



'Integrated approach on discerning fluoride contamination mechanisms in the groundwater and formulating remedial strategies for potential health hazards in Birbhum District, West Bengal'.

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
Riddha Chaudhuri
(Registration no. D-7/ISLM/45/18 dated 06/03/2018)
Doctor of Philosophy (Science)



School of Oceanographic Studies
Faculty of Interdisciplinary Studies, Law & Management
Jadavpur University
Kolkata, India
2025



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Doctor of Philosophy (Science)

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Certificate from Supervisor

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 that neither his thesis nor any part of the thesis has been submitted for any degree/diploma or any other academic award anywhere before.

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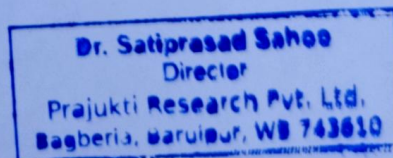
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EXECUTIVE SUMMARY

Groundwater constitutes an essential and indispensable resource whose role is critical in sustaining human life, being the principal source of potable water for an estimated 2.5 billion individuals across the globe, while simultaneously providing the necessary support for various agricultural and industrial activities that are vital for economic development. Nevertheless, the quality of this invaluable resource faces an escalating array of threats posed by both geogenic and anthropogenic contaminants, among which fluoride (F^-) has emerged as a particularly pervasive and insidious pollutant that warrants significant attention. Although it is widely recognized that low concentrations of fluoride, specifically within the range of 0.5 to 1.5 mg/L, can confer protective benefits against dental caries, it is also crucial to acknowledge that chronic exposure to elevated concentrations exceeding 1.5 mg/L can precipitate the onset of fluorosis, a debilitating and often painful condition that adversely affects the integrity and health of teeth, bones, and soft tissues. According to estimations put forth by the World Health Organization (WHO), it is alarming to note that more than 200 million individuals around the world are reliant on groundwater that is contaminated with fluoride, with a disproportionate impact observed in developing nations located in regions such as Asia, Africa, and Latin America, where limited access to treated water supplies exacerbates the public health crisis. Fluorine constitutes the lightest element within the halogen group, exhibiting the highest electronegativity and the greatest reactivity among all known chemical elements, demonstrating mobility at elevated temperatures. The typical concentration of fluorine within the lithosphere is roughly 625 mg/kg. Due to its considerable reactivity, it is absent in its pure elemental form and readily participates in various chemical reactions to produce inorganic and organic compounds collectively referred to as fluorides. Natural contamination occurs due to the leaching of fluoride-rich minerals, including fluorite (CaF_2) and apatite [$Ca_5(PO_4)_3(F,Cl,OH)$], and micas in granitic, volcanic, and sedimentary aquifers. Hydrogeochemical processes, including alkaline hydrolysis, ion exchange, and prolonged water-rock interactions, further mobilize fluoride into groundwater. Regions with arid climates, such as India's Thar Desert and Ethiopia's Rift Valley, face heightened risks due to low rainfall, high evaporation rates, and limited aquifer recharge, which concentrate dissolved ions. Conversely, anthropogenic activities, including unchecked industrial discharge, phosphate fertilizer use, and mining, exacerbate fluoride pollution in both rural and urban settings. The health implications of fluoride contamination are profound. Dental fluorosis, characterized by tooth discoloration and enamel erosion, affects millions of children in endemic regions. Skeletal fluorosis, a crippling condition marked by joint pain, bone deformities, and reduced mobility, is prevalent in areas where fluoride levels exceed 3 mg/L. Emerging research also links chronic fluoride exposure to non-skeletal disorders, including neurotoxicity, thyroid dysfunction, and renal impairment, raising urgent public health concerns. Despite global guidelines, enforcement remains inconsistent, particularly in low-income regions characterized by groundwater as the principal source of water and monitoring infrastructure is inadequate. Addressing fluoride contamination requires a multidisciplinary approach, integrating hydrogeology, public health, and socio-



economic strategies. While defluoridation technologies such as activated alumina and reverse osmosis exist, their scalability and affordability in resource-limited settings remain challenges. Furthermore, sustainable solutions must account for regional geological diversity, climate variability, and community-specific needs.

Detailed review of literature indicates that contamination of fluoride is a persistent problem in the groundwater of several regions of India. Extended areas of the states of Rajasthan, Gujarat, Andhra Pradesh, Telengana, Tamil Nadu and West Bengal document cases of fluorosis arising out of the consumption of fluoride contaminated groundwater. In the state of West Bengal, Nasipur village belonging to Nalhati I block of the Birbhum district reported the first documented case of fluorosis. Several studies indicate that the district of Birbhum has an endemic problem of groundwater fluoride contamination and consequently that of fluorosis. More than fifty thousand people living across 78 villages across the district have been found to have been suffering from fluorosis. This problem has been noted especially from western and south-western administrative blocks such as Dubrajpur, Rajnagar, Suri I and II, Md Bazar, Khoyrasole, Nalhati and parts of Rampurhat I. Owing to the absence of specific scholarly work pinpointing the sources and mobilization mechanisms of fluoride in the groundwater in Birbhum, along with assessing potential health hazards thereof and identifying locally implementable remedial measures, the current research was conducted along the aforementioned lines.

It can be noted that the contamination of fluoride is confined to regions geologically characterized by the Archean Chotanagpur Granite Gneiss, predominantly situated in the western and southwestern sectors of the district. Petrological investigations reveal that the granitic formations in these locales exhibit a significant abundance of fluoride-bearing minerals, including apatite, fluorapatite, hornblende, and feldspar, which, upon disintegration through leaching and hydrolysis processes, liberate fluoride into the surrounding groundwater. The inherently alkaline properties of the groundwater compound the issue. Statistical evaluations demonstrate a robust correlation between pH levels and fluoride concentrations. The prevalent pattern of increasing fluoride levels concomitant with temperature, total dissolved solids (TDS), and alkalinity due to prolonged leaching is similarly evident in Birbhum. As a plausible mechanism for the mobilization of fluoride from the Migmatite Gneissic rock and Pegmatites, the circulation of older, thermally enhanced groundwater from the Bakreswar - Tantloi geothermal province through profound fractures under conditions of low calcium saturation has been proposed. Surface manifestations of these deep-seated lineaments have been identified through advanced Remote Sensing techniques and subsequently mapped. It is observed that locations exhibiting elevated fluoride concentrations are predominantly situated along these penetrative lineament zones or fractures/faults. While lateritic reservoirs are typically devoid of fluoride, they may become fluoride-rich when influenced by water circulating through



these deep fractures. Therefore, these deep-seated fractures represent potential conduits for fluoride contamination. It is imperative that these areas be delineated in the field through comprehensive Geophysical surveys to enhance the accuracy of these pathway identifications.

The spatio-temporal analysis concerning the contamination levels of fluoride in groundwater has been conducted through a comprehensive examination of data that has been made accessible by the Public Health Engineering Department (PHED) of the Government of West Bengal, specifically for the temporal framework spanning the years 2016 to 2019. This thorough investigation reveals that, on average, approximately 29% of the geographical expanse of the district exhibits fluoride concentrations in the groundwater that significantly exceed the permissible statutory thresholds established by health authorities. Nevertheless, it is noteworthy that this percentage diminishes to around 21% following the monsoon season, thereby highlighting a critical role that rainfall plays in mitigating the levels of fluoride contamination, albeit in a seasonal context. Furthermore, an assessment of the potential health hazards associated with fluoride exposure, conducted in accordance with the guidelines set forth by the United States Environmental Protection Agency (USEPA) in 2011, together with an intricate geospatial analysis, has illuminated the fact that children are particularly susceptible to the adverse effects of fluorosis resulting from the consumption of fluoride-laden groundwater sources. On average, it has been ascertained that approximately 31% of the spatial extent of the district is characterized by a high health risk (with Hazard Quotient exceeding 1) for children during the pre-monsoon season, a figure that subsequently declines to around 26% in the post-monsoon period, thereby indicating a significant seasonal variation in risk levels. In terms of adult vulnerability, data suggest that roughly 11.66% of the spatial area within the district is classified as being at risk during the pre-monsoon season, a statistic that experiences a notable reduction to 4.86% in the ensuing post-monsoon timeframe. Consequently, these statistical figures serve to illustrate the considerable vulnerability faced by the population residing in Birbhum, a region that is already grappling with water scarcity issues due to its semi-arid climatic conditions and the limited availability of potable drinking water sources. Addressing this pressing issue necessitates remediation efforts that align with the sustainable development goals that have been envisaged by the United Nations, thereby underscoring the global commitment to ensure availability, for all human beings, clean and safe potable water.

