 type.

Elevated bicarbonate (HCO_3^-) levels (152-396 mg/L) indicate significant weathering of granitic rock, as mineral breakdown releases fluoride into the water, a process further enhanced by high pH ***(Subba Rao et al., 2016; Msengi et al., 2024)***. Plagioclase feldspar, a key granite component, undergoes chemical weathering in the presence of water and CO_2, resulting in the release of dissolved ions including calcium (Ca^{2+}), sodium (Na^+), and bicarbonate (HCO_3^-). This breakdown is driven by hydrolysis, where acidic water (carbonic acid, H_2CO_3) interacts with the mineral structure. Anorthite ($CaAl_2Si_2O_8$) reacts with carbonic acid (H_2CO_3) to yield kaolinite, calcium ions, and bicarbonate; albite ($NaAlSi_3O_8$) weathers to produce sodium ions and bicarbonate alongside kaolinite clay formation.

CHAPTER 5: Spatio - Temporal Variations of Fluoride Contamination and estimation of potential Health Hazards

5.1 Preface

The World Health Organization recommends a fluoride concentration of 1.5 mg/l (WHO, 2006). The Indian Council of Medical Research has set optimal fluoride levels at 1.0 mg/l and maximum levels at 1.5 mg/l ***(ICMR, 1975)***. Fluoride concentrations between 0.6 and 1.2 mg/l in drinking water are beneficial for skeletal and dental health (***; Brindha and Elango, 2011***). Consumption of fluoride-contaminated groundwater primarily poses non-carcinogenic health risks. Prolonged ingestion of such water has been associated with dental and skeletal fluorosis, as well as renal complications like renal failure ***(Brindha and Elango, 2011; Dharmaratne, 2015)***.

Dental fluorosis is a public health issue arising from drinking water with fluoride levels above 1.5 mg/l. Initial manifestations include white spots on enamel, which may progress to brown or black stains ***(Shaji et al., 2024)***. Furthermore, dental fluorosis can cause emotional distress in affected populations due to aesthetic concerns. In India, dental fluorosis is prevalent across 14 states, impacting approximately 150,000 villages ***(Pillai and Stanley, 2002)***, with higher rates in Bihar, Gujarat, Madhya Pradesh, Rajasthan, and Uttar Pradesh. Fluoride levels exceeding 4–8 mg/l in drinking water correlate with skeletal fluorosis development. Symptoms include increased bone density, joint pain resembling arthritis, joint stiffness, spinal curvature, and excessive bone growth. Individuals with skeletal fluorosis may experience muscle weakness, limb tingling, bone structure changes, and a rigid spine, with potential for abnormal growth leading to paralysis and neurological issues (***Srivastava and Flora, 2020)***. Fluoride levels surpassing 10 mg/l can result in severe skeletal fluorosis ***(Boyle and Chagnon, 1995)***. This condition is categorized into mild, moderate, and severe stages based on severity ***(Mishra et al., 2020)***. Excessive fluoride levels above 8 mg/l can also cause osteosclerosis. Alarmingly high fluoride concentrations (>10 mg/l) have been detected in groundwater, such as in Bakreshwar hot springs, potentially leading to serious fluorosis. Such exposure can negatively affect multiple organ systems, including neurological, hepatic, and renal functions. Instances of severe fluorosis have been reported in regions of Asia and Africa (Rasool et al., 2018). Neurological issues have been noted among school-aged children worldwide, highlighting a significant concern related to fluoride exposure.

Numerous studies have examined the health risks associated with excessive fluoride levels in drinking water ***(Eminke et al., 2018; Yin et al., 2021)***. The assessment of non-carcinogenic risk (NCR) from fluoride generally utilizes the Hazard Quotient (HQ), with methodologies standardized by the USEPA in 2011. The Total Hazard Quotient (THQ) aggregates individual HQs from oral and dermal exposure, with values exceeding 1 indicating potential danger from water consumption, while values below 1 suggest safety. Furthermore, this assessment is stratified by age to enhance the evaluation of health impacts across different demographic groups.

The United Nations' sustainable development goals promote equitable access to water resources and sanitation for all. In this regard, understanding the spatio-temporal variations in fluoride concentrations in groundwater is crucial for assessing the severity of related health risks ***(Podgorski and Berg, 2022)***. A thorough understanding of these mechanisms can aid in formulating long-term strategies and interventions to mitigate health risks within socio-economically disadvantaged populations.

5.2 Methodology

5.2.1 General

Secondary water quality data on fluoride contamination were sourced from the Public Health Engineering Department of West Bengal for 2016-2019 and classified by monsoon periods. These data were analyzed to discern fluoride trends in Birbhum using geo-spatial analysis tools. Rainfall data were similarly gathered from Climate Research Unit-Time Series and analyzed for correlations with fluoride levels through GIS tools, highlighting the influence of precipitation on groundwater fluoride mobilization. Health Risk Analyses were performed using PHED data with USEPA standards, and GIS maps were generated for spatial risk assessments. Primary data served to validate findings and ensure the accuracy of identified spatial patterns, revealing seasonal impacts on fluoride levels and associated health risks.

5.2.2 Spatio-temporal analysis

Groundwater quality data concerning fluoride concentration in Birbhum were obtained from PHED for 2016-2019 to analyze spatio-temporal variations. The data were categorized by monsoon periods, and over 200 groundwater samples were sorted for each year and season. Geo-spatial maps were generated employing the Inverse Distance Weighting (IDW) method, a recognized geospatial interpolation technique for predicting unmeasured attributes. This method assigns weights to sampled data based on proximity, allowing estimation of values at unsampled sites while considering geographical data characteristics. Spatial analysis tools approximated areas with excess fluoride in groundwater for both pre and post-monsoon data to assess contamination extent and temporal variations. Similarly, rainfall data from Climate Research Unit-Time Series for 2016-2019 were analyzed to produce rainfall maps via GIS platforms, with CRU-TS data converted to ASCII for compatibility, utilizing the IDW method for map creation.

5.2.3 Health Risk Assessment

A Health Risk Assessment (HRA) was performed for Birbhum district utilizing data from PHED, WB spanning 2016 to 2019, separated into pre and post-monsoon periods for seasonal analysis.

Non-carcinogenic HRA was executed following USEPA (2004) methodology, focusing on the Estimated Daily Intake (EDI) from groundwater with excessive F^- levels via oral (EDI_{oral}) and dermal (EDI_{dermal}) routes. Primary calculations involve determining individual Hazard Quotients (HQ) for both routes, culminating in a Total Hazard Quotient (THQ), which aggregates the individual HQs to reflect overall risk. THQ values ≤ 1 suggest no health risk, while values >1 indicate potential adverse health risks, with variations according to age groups due to differing standard values for adults and children.

The process and parameters are outlined below:

$\mathrm{EDI}_{\mathrm{ORAL}} = (\mathrm{C} \times \mathrm{IR} \times \mathrm{EF} \times \mathrm{ED}) / (\mathrm{BW} \times \mathrm{AT})$

$\mathrm{EDI}_{\mathrm{DERMAL}} = (\mathrm{C} \times \mathrm{SA} \times \mathrm{KP} \times \mathrm{F} \times \mathrm{ETS} \times \mathrm{EF} \times \mathrm{ED} \times 10-3) / (\mathrm{BW} \times \mathrm{AT})$

The Hazard Quotient (HQ) calculations are as follows:

$\mathrm{HQ}_{\mathrm{ORAL}} = \mathrm{EDI}_{\mathrm{ORAL}} / \mathrm{RfD}_{\mathrm{ORAL}}$

$\mathrm{HQ}_{\mathrm{DERMAL}} = \mathrm{EDI}_{\mathrm{DERMAL}} / \mathrm{RfD}_{\mathrm{DERMAL}}$

$\mathrm{THQ} = \mathrm{HQ}_{\mathrm{DERMAL}} + \mathrm{HQ}_{\mathrm{ORAL}}$

Table 5.1: Health Risk Assessment Parameters (*Williams et al., 2000; EPA 2004; Wu et al., 2011, IRIS 2016*)

Parameters	Unit	Value
Ingestion Rate (IR)	1/day	Children: 0.89 Adults: 2.00
Exposure frequency (EF)	day/year	350
Exposure duration (ED)	year	Children: 6 Adults: 30
Averaging time (AT)	days	Children:2100 Adults: 10500
Dermal permeability constant (KP)	cm/h	0.001
Fraction of skin in contact with water (F)	Nil	0.4–0.9
Body weight (BW)	Kg	Children: 15 Adults: 70
Skin surface area (SA)	cm^2	Children:7422 Adults: 18182
Exposure time in the shower (ETS)	h/day	0.13
Oral reference dose ($\mathrm{RfD}_{\mathrm{ORAL}}$)	mg/kg/day	0.06
Dermal reference dose ($\mathrm{RfD}_{\mathrm{DERMAL}}$)	mg/kg/day	0.06

The obtained THQ values facilitated the creation of geo-spatial maps. These maps were developed utilizing the IDW method within GIS frameworks. They were categorized into five distinct classes based on THQ values to elucidate the spatio-temporal distribution of health risks and pinpoint potential hotspot regions. Distinct maps were generated for both adult and pediatric populations. Spatial analysis tools were employed to estimate the spatial extent of vulnerable areas and quantify associated risks.

Moreover, the HRA maps underwent validation using primary data gathered from over fifty sites across four blocks in the Birbhum district in 2019, which were similarly categorized into pre and post-monsoon periods. These sites were integrated into the HRA maps to substantiate the validation process.

5.3 Results and Discussions

5.3.1 Spatio-temporal variations

The analysis of groundwater fluoride maps from 2016 to 2019 indicates consistently high fluoride levels in the western and southwestern districts. Specifically, areas within Dubrajpur, Suri I, Suri II, Rajnagar, Khoyrasole, and Md Bazar are characterized by significant fluoride concentrations. Notably, regions in Nalhati I and Rampurhat I also exhibit high fluoride levels. Conversely, eastern districts like Bolpur, Labpur, and Nanoor show fluoride concentrations below the WHO threshold of 1 mg/L. Additionally, the Bakreshwar – Tantoloi geothermal area in Dubrajpur has fluoride levels exceeding 14 mg/L. It is important to recognize that the spatial extent of areas with fluoride above 1.5 mg/L varies seasonally, with greater areas pre-monsoon and reduced areas post-monsoon, reflecting a mean decrease of 7.96 percentage points.