Common defluoridation methodologies predominantly employ coagulation-precipitation techniques, particularly the Nalgonda method, alongside advanced methodologies such as electro-dialysis, adsorption, and reverse osmosis. Empirical evidence suggests that these methodologies are not devoid of intrinsic challenges. Implementation of these techniques necessitates personnel with specialized technical expertise and substantial financial investment for both installation and ongoing operational costs. Furthermore, certain widely-utilized methods produce by-products, manifested as sludge or wastewater, which are often enriched with fluoride. The disposal of such by-products raises significant environmental



concerns regarding potential further contamination. Consequently, these processes may inadvertently exacerbate the very contamination issues they were designed to mitigate.

Rainwater Harvesting (RWH) has emerged as a viable remedial strategy in numerous regions suffering from fluoride pollution. A pioneering initiative in this context is the "Kilimanjaro Concept," applied in the vicinities of the East African Rift System, where fluoride concentrations have been recorded at levels exceeding 30 mg/L. RWH has been extensively researched as a potential mitigation strategy for the Birbhum district. Through geospatial analysis employing the Analytical Hierarchy Process (AHP), it has been determined that over fifty percent of the district is conducive to the implementation of RWH. Notably, the regions identified as most suitable for RWH correspond to areas with groundwater severely contaminated by fluoride. Geospatial analysis further reveals that the district harbors more than 9000 hectares of surface water bodies that could serve as reservoirs for rainwater collection, facilitating distribution among the local populace. Particularly in fluoride-affected blocks such as Suri I and II, Dubrajpur, and Khoyrasole, larger water bodies have been documented. The harvested rainwater may be utilized directly, following minimal treatment, or combined with fluoride-laden water, thereby naturally diluting the fluoride concentration. In urban locales such as Suri and Rampurhat, the exploration of rooftop rainwater harvesting is also warranted, given their capacity to store significant volumes of water for subsequent use.



CHAPTER 1: INTRODUCTION

1.1 Preface

Fluoride, a chemical element characterized by its exceptionally high toxicity, poses significant risks to human health. Even when present at remarkably low concentrations, the contamination of groundwater with fluoride has been shown to lead to grave health complications, thereby establishing it as one of the most pressing environmental challenges that confront the developing nations of the world (*Rajak et al., 2023; Chaudhuri et al., 2024*). While the inclusion of fluoride in drinking water is acknowledged as beneficial in carefully regulated quantities in order to prevent dental caries, excessive fluoride levels may precipitate endemic forms of dental and skeletal fluorosis when they surpass established safety limits (*Grandjean et al., 1992*). The prolonged ingestion of fluoride has detrimental effects on the structural integrity and functional efficacy of various tissues, organs, and organ systems within the human body. One particularly severe manifestation of fluorosis is the occurrence of debilitating skeletal deformities, which significantly impair mobility and quality of life. Fluoride does not alter the color, odor, or flavor of the drinking water, as a result, individuals are typically unable to detect its presence without the aid of specific chemical testing methods. Consequently, those who suffer from fluorosis often endure their ailments without a proper diagnosis and may be subjected to a range of treatments, including surgical procedures, with little to no alleviation of their pain or functional disabilities (*Susheela, 2003*). It is estimated that approximately 200 million individuals worldwide, including 62 million from India—of which 6 million are children—experience the adverse effects of fluorosis as a result of consuming water with elevated fluoride concentrations across nearly 17 of the country's 29 states (*Susheela, 1999*). The issue of fluoride-contaminated groundwater predominantly affects countries situated in South and Southeast Asia, where the prevalence of this environmental problem is particularly acute (*Ravenscroft et al. 2009; Rasool et al. 2015*).

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, and even 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.

1.2 Sources of Fluoride

The presence of fluoride in the environment can be attributed to the formation of fluoride compounds, which arise from the intricate combination of several elements, and these fluoride compounds are found naturally in a diverse array of food products, as well as in various sources such as water and soil. The primary minerals that are rich in fluoride include fluorite, apatite, fluorapatite, sellaite, a range of amphiboles, mica, topaz and cryolite (*Ghosh et al., 2013*), all of which are characterized by their significant abundance in a multitude of rock types and sedimentary deposits (*Chae et al. 2007; Banerjee, 2015*). Fluoride is predominantly a natural element that makes up around 0.32% of the crust, and it exhibits extensive dispersion throughout the environmental matrix, as noted in the findings of the World Health Organization (*WHO, 1984*). The initial and most prominent fluoride source of natural origin found in groundwater arises from the processes of weathering that affect minerals bearing fluoride, while the second significant natural source of fluoride contamination is attributed to volcanic eruptions, with the third major contributor being marine aerosols that release fluoride into the atmosphere and hydrosphere. Furthermore, the excessive application of phosphatic fertilizers within agricultural practices, in addition to industrial activities like manufacture of cement, smelting of aluminum, and the combustion of coal, represents major anthropogenic influences that contribute primarily to elevate the levels of fluoride present in the environment, as discussed by *Dey et al. (2012)*.

1.2.1 Geogenic Sources

Fluoride contamination present in groundwater resources constitutes a substantial and pressing global concern, with its origins predominantly attributed to geogenic sources which are fundamentally natural geological formations characterized by their ability to release fluoride ions into the groundwater system via a multitude of intricate geochemical processes that are often complex in nature. A thorough comprehension of these diverse geogenic origins is crucial for the proficient governance of fluoride levels in groundwater, alongside the development of methodologies designed to alleviate the considerable health threats linked to fluoride exposure, which prominently encompass dental fluorosis and skeletal fluorosis, both of which can adversely impact public health.

1.2.1.1 Rocks and minerals

Throughout the globe, the lithological factors and characteristics pertaining to various types of rock formations are widely recognized as the most significant contributors to the variations in fluoride concentration observed within groundwater systems. In the majority of documented instances, it has been ascertained that the primary rock type influencing this



phenomenon is predominantly igneous in nature, while sedimentary rock types have been identified as the second most prevalent category encountered in these assessments (*Chowdhury et al., 2019; Li et al., 2023; Chaudhuri et al., 2024*). Rocks that are characterized by the presence of fluoride-rich minerals serve as the primary reservoirs of fluoride, a fact that has been well-documented in the literature, particularly by the World Health Organization in the year 1984. In accordance with the findings presented by (*Srivastava and Lohani, 2015*) in their study, it has been determined that there exists an extensive array of nearly 150 distinct minerals that are known to bear fluoride, with the vast majority of these minerals belonging to the silicate class, while a smaller number are classified as phosphates. The inherent composition of these geological formations plays a critical role in determining the quantitative value of fluoride that can be extracted or found within them. Specifically, in ultramafic rocks, the concentration of fluoride is typically observed to be around 100 mg/kg, whereas this concentration markedly increases to approximately 1000 mg/kg within alkaline igneous rocks, and can reach as high as 1300 mg/kg in marine shale deposits (Ozsvath, 2009). The average fluoride content within the Earth's crust is approximately 625 mg/kg; however, this value exhibits variability depending on the specific types of rock being examined, as noted by (*Vinthaage and Bhattacharya, 2015*). Conversely, it is important to recognize that the concentration of fluoride within sedimentary rock formations may be significantly elevated if these rocks contain clay minerals that are enriched with fluoride or the mineral fluorapatite, as discussed by (*Ozsvath, 2009*). With respect to igneous rock formations, *Roelandts et al. (1987)* discerned a noteworthy positive relationship between the levels of fluoride ions (F^-) and phosphorus pentoxide (P_2O_5), which consequently led them to suggest that the mineral apatite plays a significant role in moderating the concentration of fluoride ions. Additionally, their research indicated that other key minerals, namely amphibole and biotite, also contribute considerably to the fluoride content in these igneous rock formations, alongside the aforementioned mineral apatite, further underscoring the complexity of the geochemical interactions involved. The granite group of rocks are known to encompass various minerals, including amphiboles, muscovite, and hornblende, which are recognized for their elevated fluoride content. These particular minerals serve as one of the principal sources of fluoride in groundwater systems, primarily due to the weathering processes that they undergo, as highlighted by (*Vinthaage and Bhattacharya, 2015*) study. Additionally, in hydrothermal vein deposits, the mineral fluorite is frequently encountered in the form of flourspar, as described by (*Ozsvath, 2009*).

1.2.1.2 Geothermal sources

In numerous geographical areas around the world, one of the principal sources contributing to the presence of fluoride within the environment is attributed to the various processes associated with volcanic and geothermal activities, which release significant quantities of this element into the atmosphere and surrounding ecosystems. According to estimations derived from scientific analyses, it is projected that volcanoes and associated volcanic phenomena collectively emit an impressive range of inorganic fluorides, with figures ranging from approximately 60 to as much as 6000 kilotons on a global scale (*Camargo 2003*).