Table 5.2 : Spatial extent of areas with F>1.5mg/L (in percentage)

Year	Pre-Monsoon (%)	Post- Monsoon (%)	Change
2016	31.36	25.55	7.81
2017	28.78	21.23	7.55
2018	30.34	22.36	7.98
2019	29.08	20.45	8.53

Table 5.2: Mean values of fluoride concentration in groundwater

Year	Mean Pre-Monsoon Value (mg/L)	Mean Post-monsoon value (mg/)	Change (%)
2016	0.98	0.830	18.07
2017	1.09	0.89	22.47
2018	0.96	0.78	18.75
2019	0.71	0.58	22.41

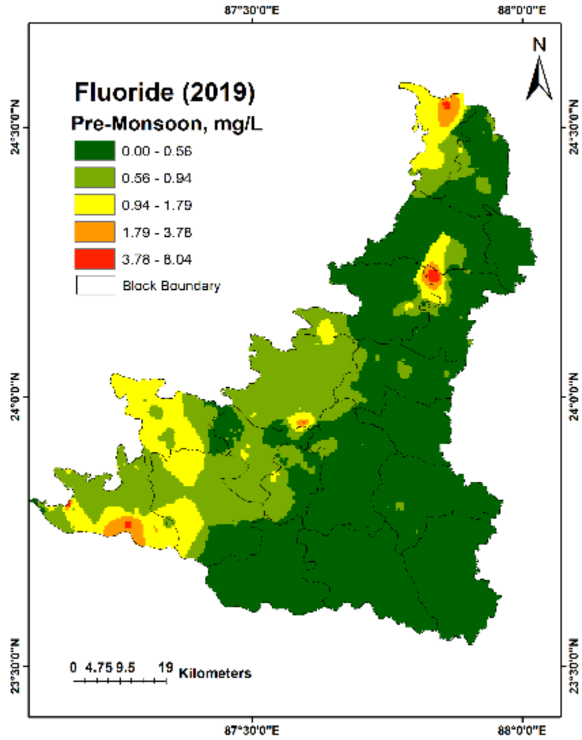


Fig 5.1: Spatial disposition of fluoride concentrations in groundwater, pre-monsoon 2018

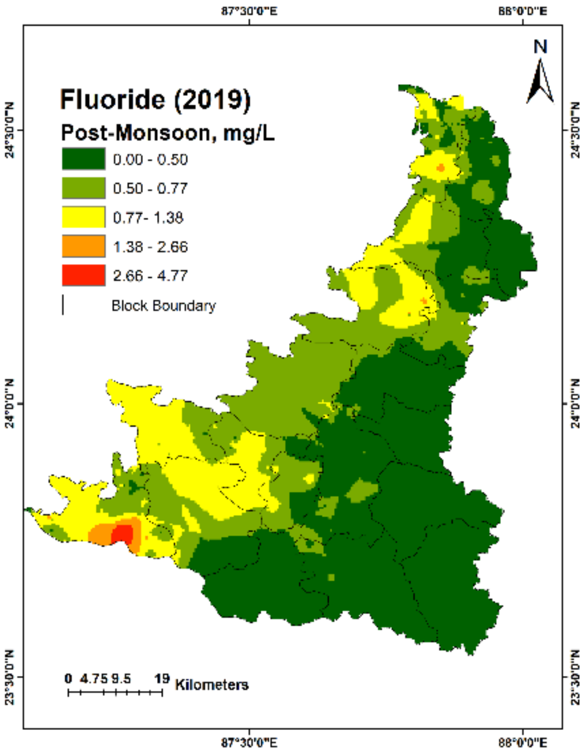


Fig 5.2: Spatial disposition of fluoride concentrations in groundwater, post-monsoon 2018

5.3.2 Health Risk Analysis

Health risk assessments by USEPA indicate a significant portion of Birbhum's residents face health risks from high fluoride levels in groundwater. High Total Hazard Quotients (THQ) have been observed in both children and adults, presenting a public health issue. Specifically, areas like Khoyrasole and Rajnagar show alarming THQ values, with adults reaching 7.34 and children exceeding 15. A THQ above 1 signifies hazardous conditions for both demographics. Comparative analyses reveal that children exhibit higher THQ values than adults. Geospatial risk assessment maps indicate a more pronounced spatial distribution of risks for children, denoting greater susceptibility. A detailed comparison illustrates a significant disparity in risk exposure between children and adults. Additionally, the geographical extent of high-risk areas declines with seasonal changes. High-risk zones for fluoride-contaminated groundwater fluctuate seasonally, with greater prevalence pre-monsoon and reduced post-monsoon. While variations in THQ values are evident, a consistent decline in high-risk areas has been documented. The adult population shows a mean difference of 6.67 percentage points in spatial coverage, while the child population shows a difference of 4.91 percentage points.