Following the cessation of these volcanic activities, observations point out that the concentration of fluoride within the affected areas can remain elevated for an extended period, potentially lasting for several years (*Araya et al., 1993*). This phenomenon can be attributed to the fact that due to the similarity in ionic radii, there is a rapid and efficient substitution of hydroxide ions (OH^-) with fluoride ions (F^-) that takes place during the complex process of magmatic differentiation (*Sivasankar et al., 2016*). As a result, it is frequently observed that there exists a characteristic correlation of fluoride-containing minerals alongside formations, including, but not limited to, hydrothermal vein deposits, late-stage pegmatitic granites and igneous rocks whose crystallization occurs from magmas that are highly evolved and differentiated (*Nagudi et al. 2003; Scaillet and MacDonald 2004*). High-temperature geothermal fluids, which are characterized by their elevated thermal energy and unique chemical properties, have the potential to significantly enhance the dissolution processes of fluoride-rich minerals, including but not limited to fluorite and apatite, ultimately resulting in the release of fluoride ions into the surrounding groundwater system. Furthermore, the dynamic interaction between groundwater and geothermal gases—gases that may contain varying concentrations of fluoride—can play a substantial role in further increasing the concentrations of fluoride detected within the groundwater, thereby exacerbating the overall fluoride levels present in that particular hydrological environment (*Onipe et al., 2021; Regenspurg et al., 2022; Mustafa et al., 2023*). Furthermore, it has been established that Pre-Cambrian geological formations characterized by compositions that are granitic and amphibolitic in nature are largely responsible for the elevated concentrations of fluoride observed in the thermal waters of hot springs (*Marbaniang et al. 2014*). Additionally, another significant source contributing to the overall fluoride levels in the environment consists of volcanic rocks, which are known to produce fluoride concentrations that can reach approximately 2000 mg/kg within the dynamic and complex geological settings of subduction zones (*Anazawa 2006*).

1.2.1.3 Atmospheric depositions

The atmospheric air plays a significant role in the contribution of fluoride to the environmental landscape, with measured concentrations ranging from a minimal 0.01 to a more substantial $0.4\mu\text{g}/\text{m}^3$, while the contribution from precipitation exhibits a wide variability, encompassing almost imperceptible amounts up to 0.089mg/L (*Gupta et al., 2005*). The fluorides present within the atmosphere are known to exist in various forms, which can be categorized broadly as either gaseous or particulate; furthermore, the sources responsible for these emissions can be traced back to both natural phenomena as well as human-induced activities. Among the prominent gaseous emissions are compounds such as sulfur hexafluoride, hydrogen fluoride, fluorosilicic acid, and silicon tetrafluoride, while particulate emissions typically consist of substances like calcium fluoride, aluminium fluoride, lead fluoride, and sodium hexafluoride, as outlined in the World Health Organization's 2002 report. Atmospheric fluorides ultimately find their way to the surface of the Earth through mechanisms such as fallout in the form of particulate matter or via the process of rainfall, thereby facilitating their deposition onto terrestrial ecosystems. Once



these compounds have settled upon the surface, rainwater, which percolates through the soil, carries with it these fluorides into the groundwater zone, as discussed by *(Brindha and Elango, 2011)* in their research. The transport of atmospheric fluoride compounds over extensive distances is enabled by atmospheric circulation processes, which subsequently lead to their removal through both dry and wet deposition methods, a phenomenon detailed by Walna et al. in their 2013 study. Among the various air pollutants that are classified as airborne fluorides, it is noteworthy that hydrogen fluoride (HF) and silicon tetrafluoride have been identified as the most detrimental and damaging to environmental health, as indicated in the findings by *Malayeri et al., 2012*.

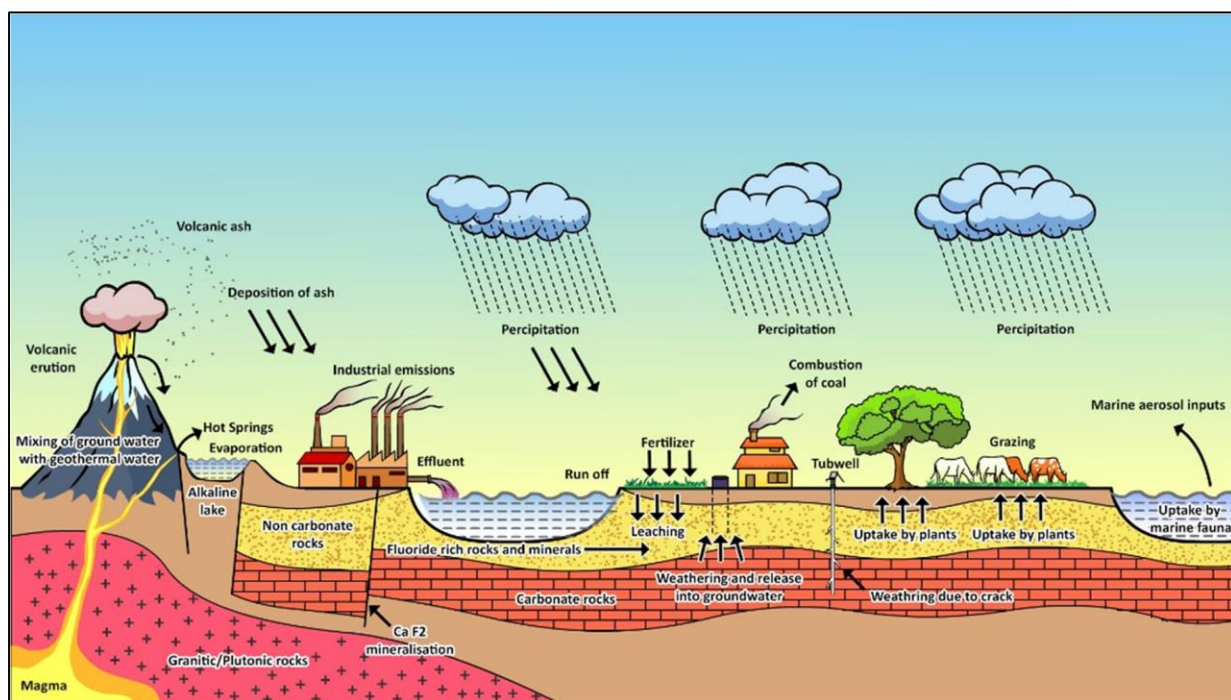


Figure 1.1 . Revised schematic representation of the fluorine hydrogeochemical cycle following the framework of *Edmunds and Smedley (2005)*.

1.2.2 Anthropogenic sources

Fluoride contamination in groundwater has traditionally been attributed to geogenic processes, such as the dissolution of fluoride-rich minerals. However, anthropogenic activities have increasingly emerged as significant contributors to elevated fluoride levels in aquifers. This essay explores the anthropogenic sources of fluoride contamination in groundwater, including industrial discharges, agricultural practices, mining activities, and urbanization.

Fluoride enters groundwater through both natural processes (e.g., dissolution of fluorite, apatite, and micas) and human activities. While geogenic fluoride is governed by geology and climate, anthropogenic fluoride arises from:



- **Industrial effluents** (e.g., coal combustion, aluminum smelting).
- **Agricultural runoff** (e.g., phosphate fertilizers, pesticides).
- **Mining operations** (e.g., fluorite extraction, tailings).
- **Urban wastewater** (e.g., landfill leachate, fluoridated water systems).

The distinction between natural and anthropogenic sources is often blurred, as human activities can accelerate natural fluoride release (*Brindha & Elango, 2011*). For example, over-extraction of groundwater lowers water tables, increasing fluoride concentration through evaporative enrichment.

1.2.2.1 Industrial Sources

Coal is known to possess a fluoride concentration that ranges from 50 to 300 milligrams per kilogram, a significant amount that is released into the atmosphere as a result of the combustion process (*Fuge, 2019*). Furthermore, fly ash, which is a notable byproduct generated from coal-fired power plants during their operational processes, contains a considerable quantity of soluble fluoride that can reach levels of up to 1,000 milligrams per kilogram, and this soluble fluoride is capable of leaching into the surrounding groundwater systems, thereby posing potential environmental concerns. In the context of the Guizhou Province in China, it has been observed that the disposal sites for fly ash that are located in proximity to coal power plants have resulted in significantly elevated levels of fluoride in the groundwater, with concentrations ranging from 6 to 15 milligrams per liter, and these elevated fluoride levels have been shown to correlate closely with the extent of coal utilization in the region, as reported by (*Li et al., 2014*).

Aluminum smelting operations utilize cryolite (Na_3AlF_6), as a key component in the production process, which subsequently results in the release of effluents that are significantly enriched with fluoride compounds. In the Indian state of Odisha, it has been observed that groundwater in proximity to aluminum manufacturing facilities exhibits fluoride concentrations that surpass the threshold of 5 mg/L, as documented in the research conducted by Mukherjee et al. in the year 2018. Likewise, the industrial production of phosphate fertilizers is known to generate a byproduct, specifically fluorosilicic acid (H_2SiF_6), which has the propensity to permeate through geological layers and infiltrate aquifers, leading to potential environmental concerns. In the Safi Basin of Morocco, empirical studies have revealed that fluoride concentrations in the vicinity of fertilizer manufacturing plants are reported to range between 4 and 10 mg/L, as highlighted in the findings of Boukhris et al. in the year 2020.