Table 5.3: Spatial extent of high health risk zones THQ>1 (in percentage)

	THQ Adult			THQ Child		
Year	Pre-Monsoon(%)	Post-Monsoon(%)	Difference	Pre-Monsoon(%)	Post-Monsoon(%)	Difference
2016	11.63	5.02	6.61	35.23	28.67	4.56
2017	14.38	7.23	7.55	36.68	32.02	4.66
2018	12.88	5.14	7.74	31.14	24.63	6.51
2019	7.73	2.08	5.65	25.64	19.66	5.98

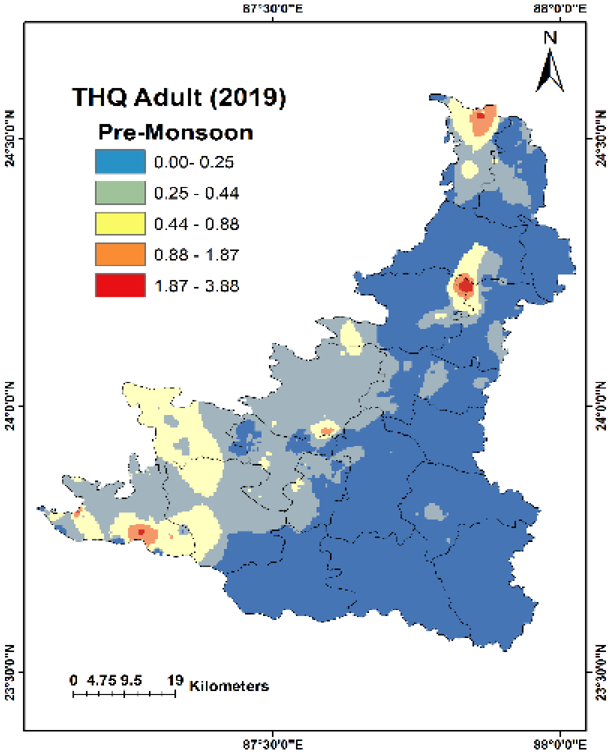


Fig 5.3: Spatial disposition of health risks in adults, pre-monsoon 2019

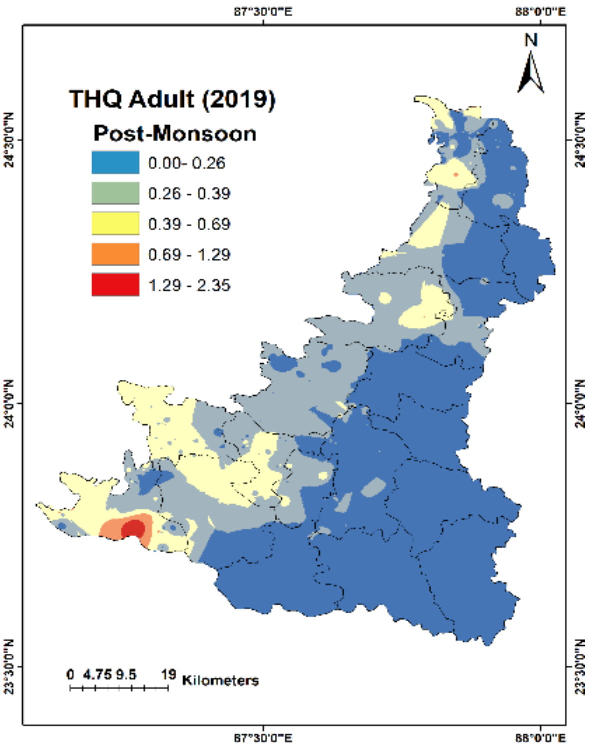


Fig 5.4: Spatial disposition of health risks in adults, post-monsoon 2019

The distribution of fluoride contamination in groundwater shows a uniform pattern, particularly in the western and south-western administrative districts with higher fluoride levels exceeding legal limits. The regions of Durbajpur, Suri I and II, Rajnagar, Khoyrasole, and Md. Bazar exhibit consistently elevated fluoride concentrations compared to other areas. Geological analysis indicates that the western and south-western districts are primarily composed of Archean Chotanagpur Granite-gneiss formations. In these granitic aquifers, fluoride enrichment occurs due to leaching of fluoride-bearing minerals, intensified by prolonged rock-water interactions, as evidenced by ***Das and Nag (2017)*** and ***Thapa et al. (2020)***. In contrast, certain areas within Rampurhat I & II show sporadic higher fluoride levels due to older alluvial deposits influenced by clay layers that enhance fluoride concentrations through ion-exchange and adsorption ***(Thapa et al., 2020; Mukherjee and Singh, 2020)***. Conversely, lower fluoride concentrations are evident in southern and south-eastern regions adjacent to Burdwan and Murshidabad, attributed to their geological composition of newer alluvial deposits. The lack of fluoride-bearing minerals in these areas indicates a minimal geological contribution to fluoride enrichment in groundwater supplies. The highest fluoride concentrations in groundwater are found at the Bakreshwar hot springs. This hot spring complex, located at the eastern end of the SONATA Geothermal province, is characterized by its high fluoride levels. The Bakreshwar hot springs are situated near the SONATA and ONGC fault systems, leading to highly fractured basement rock formations that enable groundwater circulation through deep granitic aquifers, as noted by ***Mukherjee et al. (2020)***. A significant geothermal gradient and high heat flow rate have been recorded, with temperatures reaching approximately 200°C at a depth of 3 kilometers. This thermal environment facilitates the dissolution of fluoride from source minerals within the deep confined aquifers. Moreover, the groundwater's extended residence time enhances the dissolution of fluoride-bearing minerals, influenced by complex rock-water interactions in the Granitic aquifers.

6. Remedial Measures

6.1 Preface

Excessive fluoride concentrations above 1.5 mg/L are known to cause severe health issues, particularly in dental and skeletal systems ***(Podgorski and Berg, 2022)***. This is especially pertinent for children, who are more vulnerable to fluoride's adverse effects ***(Liu et al., 2023; Zhang et al., 2024)***. The previous chapter revealed that about 31% of Birbhum district is highly susceptible to fluoride exposure in children pre-monsoon, decreasing to 26% post-monsoon. While the risk for adults diminishes, approximately 11% and 5% of the district remain classified as high-risk areas during pre-monsoon and post-monsoon, respectively. Significant fluoride contamination exists in extensive western and south-western block regions, necessitating urgent, comprehensive remedial strategies to address groundwater fluoride consumption risks. Various solutions have been proposed for fluoride removal, primarily focusing on two techniques:

- De-fluoridation technologies
- Use of alternative water sources

De-fluoridation techniques aim to systematically eliminate fluoride ions from water, reducing concentrations below permissible health standards. These processes often involve chemical coagulants and adsorptive materials, or advanced methods such as electro-coagulation, electro-dialysis, and reverse osmosis, to effectively lower fluoride levels. The subsequent section includes a comprehensive table summarizing the various fluoride removal methods **(Table 6.1).**

The utilization of alternative water sources presents an economical, community-focused substitute for conventional de-fluoridation techniques. Rainwater Harvesting (RWH) represents a significant initiative in this context. RWH serves as a vital approach to combat water scarcity, especially in arid and semi-arid zones. This method entails the collection and preservation of rainwater for diverse applications, enhancing water security, mitigating flood risks, and addressing climate change. The practice is increasingly recognized for its potential to furnish a sustainable water supply and contribute to environmental preservation ***(Sakati et al., 2024; Qader et al., 2024).*** RWH systems have been systematically and extensively implemented in various rural areas across multiple nations, including Brazil, China, New Zealand, Australia, Singapore, and Thailand, reflecting their acknowledged significance in effective water resource management. Brazil notably excels as the leading nation in the adoption and implementation of rainwater harvesting practices at a large scale, showcasing its dedication to sustainable water management. Moreover, countries with abundant water resources, such as Germany, have proactively adopted rainwater harvesting strategies, indicating a widespread acknowledgment of the value and necessity of these systems across differing geographical settings. In India, the integration of rainwater harvesting techniques primarily aims to alleviate flooding impacts while simultaneously enhancing groundwater recharge, addressing both immediate and long-term water management issues. Tamil Nadu is recognized as the first Indian state to mandate rooftop rainwater harvesting structures in all residential buildings, thereby establishing a benchmark for water conservation initiatives ***(Vasudevan and Natarajan, 2021)***. Additionally, several other Indian states, including Karnataka, Andhra Pradesh, Rajasthan, Gujarat, Himachal Pradesh, and others, have participated in the deployment of rainwater harvesting systems, further advancing national efforts to enhance water resource management.

The National Water Policy (NWP), which was established in the year 2012 by the Ministry of Water Resources, Govt. of India, emphasizes the imperative necessity for the highly efficient and strategic utilization of the nation's water resources in a manner that promotes sustainability and conservation. In pursuit of this objective, the Central Groundwater Board has embarked on comprehensive and extensive mapping exercises that have successfully identified approximately 448,760 square kilometres of land deemed suitable for the implementation of artificial recharge methods, within the broader context of a total geographical area encompassing 3,287,263 square kilometres across the entirety of the country, thereby facilitating the effective planning and execution of targeted rainwater harvesting initiatives ***(Ministry of Water Resources, Govt. of India,.2012)*** Moreover, states such as Punjab and Tamil Nadu have demonstrated remarkable proactivity by providing financial subsidies to farmers who adopt and implement rainwater harvesting systems, and as a result, these states are not only enhancing agricultural productivity but also serving as exemplary models of sustainable agricultural practices that can be emulated by others. In the state of West Bengal RWH policies, christened "*Jal dharo, Jal bharo",* have been initiated by the Govt. of West Bengal. It is the part of a broader strategy to enhance sustainable water management practices and ensure water security for agricultural and domestic use.