1.2.2.2 Agricultural Sources

In arid regions characterized by limited precipitation and scarce water resources, agricultural practitioners frequently resort to the utilization of groundwater that is rich in fluoride content for the purpose of irrigation, which inadvertently leads to the accumulation



and subsequent concentration of fluoride within the soil profiles. Following this, the process of leaching that occurs during the monsoon season facilitates the transfer of fluoride ions back into the underlying aquifers, establishing a cyclical interaction between the surface soil and the groundwater resources. This repetitive process, particularly evident in the Laguna Region of Mexico, has resulted in a significant elevation of fluoride concentrations within the groundwater, reaching levels as high as 7.0 mg/L, as documented in the study conducted by *Armienta and Segovia, 2008*.

1.2.2.3 Mining operations

Fluorite (CaF_2) extraction activities yield waste rock and tailings that subsequently liberate fluoride ions as a result of weathering processes. In the Namaqualand region of South Africa, groundwater in proximity to fluorite extraction sites exhibits concentrations of fluoride ranging between 6.0 to 12.0 mg/L (*McCaffrey & Willis, 2001*). The mining of bauxite exposes lateritic deposits with elevated fluoride content, while the processing of phosphate rock entails the release of fluorosilicic acid. Groundwater in the Cockpit Country of Jamaica presents fluoride levels surpassing 5 mg/L, attributable to the influence of bauxite tailings (*Evans et al., 2016*).

1.2.2.4 Wastewater sources

Landfills designated for the disposal of industrial waste facilitate the leaching of fluoride into groundwater supplies. In Lagos State, Nigeria, the subterranean water situated near waste management facilities displays fluoride concentrations between 3.5 to 6.7 mg/L (*Ayantobo et al., 2012*). The artificial addition of fluoride to drinking water, generally maintained at levels of 0.7 to 1.2 mg/L, may lead to heightened fluoride exposure in regions where naturally occurring fluoride is already prevalent. In Ethiopia's Rift Valley, the convergence of both natural and human induced sources has led to fluoride concentrations soaring to as high as 18.0 mg/L (*Rango et al., 2012*).

1.3 Controls on the concentration and mobilization of Fluoride in groundwater

Numerous geogenic factors significantly influence both the concentration levels and the mobilization processes of fluoride within the groundwater systems present in various geological environments. In particular, a vital role is played by hydrogeochemistry in determining the specific degree to which fluoride can become concentrated in the aqueous solutions, while concurrently, the tectonic factors exert their influence over the various mechanisms by which fluoride is mobilized throughout the groundwater. Nevertheless, it is essential to recognize that the intricate interplay of a multitude of geological factors, which includes but is not limited to the lithological composition, the prevailing hydrochemical conditions, as well as the tectono-structural characteristics inherent to the region in question, collectively dictate the extent of both contamination and mobilization of fluoride within the groundwater resources.



1.3.1 Geochemical controls

Certain factors that regulate the concentration of fluoride in groundwater include pH levels, temperature, anion exchange capacity, where hydroxide ions (OH^-) replace fluoride ions (F^-), the length of time that water interacts with geological substrates, the solubility of minerals containing fluorine, the characteristics of the geological formations that the water traverses, and the deficiency of ions and colloids that could precipitate (*Farooqi 2007*). Given that arid and semiarid regions experience minimal precipitation coupled with elevated evaporation rates, the hydraulic conductivity of groundwater is consequently diminished (*Su et al. 2006*). This results in a reduced groundwater recharge rate, thereby prolonging the interaction between water and rock. Such prolonged interactions lead to an increase in fluoride concentrations within groundwater. It has been observed that elevated fluoride concentrations tend to occur in regions characterized by low-lying plains, whereas diminished concentrations are noted in elevated terrains. This phenomenon can be attributed to the prolonged contact of water with the aquifer in plains, leading to a slowed groundwater movement (*Dissanayake 1991*). The duration of water retention within the aquifer is crucial as it influences interactions with geological substrates, thereby establishing a direct correlation between fluoride concentration and retention time (*Czarnowski et al. 1996*). The precipitation of less soluble minerals such as calcium carbonate (CaCO_3) is instigated by increased rates of evaporation, which consequently leads to a reduction in calcium ion concentrations within groundwater. This reduction enhances the dissolution of fluorite minerals (*Vithnage and Bhattacharya 2015*). The pH level serves as a fundamental factor influencing fluoride concentrations in groundwater. The release of sodium (Na^+) and bicarbonate (HCO_3^-) ions results in an elevation of pH values, which subsequently promotes the further dissolution of fluoride-containing minerals (*Rango et al. 2009*). At diminished pH levels, fluoride is prone to forming complexes with aluminum and iron found in the soil matrix. When pH falls below 4.0, fluoride is significantly adsorbed by clay minerals such as illite, chlorite, and smectite, whereas the adsorption process declines above pH 6.5. At pH levels exceeding 7, which signify alkaline conditions, anionic exchanges transpire, wherein hydroxide (OH^-) ions replace fluoride (F^-) ions from minerals like biotite, muscovite, and clay minerals (*Li et al. 2014*).

According to *Handa (1975)* and *Saxena and Ahmed (2003)*, the processes that enable the mobilization of fluoride within groundwater systems remain relatively ambiguous. The anion exchange mechanism can amplify fluoride concentrations in aqueous environments to levels reaching 30 mg/L, as indicated by *Rasool et al. (2017)*. As previously highlighted, the resemblance in ionic radii permits the substitution of fluoride ions (F^-) in positions typically occupied by hydroxide ions (OH^-) due to their analogous atomic dimensions and a singular negative charge, as noted by *Farooqi et al., (2007)* and *Sivasankar et al., (2016)*. It has also been demonstrated that at reduced pH levels, fluoride tends to be adsorbed by clay minerals. Consequently, alkaline conditions are favorable for the augmentation of fluoride ion concentrations in groundwater, as observed by *Singh et al., (2015)*. When the pH surpasses 7, which signals alkaline conditions, anion exchange processes are promoted, allowing F^- ions



to be replaced by OH^- ions in fluoride-rich mineral matrices (*Li et al. 2014*). Prolonged water retention facilitates the exchange of calcium ions (Ca^{2+}) with sodium ions (Na^+), culminating in the generation of sodium-rich water, which is conducive to the leaching of fluoride from groundwater sources, as discussed by *Karro and Uppin (2013)*. The liberation rate of fluoride from fluorite (CaF_2) is significantly enhanced in the presence of surplus bicarbonate ions (HCO_3^-), as noted by *Handa (1988)*. This, in turn, results in an elevation of the water's pH, alongside other water quality parameters such as electrical conductivity (EC), total dissolved solids (TDS), and redox potential (Eh). The presence of heightened fluoride concentrations within groundwater is exacerbated by lower concentrations of Ca^{2+} and Mg^{2+} , while Na^+ is present in elevated concentrations, as observed by *Farooqi et al., (2007)*. In acidic conditions, clay minerals demonstrate a propensity to adsorb fluoride ions, whereas in alkaline conditions, fluoride ions (F^-) are liberated, as indicated by *Sarma and Rao (1997)*. Nevertheless, the fundamental chemical mechanisms responsible for fluoride contamination in groundwater encompass dissolution, hydrolysis, precipitation, adsorption, ion exchange, and biochemical reactions, as reported by *Saxena and Ahmed (2003)*. Increased fluoride concentrations in water derived from arid and semi-arid regions can be attributed to the concentration of soluble constituents resulting from evaporation and evapo-transpiration, as elucidated by *Jacks et al. (2005)*.