The initiative focuses on rainwater harvesting, groundwater recharge, and the construction of water storage facilities to mitigate the effects of drought and water scarcity, particularly in the western districts of West Bengal, such as Birbhum ***(Biswas et al.,2022)***. Therefore, detailed geo-spatial analysis has been conducted in the study to identify potential sites for conduction of Rain Water Harvesting in the district of Birbhum. This method has been identified as the fittest choice as the primary amelioration strategy for offsetting health risks associated with consumption of groundwater having above the statutory levels of fluoride.

Table 6.1. Popular methods of defluoridation of water

Removal method	**Capacity dose**	**Working pH**	**Interferences**	**Advantages**	**Disadvantages**	**Relative cost**
Precipitation						
Alum (aluminum sulfate)	150 mg/mgF	Non-specific	_	Established process	Sludge produced, treated water is acidic, residual Al present	Medium-high
Lime	30mg/mgF	Non-specific	_	Established process	Sludge produced, treated water is alkaline	Medium-high
Alum+lime (Nalgonda)	150mg alum+ 7mg lime/mgF	Non-specific, optimum 6.5	_	Low-tech, established process	Sludge produced, high chemical dose, residual Al present	Medium-high
Gypsum + fluorite	5 mg gypsum + <2 mg fluorite/mgF	Non-specific	_	Simple	Required trained operators, low efficiency, high residual Ca, SO_4	Low - medium
Calcium chloride	3 mg $CaCl_2$/mgF	6.5-8.0	_	Simple	Requires additional flocculent (e.g., $FeCl_3$)	Medium-high
Adsorption/ion exchange						
Activated carbon	Variable	<3	Many	_	Large pH changes before and after treatment	High
Plant carbon	300 mgF/kg	7	_	Locally available	Requires soaking in potassium hydroxide	Low - medium
Zeolites	100 mgF/kg	Non-specific	_		Poor capacity	High
Defluoron 2	360 gF/m^3	Non-specific	Alkalinity		Disposal of chemicals used in resin regeneration	Medium
Clay pots	80 gF/kg	Non-specific	_	Locally available	Low capacity, slow	Low
Activated alumina	**1200 gF/m^3**	**5.5**	**Alkalinity**	**Effective, well-established**	**Needs trained operators, chemicals not always available**	**Medium**
Bone	900gF/m^3	>7	Arsenic	Locally available	May give taste; degenerates, not universally accepted	Low
Bone char	1000gF/m^3	>7	Arsenic	Locally available, high capacity	Not universally accepted; may give adverse color, taste	Low
Other						
Electrodialysis	High	Non-specific	Turbidity	Can remove other ions; used for high salinity	Skilled operators; high cost;	Very high
Reverse osmosis	High	Non-specific	Turbidity	Can remove other ions; used for high salinity	Skilled operators; high cost	Very high

After Kashyap et al., (2021); Karunanithi et al., (2023)

6.2 Methodology

6.2.1 Data

Table 6.2: Different influencing parameters and their sources

Sl No	Rainwater Harvesting Influencing Factors	Data Sources	Description
1	Rainfall	CRU TS Data (Climate Research Unit Time Series Data) (1991-2023) https://crudata.uea.ac.uk/cru/data/hrg/	Resolution 0.5×0.5
2	Slope	SRTM DEM https://earthexplorer.usgs.gov/	Resolution 30 meters
3	Aspect		
4	Drainage Density		
5	Distance From River		
6	Land use and Land cover	Landsat-8 https://earthexplorer.usgs.gov/	Resolution 30 meters
7	NDVI		
8	Soil	National Bureau of Soil Survey and Land Use Planning	

In order to generate rain water harvesting map, it is important to collect and process several input data from various sources for further geo-spatial assessments. Table 6.2 gives detailed information on the different types of data collected and their relevant sources, that are pertinent in identifying areas fit for rain water harvesting. For the purpose of creating surface water maps, to assess the usability of surface water bodies such as ponds etc. for rainwater harvesting, LANDSAT 8 data were used. Unsupervised classification methodology was applied to create the final surface water maps. Surface water bodies above >0.1 hectares were mapped separately.

6.2.2 Factors influencing Rainwater Harvesting (RWH)

Critical factors affecting the feasibility of RWH are outlined below:

- Rainfall: Rainfall significantly impacts the efficacy and potential of RWH systems, influencing water collection and storage volumes, which affect their economic viability.
- Slope: Slope is a vital geospatial parameter affecting hydrology and geomorphology, critical for understanding water flow and natural disaster risks
- Aspect: Aspect refers to the land surface orientation and is crucial for analyzing environmental flow directions.
- Drainage Density: In geospatial analysis, drainage density quantifies the total length of drainage channels per watershed area, serving as a vital indicator of hydrological characteristics, influencing erosion and ecological health.
- Distance from River: Distance to the river is a significant factor in assessing the feasibility of rainwater harvesting projects, typically measured in meters.
- Land Use Land Cover (LULC): LULC is an essential tool for monitoring land use changes, employing Remote Sensing (RS) and GIS methodologies.
- NDVI: The Normalized Difference Vegetation Index (NDVI) is a critical metric for assessing vegetation health and land cover changes through satellite imagery, reflecting the density and health of vegetation. NDVI values range from -1 to 1, with higher values indicating healthier vegetation, and it plays a key role in agriculture, environmental monitoring, and land management.
- Soil Texture: Soil texture is a pivotal variable in rainwater harvesting, influencing soil's infiltration, retention, and runoff characteristics essential for effective water resource management. The soil's ability to retain or facilitate water percolation affects RWH system design, with varying textures impacting practice viability

6.2.3 Analytical Hierarchy Process (AHP)

The Analytical Hierarchy Process, developed by Thomas L. Saaty in 1980, has evolved into a prominent multi-criteria decision-making method widely cited in academic literature (. This methodology excels in addressing complex problems across various disciplines. Unlike traditional statistical methods, AHP evaluates both individual and collective factor impacts for comprehensive decision analysis. AHP is a systematic approach for organizing and analyzing complex decisions, employing pairwise comparisons to establish priorities for main goals. It enables the assessment of criteria across hierarchical levels, aiding researchers in evaluating geosystem factors and visualizing landscape variability ***(Cherkashin & Frolov, 2023)***. In geo-spatial analysis, AHP serves as a structured framework for prioritizing criteria and sub-criteria for site selection, assigning weights based on importance (. The AHP framework comprises four stages: hierarchical organization of issues, systematic data arrangement through pairwise comparisons, assessment of individual parameter priority weights, and verification of evaluation consistency ***(Chaulagain et al., 2023; Wubalem et al., 2021)***. This study incorporates eight parameters for identifying rainwater harvesting areas, including rainfall, soil texture, LULC, NDVI, slope, aspect, drainage density, and distance from the river.

6.3 Results and Discussions

6.3.1 Rainwater Harvesting factors

In the present study, variables including NDVI, Rainfall, Drainage Density, and Aspect demonstrate an inverse relationship with rainwater harvesting, as elevated values of these parameters signify a diminished feasibility of rainwater harvesting as a method of amelioration. Conversely, variables such as distance from river and Slope exhibit a positive correlation with rainwater harvesting, indicating that increased values of these factors correspond to an enhanced applicability of rainwater harvesting.

6.3.2 Rainwater Harvesting map

The finalized rainwater harvesting map was categorized into five principal classes, each representing distinct levels of rainwater harvesting potential, which range systematically from very low to very high classifications. Notably, it was observed that approximately 23.27% of the overall study area was classified within the very low category, while 26.97% of the area was categorized as low, 26.3% of the regions exhibited moderate values, 16.65% of the area fell into the high class value, and a mere 8.80% of the region was classified within the very high values. It has been discerned that the northern and western sections of the district exhibit a higher suitability for rainwater harvesting practices, primarily attributable to the lower rates of rainfall and gentler slopes that characterize these regions, whereas the areas experiencing elevated precipitation levels combined with steep slopes contribute to the designation of the low harvesting zones. Thus, the potential for rainwater harvesting demonstrates a significant variation, with a marked suitability evident in the northern and western quadrants, juxtaposed against a diminished suitability observed in the southern and eastern directions.