1.3.2 Tectonic controls

A considerable influence is ascribed to the tectonic attributes of a specific area in augmenting fluoride concentrations within groundwater. Observations have indicated that regions exhibiting heightened levels of fluoride in groundwater are associated with particular tectonic environments. The geographical areas affected by fluoride contamination correspond to specific tectonic regimes. Zone 1 is aligned with convergent boundaries, while zone 2 runs parallel to transform faults, which correspond to the northern and eastern peripheries of the African continent. Zones 3, 4, and 5 are related to subduction zones (*Chowdhury et al., 2019*). Elevated levels of fluoride are evident along the Circum-Pacific ring of fire, which constitutes a principal global volcanic region. Consequently, a robust association between volcanic regions and heightened fluoride concentrations can be inferred. The highest documented instances of fluorosis, as well as the peak fluoride levels in aquatic sources, are typically recorded from intra-continental hotspots, aborted rift zones, and Andean-type magmatic formations (*Chowdhury et al., 2019*). The East African Rift System (EARS) is particularly significant for elucidating the connection between tectonics and fluoride pollution. The EARS represents an active continental rift system extending from the Jordan Valley through Sudan, Ethiopia, Uganda, and Kenya to Tanzania. Substantial volcanic activity has been recorded in this area historically, and it currently hosts both active and dormant volcanoes, including Mount Meru, Mount Kenya, Mount Kilimanjaro, and the Crater Highlands of Kenya (*Saemundsson, 2008*). In this context, fluoride contamination may reach levels as high as 70 mg/L. *Ghiglieri et al., (2020)* assert that volcano-tectonic dynamics significantly influence fluoride distribution in the groundwater of the EARS region, which can be elucidated through the interplay of faults and lithology, volcanism, and the extent of tectonic



segmentation. In the EARS, the highest fluoride contamination levels have been detected in geothermal springs (*Kloos and Haimanot, 1999*). Calc-alkaline volcanoes in the EARS continental rift produce relatively fluorine-rich lavas (*Gasparon et al., 1993*), as do continental arcs like the Andes and island arcs such as Japan (*Rosi et al., 2003*). In such aquifers, regional thermal regimes combined with felsic volcanic rocks within elevated geothermal zones contribute to significant fluoride contamination (*Alemayehu et al., 2006; Furi et al., 2011*). The waters sourced from geothermal springs exhibit concentrations of fluoride that significantly surpass the standards established by the World Health Organization (WHO). Thermal springs serve as surface indicators of geothermal energy presence. The thermal energy of these springs is partially derived from the radioactive decay of elements such as uranium (U), thorium (Th), and potassium (K) found within high-heat-producing granitic formations (*Karakus 2015*). Within the Indian subcontinent, geothermal provinces are typically linked to either deeply seated rift zones or subduction tectonics. In the Himalayan geothermal belt, provinces associated with subduction are evident, while rift-related provinces characterize the broader Indian landscape. The notable geothermal provinces identified in India include the Himalayan geothermal province, the West Coast geothermal province, the Sonata (Son-Narmada-Tapti) geothermal province, the Cambay geothermal province, and the Godavari rift geothermal province. The formation of the Himalayan Geothermal Belt (HGB) is attributed to the collision between the Indian lithospheric plate and the Eurasian plate, marked by key tectonic features such as the Indus Tsangpo Suture Zone (ITSZ), the Main Boundary Thrust (MBT), and the Main Central Thrust (MCT). Leucogranitic intrusions can be observed along the MCT (*Chandrasekhar and Chandrasekharam 2011*). The combination of shear heating from the subducting slabs and the heat generated from radioactive decay contributes to the formation of granite melts (Harris et al., 2000). These processes could be responsible for the elevated fluoride levels detected in geothermal waters. An investigation conducted by *Chatterjee et al., (2017)* on water samples from various hot springs within the Uttarakhand geothermal field, a component of the HGB, revealed that the samples collected from Badrinath and Gari village exhibited alarmingly high fluoride concentrations, reaching up to 6.7 ppm. The SONATA geothermal province is influenced by extensive mid-continental rifts that extend to mantle depths (*Kalia, 1988*). In the eastern regions, thermal waters that traverse the granitic formations of the Chotanagpur Granite Gneiss Complex (CGGC) reveal fluoride contamination levels that considerably exceed permissible limits (*Minissale et al., 2000; Chandrasekhar and Chandrasekharam 2011; Singh et al., 2015*). The Taptapani hot springs in Odisha and the Bakreshwar hot springs in West Bengal also demonstrate significantly elevated fluoride concentrations. Within the Cambay Geothermal Province, the most prominent hot springs are located in Tuwa, amidst Godhra granite, where fluoride levels range from 2.5 to 4 mg/L (*Singh and Chandrasekharam 2010*). Neotectonic and subsequent lineament tectonic events may further exacerbate fluoride contamination. In Sri Lanka's Highland and Vijayan rocks, numerous deep lineaments and faults, resulting from Precambrian and later tectonic activities, may serve as focal points for fluorine outgassing (*Vithanage 1989*).



1.4 Global Scenario of Fluoride contamination

The consumption of water with elevated fluoride levels can be observed in extensive geographical regions characterized by unique lithological and tectonic features, thereby challenging the prior assumption that fluorosis is confined solely to tropical nations (*Dissanayake and Chandrajith, 2009*). As per the World Health Organization report presented by *Fawell et al., (2006)*, regions with high fluoride concentrations are prevalent along these geographical corridors. These corridors are linked to a) granitic and gneissic formations, b) volcanic structures, c) tectonic zones, and d) marine sediment deposits in elevated terrains. *Dahi (2009)* delineated five such global corridors that extend linearly and interconnect various nations (*Chowdhury et al., 2019*).

The initial corridor represents a significant and extensive linear extension that stretches southward from the geographical boundaries of Turkey all the way down to the nation of Tanzania. Initiating its course in Turkey, this corridor navigates through the region of Syria, subsequently advancing in close proximity alongside the territory of Jordan, before making its entry into the African continent via the country of Egypt, where it then continues its descent southward through the nations of Sudan, Somalia, Ethiopia, and Tanzania, while also traversing through Kenya, South Africa, and ultimately concluding its journey in Mozambique. The heightened concentrations of fluoride that are prevalent within this specific corridor can be predominantly attributed to the distinctive geological formations present in the area, as well as the complex interactions between water and rock that occur therein. This particular region is extensively documented within the scientific literature and is notably characterized by significant volcanic activity that is closely associated with the East African Rift system, a geological feature that extends its reach from the Jordan Valley all the way down to Tanzania. Within this corridor, there exists a notable incidence of fluoride contamination, particularly in close proximity to geothermal springs that are located throughout this region, as highlighted by the research conducted by *Fawell et al., (2006)*. Furthermore, it is essential to note that this corridor predominantly exhibits a climate that is classified as dry and arid, characterized by high relief, with Aridisols being recognized as the primary soil type prevalent throughout the area.

The subsequent corridor, which has been designated as Belt 2, manifests as a substantial linear expanse that stretches between the nation of Egypt and the country of Mauritania. It initiates its trajectory in Egypt and subsequently progresses westward through the territories of Libya, Algeria, and Morocco. Upon reaching Morocco, this corridor makes a pronounced and significant southern turn, thereby establishing a crucial linkage between Mauritania and Western Sahara along the western periphery of the African continent. A considerable contributor to the elevated fluoride levels observed within the groundwater of this corridor is the presence of ancient granite formations, alongside the Pre-Cambrian basement gneisses that are characteristic of the geological landscape. These distinctive geological formations play a pivotal role in the contribution of fluoride to the groundwater systems found within Algeria and Libya, while the meta-rhyolites in the Mauritania region



fulfill a similar function in facilitating the presence of fluoride. Tectonically speaking, this corridor is aligned in a manner that is parallel to the West African mobile belt, which is an important structural feature in the region. It is noteworthy that Western Sahara and Morocco rank among the largest global exporters of phosphate, and a multitude of researchers have established a connection between the extraction of phosphate and the increased incidence of fluorosis that is observed within these nations, as evidenced by the findings of *Maadid et al.*, (2017). The dominant soil type encountered in this corridor is also categorized as Aridisols, and the overarching climate is classified as desert temperate, which further influences the environmental conditions.

The third belt, which has been designated as Belt 3, constitutes yet another significant linear corridor that traverses a vast geographical expanse stretching from the nation of Turkey all the way to the expansive territory of China. This particular belt originates in Turkey and encompasses a wide array of regions, including Iraq, Iran, Afghanistan, Pakistan, India, northern Thailand, and various segments of China. The trajectory of this corridor progresses eastward from Turkey towards India, where it subsequently makes a pronounced and significant deviation towards the north. Within the geographical areas of Iraq and Iran, the existence and subsequent degradation of both volcanic and calc-alkaline formations may be critical contributors to the elevated concentrations of fluoride that are found within the groundwater resources. Furthermore, regions that are adjacent to metamorphic rocks in Iran have also been noted for exhibiting high levels of fluoride. Alkaline granites and pegmatitic veins within the geological formations of Afghanistan is likely responsible for contributing to the significant concentration of fluoride that can be detected within local groundwater supplies. The arid and dry climatic conditions, when considered in conjunction with various geological factors, further exacerbate the issue of fluoride contamination within Afghanistan and Pakistan by accelerating weathering processes of fluoride rich minerals. In the context of India, it can be posited that the granitic aquifers, the hydrogeological influences stemming from fractures, and the utilization of phosphatic fertilizers are likely to be the primary sources contributing to groundwater fluoride contamination. In both the regions of China and northern Thailand, elevated levels of fluoride have been detected in areas that are in close proximity to hot springs; however, it is important to recognize that geological factors, particularly the presence of granitic aquifers, also play a crucial role in enhancing the concentrations of fluoride found within the groundwater resources in China. The climatic conditions prevailing within this particular belt exhibit a remarkable diversity, predominantly characterized by a temperate desert climate, although it is essential to note that substantial areas also experience a tropical climate, with a variety of soil types that range from Aridisols to Endisols being present throughout the region.