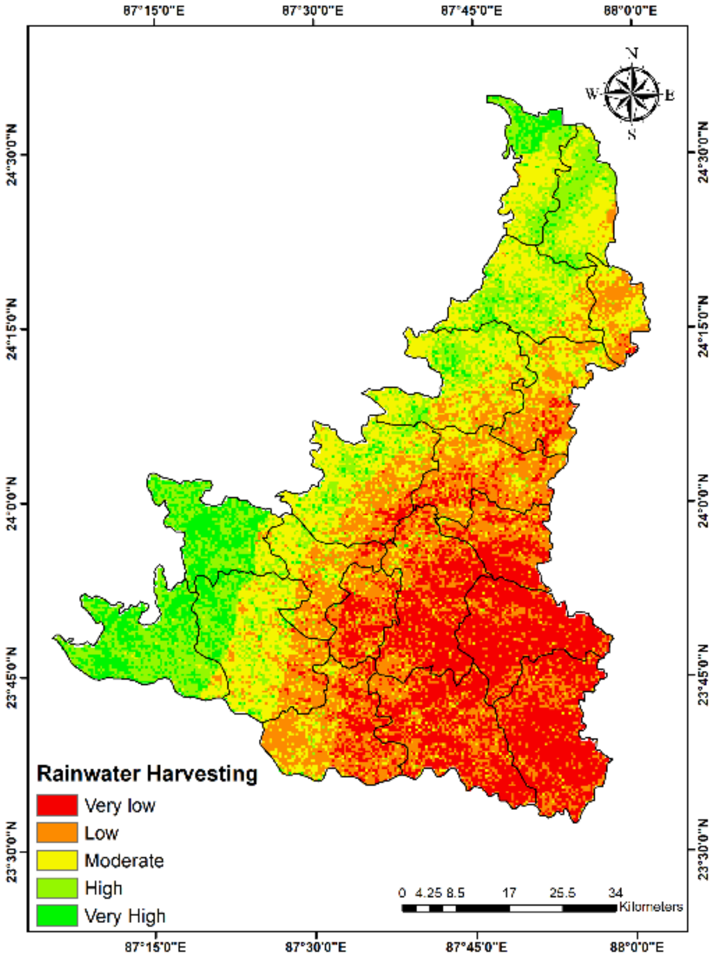


Fig. 6.1 Rainwater Harvesting (RWH) map

In response to the challenges posed by fluoride contamination, a variety of technologies have been developed and implemented with the objective of defluoridating water supplies to render them safer for human consumption. Nonetheless, it is important to note that while these technological solutions demonstrate a high level of efficiency in removing fluoride, they are accompanied by a range of significant challenges and complications that must be carefully considered. These challenges include the requirement for operations that are often prohibitively expensive, the necessity for specialized technical expertise to implement and maintain these systems, as a substantial number of these technologies necessitate ongoing monitoring and maintenance, alongside a continuous need for raw materials to sustain their functionality, among various other logistical issues. Furthermore, many of these defluoridation systems demand substantial infrastructural support, such as a reliable and consistent electricity supply and access to appropriate laboratory facilities for testing and analysis. Additionally, it is crucial to recognize that several of the existing defluoridation technologies generate negative environmental impacts through the production of sludge or wastewater that contains alarmingly high concentrations of fluoride, thereby creating further complications. The disposal of these hazardous wastes presents its own set of challenges, as improper handling and disposal of such byproducts could potentially lead to the very contamination issues that these technologies were originally designed to remedy. Moreover, envisioning the widespread adoption of defluoridation technologies as a broadly accepted remedial strategy within the Birbhum district poses considerable difficulties, not only because of the extensive geographical range of the fluoride risk zones but also due to the socio-economic characteristics of the affected population. In contrast to these complex technological solutions, water management-based remedial approaches, particularly Rain Water Harvesting (RWH), present a much simpler method of managing water resources, as they do not necessitate significant technical expertise or substantial capital investment. Consequently, these methods are inherently more feasible for implementation on a broader scale, especially at the grassroots level where local communities can engage directly.Therefore, in light of the pressing concerns regarding water quality and public health, extensive investigations have been undertaken to critically assess the viability and applicability of various innovative water management technologies, with a particular and focused emphasis placed on Rain Water Harvesting (RWH) as a principal and potentially transformative strategy for effectively addressing the significant health risks that are associated with fluoride exposure within the population at large. A comprehensive geo-spatial analysis aimed at determining the feasibility of implementing RWH in the district of Birbhum reveals that approximately 25% of the spatial area within the district may be categorized as highly to very highly conducive to the establishment of such systems, while an additional 24% of the area is identified as being moderately conducive.In summary, the practice of rainwater harvesting emerges as a highly promising alternative source of water that could be harnessed extensively within the district of Birbhum to address local water scarcity issues. This approach not only has the potential to provide water that adheres to statutory fluoride limits, thereby ensuring public health and safety, but also offers much-needed relief during periods characterized by water stress and scarcity. The existing water bodies in the district can be effectively utilized for this purpose, contingent upon their respective depths, serving as valuable repositories for water storage. Furthermore, rooftop rainwater harvesting can be widely implemented, particularly within public utility buildings such as educational institutions, government offices, and other similar structures, which inherently provide substantial areas conducive to water collection.

7. Conclusions and Future Scope of Work

7.1 Conclusions

A spatio-temporal analysis reveals that fluoride concentrations in Birbhum district's groundwater surpass permissible limits, posing a public health risk. The western and southwestern regions are particularly impacted by fluoride contamination in groundwater. Fluoride levels, both in absolute and spatial terms, tend to diminish following the monsoon season. Health Risk Analysis indicates that children are disproportionately at risk from fluoride-contaminated groundwater, with 30% of the area classified as high-risk zones. Adults also face risks, though to a lesser extent in both concentration and affected area compared to children. The highest fluoride concentrations are found near the Bakreshwar hot springs, suggesting they may be a primary source of contamination in the district's groundwater.

Rainwater Harvesting (RWH) has been identified as the most effective strategy for mitigating health risks from fluoride-contaminated groundwater. The Analytic Hierarchy Process (AHP) indicates that western segments of the district, with high fluoride levels, are well-suited for RWH system implementation. Large water bodies in these areas can serve as repositories for rainwater collection, which can be used directly or mixed with contaminated water for safe consumption. Additionally, areas with extensive built-up environments are appropriate for rooftop rainwater harvesting initiatives. Establishing rainwater repositories can address fluoride contamination and alleviate water scarcity in Birbhum, a semi-arid region with insufficient drinking water resources. The low technical and capital investment required for RWH units makes this approach an appealing, community-driven solution to local water quality and quantity challenges..

7.6 Future Scope of Work

The present research may be explored, in greater depth by incorporating the following suggestions:

- Conduction of extensive Geophysical investigations to confirm the suggested fracture zones as a transit route for fluoride-bearing groundwater.
- Detailed Risk Analysis maybe conducted in order to ascertain the vulnerable sections of the populations, segregated along the lines of major socio-economic factors including income, access to water etc.

Model RWH collection and dissemination units maybe developed on the ground, with the help of local administration, to assess feasibility and efficacy of the proposed ameliorative solutions.

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