Belt 4 presents itself as an extensive linear geological formation that stretches across a significant distance, beginning from the majestic Sierra Nevada mountain range situated in the northern regions of North America and traversing all the way down to the remarkable Andes mountain range located in South America. This geological belt initiates its trajectory



in the Sierra Nevada to the northernmost point, subsequently advancing through the formidable Rocky Mountains located within the United States, and further extending its reach into the diverse terrains of Mexico, Colombia, Peru, and Bolivia, ultimately culminating at the breathtaking Andes mountains, which serve as a dramatic terminus. This particular geological formation can be aptly categorized as a Volcanic Fluoride Belt, primarily due to its intrinsic association with a multitude of both active and dormant volcanoes that pepper the landscape throughout its expanse. The intricate dynamics associated with active volcanic processes, in conjunction with the resultant ash emissions and acid precipitation, significantly contribute to the observed elevated concentrations of fluoride that are prevalent within this specific region. While the presence of hot springs and the increased temperatures of groundwater play a pivotal role in enhancing fluoride solubility within the geographical confines of Colombia and the Sierra Nevada, it is equally essential to recognize that the pH levels of the water also exert a critical influence on this phenomenon. The predominant soil type that characterizes this extensive belt is classified as Andisol, which is known for its fertility and agricultural potential, and the overarching climate that prevails in this region is categorized as desert tropical, which is marked by distinct seasonal variations in temperature and precipitation.

Belt 5 is characterized as a linear geological expanse that extends in a southwesterly direction from the island nation of Japan, traversing through the various archipelagos of the Philippines and the sprawling landscapes of Indonesia. This particular geological belt is similarly categorized as a Volcanic Fluoride Belt, given its significant connections to a diverse array of both active and dormant volcanoes that are strategically positioned along its route. The primary factors that contribute to the elevated levels of fluoride that are detected within the groundwater supplies of Indonesia and Japan are predominantly the volcanic rocks and the ash that are intrinsically linked to the active subduction zones that characterize the geological activity of this region. However, it is noteworthy to mention that, within the Philippines, the presence of hot springs also plays an instrumental role in the substantial contributions to the fluoride levels that are observed in the local water supplies. Furthermore, it has been documented that the lakes located within Indonesia demonstrate exceedingly high concentrations of fluoride, with some measurements surpassing an impressive threshold of 1266 parts per million (ppm). The climate that characterizes this expansive belt is distinctly categorized as temperate and humid, which fosters a unique biodiversity and ecological richness, while the dominant soil type that prevails throughout this region is identified as Andisols, which are known for their volcanic origin and associated agricultural viability.

1.5 Indian Scenario of Fluoride Contamination

In the 21st century, it has been observed that within the vast geographical expanse of India, there exists a staggering population exceeding 35 million individuals residing in 19 different states, who are consuming drinking water that contains fluoride concentrations that surpass the established permissible limits. This alarming situation is further aggravated by the fact that the bulk of the supply of potable in India, is derived from groundwater sources, which is



pronounced in rural belts where the dependance on groundwater escalates to an alarming 90% (*Shankar et al., 2011*). According to the comprehensive study conducted by *Teotia and Teotia (1994)*, it has been reported that India harbors a substantial deposit of fluoride, totaling around 12 million tons, out of a grand total of 85 million tons that can be found in the Earth's crust. In the year 1991, it was documented that 13 states and Union Territories of India's exhibit elevated fluoride concentrations in their water supply, a figure that alarmingly increased to 17 states by the year 1999, as reported by *UNICEF (1999)*. In a concerning statistic, it is estimated that approximately 66.62 million individuals in India have been adversely affected by fluorosis, a condition that has resulted in the crippling of over five hundred thousand people. There are at least 20 states in India, including but not limited to Andhra Pradesh, Rajasthan, and Gujarat—where a staggering 70-100% of districts are reported to be affected—along with Punjab, Bihar, Karnataka, Haryana, Maharashtra, Tamil Nadu, Madhya Pradesh, Uttar Pradesh, and parts of Delhi which are experiencing substantial impacts, with 40-70% of districts affected, as well as Kerala, Assam, Orissa, Jammu & Kashmir and West Bengal, where 10-40% of districts are affected, and even regions such as Uttaranchal, Jharkhand, and Chhattisgarh have been identified as significantly impacted. It has been determined that in 25 districts within the state of Gujarat, the levels of fluoride present in the water supply exceed the permissible standards set forth by both the Indian Council of Medical Research (ICMR) and the World Health Organization (WHO). Consequently, India is grappling with yet another critical public health issue related to water contamination, subsequent to the challenges posed by arsenic contamination in drinking water supplies (*Susheela, 2007*). The geological and climatic factors unique to India are predominantly responsible for the heightened risk of fluoride contamination, as noted by *Brindha et al., (2016)*.

The states of Andhra Pradesh, Rajasthan, Tamil Nadu, Telangana, Gujarat and West Bengal have been regions within the Indian subcontinent that are severely affected by fluoride contamination, as evidenced by the research conducted by *Ali et al., (2016)* and *Thivya et al., (2015)*. In nearly all instances, it is the geological conditions that serve as the predominant driver of the widespread contamination of fluoride that has been observed in these areas.

Rajasthan, recognized as the largest state in India in terms of land area, harbors approximately 18 districts, encompassing around 11 million residents who are adversely affected by groundwater that exhibits fluoride concentrations exceeding the permissible limits established by health authorities (*Ali et al., 2016*). In a concerning development, all 32 districts within the state of Rajasthan have been officially classified as highly affected by groundwater fluoride contamination. The districts that have been identified as the most severely impacted include Nagaur, Jaipur, Sikar, Jodhpur, and Barmer, as documented by *Chandra et al., (1998)*. From a geological perspective, a substantial portion of Rajasthan is composed of ancient geological formations such as the Pre-Cambrian Aravalli supergroup, the Delhi Supergroup, the Bhilwara supergroup, and the Marwar supergroup, with additional regions that include the Deccan traps and other Phanerozoic formations, as noted by *Sundaram and Pareek, 1995*. The detrimental impact of high fluoride contamination is



particularly pronounced within the state of Rajasthan, with **Handa (1975)** highlighting the serious effects that this contamination has on public health. Within the northern regions of the state, there is a prevalent occurrence of exceedingly high fluoride levels, as indicated by Suthar in 2008, which can be attributed to the presence of host rocks such as quartzite, sandstone, phyllites and mica schists that contain fluoride. The prolonged interaction between aqueous solutions and these geological formations, further exacerbated by the prevailing arid conditions, has been identified as the principal factor leading to the significant fluoride contamination evident in these regions. Particularly, the district of Nagaur has been designated as the most adversely impacted area, where fluoride concentrations can escalate to concerning levels of up to 5.91 mg/L, resulting in hazardous water quality that affects nearly the entirety of the district's population (**Hussain et al., 2012**).

Gujarat stands as a state that has been profoundly affected by fluoride, rendering it one of the most severely afflicted regions in terms of this particular environmental contaminant within the Indian context. The inhabitants residing in a total of 18 distinct districts throughout the state find themselves in a precarious situation, as they are particularly susceptible to the adverse health effects associated with fluorosis, a condition that arises largely due to the alarming presence of elevated fluoride concentrations within the groundwater resources of the area, as documented by **Barot (1998)**. Geologically, the state of Gujarat is characterized by a remarkable diversity, with a complex array of rock formations; specifically, the Precambrian geological period is represented by the ancient rocks of the Delhi supergroup and the Aravalli supergroup, while the Mesozoic Kutch basin along with the Cretaceous to Cenozoic Deccan traps predominantly constitute the Phanerozoic rock layers that are prevalent throughout the region. Notably, a significant portion of Gujarat's landmass is dominated by the extensive coverage of the Deccan traps, which are formed from ancient volcanic activities. The northeastern section of the state is primarily covered by unconsolidated alluvial deposits, while the central and western regions exhibit a predominance of fluvial sediments, as elaborated upon by Chopra and Choudhury in their 2011 study. The principal factor contributing to the contamination of groundwater with fluoride can be traced back to the dissolution processes involving fluoride-rich minerals that are inherently present within the granitic rock formations that underlie the landscape. In the district of Mehsana, notably high concentrations of fluoride in groundwater have been documented, a phenomenon that can be attributed to the significant presence of highly weathered granitic gneiss formations in the area, as noted in the research conducted by **Dhiman and Keshari (2006)**. In a similar vein, the district of Bharuch exhibits elevated fluoride levels in its groundwater, which can be linked to the leaching processes that occur with fluoride-rich minerals (**Nayak et al., 2009**). From a geological perspective, the Cambay basin is characterized by granitic formations that have been intruded by amphibolitic and pegmatitic dykes, which upon leaching contribute to the contamination of groundwater, consequently resulting in a high fluoride concentration, as discussed in the work of **Gupta et al., (2005)**.



Andhra Pradesh and Telangana were historically unified as a single state until the year 2014, at which point Telangana was established as a separate entity, marking a significant geopolitical change in the region. The geological composition of Andhra Pradesh showcases an extensive array of rock types, ranging from some of the most ancient formations to those that are more recent, including a diverse mix of igneous, metamorphic, and sedimentary rocks that contribute to the state's geological complexity. The Peninsular Gneissic complex, which constitutes a significant portion of this region, is primarily composed of Archean age rocks, which themselves exhibit an assemblage of schists and gneisses that reflect the intricate geological history of the area. The Glacial Talchir formation, which is an essential component of Gondwanan deposits, primarily consists of limestone and grey shale bands that further enrich the geological diversity of Andhra Pradesh. The district formations from the Pre-Cambrian Cuddapah and Kurnool supergroups can be identified in several districts, including Kadapa, Kurnool, Guntur, Chittoor, Krishna and Prakasam, highlighting the extensive geological history of the region. Tertiary geological formations are predominantly found within the Vishakhapatnam, West Godavari and East Godavari districts, while Quaternary deposits manifest as substantial alluvial blankets that can be observed within the deltas and river valleys located along the eastern coastline. On the other hand, Telangana is primarily composed of the Peninsular Gneissic complex, while it also features portions of the Deccan traps, Gondwana deposits, and Cuddapah supergroups throughout its geological framework. The Nalgonda district stands out as a region that is severely affected by fluoride, presenting a significant public health concern. Within Nalgonda, the granitic and gneissic rocks are characterized by elevated fluoride concentrations, and the interaction between these geological materials and groundwater is a contributing factor to the fluoride contamination that has been documented, as reported by *Mondal et al., (2009)*. The presence of fractured and weathered granites and granitic gneisses, which are rich in fluoride minerals such as fluorite, can be observed across various regions of Nalgonda, and this geological feature facilitates the release of fluoride into the groundwater system, as established by *Brindha et al., (2016)*. Moreover, the heightened concentrations of fluoride in the Prakasam district can be ascribed to rock - water interactions, which facilitate the leaching of diverse rock types, including those classified as Charnockite and Khondalite, alongside unclassified metamorphic formations and intrusive bodies such as pegmatites, pink granites, anorthosites and gabbro (*Reddy et al., 2016*). Additionally, the Medak district located within Telangana displays significant fluoride levels in its groundwater, a phenomenon that similarly arises from the interplay between groundwater and fluoride-laden minerals inherent in the granitic and gneissic formations of the area, particularly minerals like apatite, biotite, and hornblende, as emphasized by *Narsimha and Sudarshan (2017)*.

Tamil Nadu, which is recognized as the southernmost state within the vast geographical expanse of India, serves not only as a cultural hub but also possesses significant geological characteristics that merit extensive study and analysis. In terms of its geological composition, Tamil Nadu primarily consists of ancient Archean and Proterozoic rock formations, which are integral components of both the Dharwar craton and the Southern Granulite Terrain, highlighting the region's complex geological history and structural significance. These



geological formations are rich in fluoride-bearing minerals, including but not limited to pyrite, pyrrhotite, chalcopyrite, and biotite (*Manikandan et al., 2012*), which emphasizes the mineralogical aspects of the region's geology. The occurrence of Gondwana rocks is notably aligned parallel to the eastern coastline, particularly in areas such as Sivaganga within the Vaigai river valley, Sriperumbudur, Satyavedu, Kanjeevaram, and Chengalput, which are strategically situated in the Palar basin, thus indicating the geographical distribution and significance of these rock formations. Within the Thoothukudi district, there exists a pronounced fluoride contamination, which can be attributed to the geological presence of hornblende biotite gneiss, charnockites, and various alluvial sediments (*Singaraja et al., 2014*). Furthermore, fluoride-bearing geological formations such as peninsular gneiss and charnockite, which contain essential minerals like apatite, hornblende, and biotite, play a crucial role in the elevated fluoride levels observed in Dindigul district, primarily through the processes of weathering and mineral dissolution, as elucidated by *Chidambaram et al., (2013)*. The interconnected fracture zones, in conjunction with host rocks rich in fluoride and the interaction of these rocks with groundwater, significantly contributes to the high fluoride concentrations that are observed in the groundwater systems of Erode district, as reported by *Karthikeyan et al., (2010)*. Additionally, *Selvam (2015)* posits that the arid climatic conditions combined with an elevated evaporation rate and minimal precipitation contribute to the groundwater salinization in Tuticorin, which subsequently promotes the leaching of fluoride into the groundwater reservoir. According to the research conducted by *Thivya et al., (2015)*, the region of Madurai exhibits elevated concentrations of fluoride within its groundwater, a phenomenon that can be traced back to the underlying granitic and biotite gneiss country rocks that contain notable quantities of minerals rich in fluoride like apatite and fluorapatite.

In contrast, the state of West Bengal, particularly in its western districts are substantially impacted by the pervasive issue of fluoride contamination within its groundwater resources, a situation that has garnered attention from researchers and public health officials alike. Notably, it has been documented that approximately 60 blocks across various districts including Bankura, Bardhaman, Birbhum, Purulia, West Midnapur, Malda, and Uttar Dinajpur are experiencing substantial fluoride contamination, raising concerns regarding public health and safety. *Gupta et al., (2012)* illuminate the concerning levels of fluoride present in the groundwater of the Raniganj coalfield area, which is characterized by Gondwana coal deposits, revealing that nearly 10% of the water samples surveyed exhibited fluoride concentrations that exceed the standards set forth by the World Health Organization (WHO) and the Bureau of Indian Standards (BIS). Moreover, a study by *Mishra et al., (2020)* highlighted the alarming increase in fluoride levels found in the groundwater sourced from the Gangetic alluvial plains, underscoring the widespread nature of this contamination issue. According to *Datta et al., (2014)*, the majority of districts in West Bengal reported fluoride concentrations that remained within acceptable tolerable limits, with the notable exception of the western regions of the state—specifically Bankura, Purulia and Birbhum—where groundwater displays exceedingly high fluoride concentrations that are cause for concern. In the Purulia district, particularly within the Hura, Purulia I, and Purulia II blocks, fluoride



levels in groundwater have been documented to reach alarming heights of 10.75 mg/L, as noted by Bhattacharya and Chakrabarti in their 2011 study. The underlying geological formations of the district consist of Pre-Cambrian rocks that are rich in fluoride-bearing minerals such as fluorite, apatite, and hornblende, which upon weathering contribute to the elevated fluoride levels found within the groundwater resources. Similarly, Bankura exhibits a comparable geological composition that primarily consists of fluoride-rich mineral deposits, further exacerbating the fluoride contamination issues faced by the local population.

The first documented instance of fluorosis, which is a debilitating condition caused by excessive fluoride intake, as well as the identification of fluoride-contaminated groundwater in West Bengal, can be traced back to the year 1996, specifically originating from Nasipur village located in the Nalhati block of Birbhum district, as reported by ***Patra et al., (2010)***. Within the Birbhum district, which encompasses a vast area of approximately 4545 square kilometers, there exists a significant population of about 52,563 individuals who are distributed across 78 villages and hamlets situated within seven administrative blocks, namely Khoyrasol, Nalhati I, Rajnagar, Rampurhat I, Suri II, Mayureshwar I, and Sainthia, and they are all adversely affected by the debilitating effects of fluorosis, as highlighted by ***Mondal et al., (2014)***. The presence of fluoride has been documented across a variety of geological terrains in Birbhum, including granitic, basaltic, and alluvial aquifers, thus demonstrating the widespread nature of this issue and its implications for public health and environmental safety.

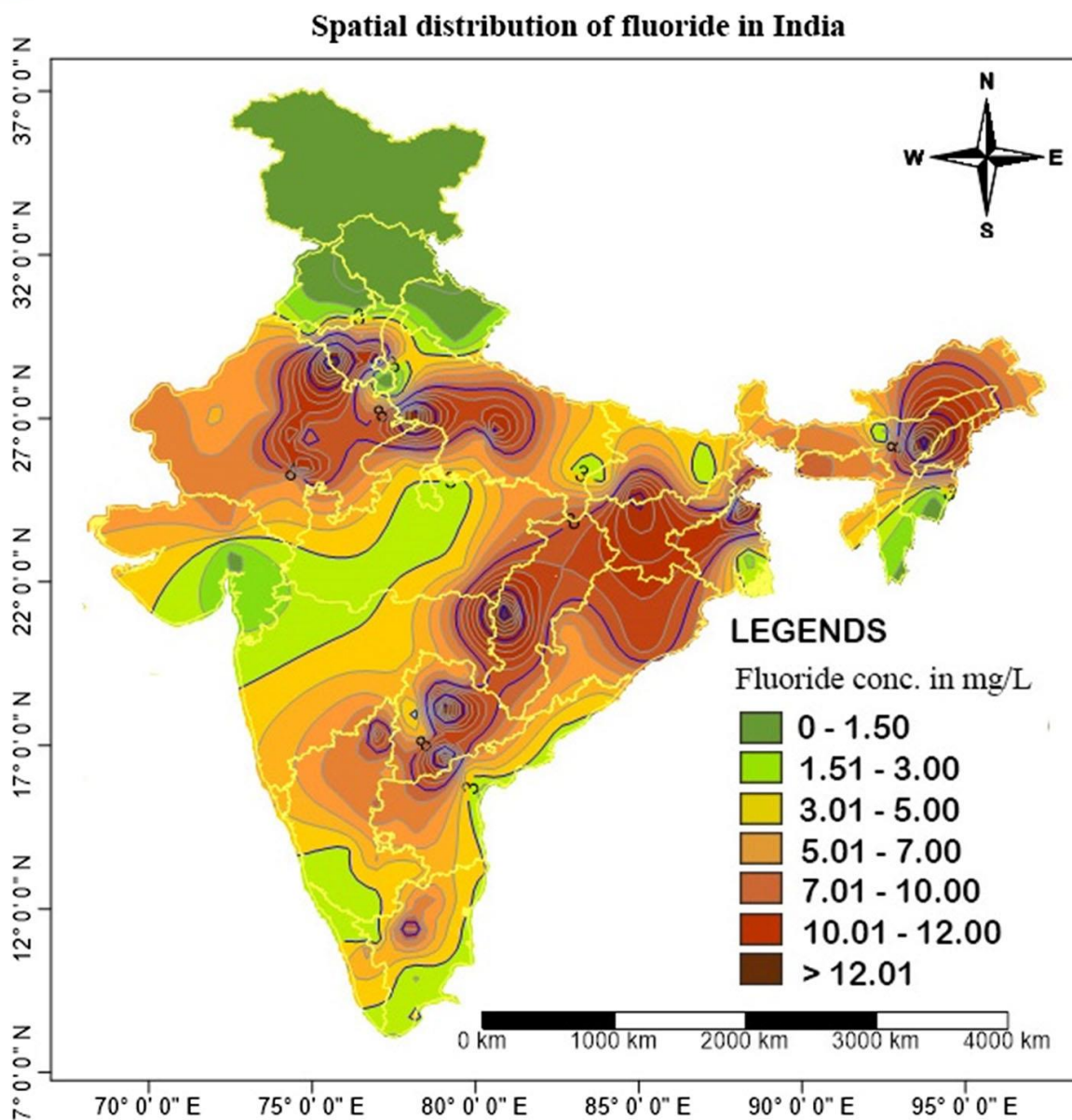


Figure 1.2 Spatial Dispensation of Fluoride concentrations in India (Digitization of GSI Maps)



CHAPTER 2: REVIEW OF LITERATURE

2.1 Preface

Fluoride contamination in groundwater represents a profoundly significant global issue that warrants considerable attention due to the myriad potential health risks it poses, particularly concerning conditions such as dental and skeletal fluorosis, which can have long-lasting and detrimental effects on human health. This pressing concern is not confined solely to underdeveloped nations; rather, it is a pervasive issue that affects both developed and developing countries alike, with the severity of fluoride contamination manifesting in varying degrees that are largely contingent upon a complex interplay of regional geological and environmental factors that differ from one locale to another. The occurrence of fluoride in groundwater is heavily influenced by a variety of natural processes, including but not limited to the weathering and breakdown of fluoride-rich minerals, as well as human-induced activities such as the improper disposal of industrial waste, which can exacerbate the levels of fluoride present in these crucial water resources. In order to effectively address the multifaceted challenge of fluoride contamination, it is imperative to adopt a comprehensive and integrated approach that encompasses continuous monitoring of fluoride levels, thorough risk assessment procedures and the development and implementation of sustainable and efficient remedial technologies that can mitigate the adverse effects of fluoride exposure. The subsequent sections of this document will provide an exhaustive review of the various mechanisms that contribute to fluoride contamination in groundwater, the potential health impacts that may arise from such exposure, and a comprehensive overview of the technologies currently available for the effective removal of fluoride from contaminated water sources.

2.2 Sources and controls on mobilization of fluoride in groundwater

Brindha and Elango, (2011) are of the opinion that fluoride in groundwater originates from both natural and anthropogenic sources. Natural sources include geological conditions with fluoride-bearing minerals like apatite and fluorite, and volcanic ash. Anthropogenic sources involve agricultural fertilizers, particularly phosphate fertilizers, and coal combustion, which releases fluoride into the environment. Controls on fluoride mobilization include monitoring groundwater concentrations, implementing artificial recharging structures, and utilizing exsitu treatment methods such as adsorption and reverse osmosis to reduce fluoride levels before consumption.

According to *Padhi and Muralidharan (2012)*, the sources of fluoride mobilization in groundwater include leachable fluoride from soils and fluoride-bearing minerals such as fluorite, fluorapatite, and hornblende. The controls on this mobilization are influenced by the physico-chemical conditions of the soil, such as its alkaline nature and the presence of silt and clay, which enhance adsorption and leaching. Additionally, groundwater flow dynamics



and weathering processes play significant roles in the concentration and distribution of fluoride in the study area.

Hallet (2012), his attempted to understand the mineralogy of fluoride mobilization, found that the principal sources of fluoride (F) in groundwater from the study granites, with apatite, biotite, fluorite, amphiboles, and titanite identified as key F-bearing minerals. The mobilization of fluoride is influenced by weathering processes and regolith development, which affect its distribution. Batch leaching experiments indicated that weathered samples, despite low total F content, can release mobile and water-soluble F to groundwater.

Roy and Das (2013) are of the opinion that the sources of fluoride in groundwater include the dissolution of fluoride-containing rock minerals and artificial contributions from phosphate fertilizers, sewage sludges, and pesticides. The mobilization of fluoride is influenced by factors such as the amount of soluble and insoluble fluoride in source rocks, soil temperature, rainfall, and the oxidation-reduction process.

Li et al. (2013) in their investigation conducted in the Datong Basin, China, identified that the fluoride present in groundwater predominantly originates from fluorine-rich minerals including fluorite, biotite, and amphibole. The mobilization of fluoride is controlled by factors including fluorite solubility, prolonged water-rock interactions, residence time, and evapotranspiration intensity. Seasonal variations and agricultural activities also influence fluoride concentrations, with higher levels observed in winter due to reduced dilution from precipitation and irrigation. The hydrochemical type transitions from Ca-HCO₃ in recharge areas to Na-Cl-SO₄ in discharge areas, facilitating fluoride enrichment.

Dutta et al., (2014) found that the mobilization of fluoride in groundwater is primarily influenced by the mineral composition of aquifer sediments and the chemical interactions in solution. According to their findings Na-rich solutions significantly enhanced fluoride release, with silty-clay samples releasing six times more fluoride than sand samples. Key controls include the weathering of muscovite/biotite in sand and ion-exchange mechanisms in silty-clay. Additionally, the Na/Ca ratio and the presence of HCO₃ are crucial in facilitating fluoride mobilization from the sediment matrix.

Wei et al., (2015) found that the mobilization of fluoride in groundwater is primarily controlled by the solubility of fluorite (CaF₂) and influenced by geogenic processes. Key factors include temperature, solution composition, pH, CO₂ partial pressure, and the presence of carbonate minerals in the aquifer. Fluoride concentration is highest in NaHCO₃ type solutions, while dissolved CO₂ can increase fluoride levels in non-bicarbonate systems but decreases it in calcite-bearing aquifers. The solubility of fluorite sets the upper limit for fluoride concentration in groundwater.

Dong et al. (2015) opined that the mobilization of fluoride in groundwater is primarily controlled by the alkaline environment, characterized by high levels of HCO₃⁻, Na⁺, TDS, and EC, along with calcium deficiency. Sources include weathering and leaching of fluoride-containing minerals from granitic and basaltic formations, as well as volcanic eruptions that



deposited fluoride-rich materials. In confined aquifers, lithology significantly influences fluoride concentration, particularly in lacustrine platform zones, where slow groundwater flow allows for higher fluoride accumulation.

Dehbandi et al., (2017) in their research found that the sources and controls on the mobilization of fluoride in groundwater in the endemic fluorosis belt of central Iran include the presence of various fluoride-bearing minerals and clay minerals in soils and aquifer materials. Geochemical modeling indicated that groundwater is mostly oversaturated with calcite and dolomite, while fluoride concentrations are negatively correlated with pH and bicarbonate. Additionally, water-rock interactions and the influence of clay minerals are key geochemical mechanisms driving fluoride enrichment in groundwater.

Haji et al., (2018) in their work in the Southern Main Ethiopian rift found that fluoride in groundwater is primarily sourced from geogenic origins, including fluoride rich minerals like topaz, fluorite, and biotite, influenced by rock types like sedimentary and volcanic rocks. The controls on fluoride mobilization include hydrogeological and hydrodynamic conditions, with stagnant flow environments facilitating fluoride accumulation through silicate hydrolysis and ion exchange processes. Robust hydrodynamic activity in elevated terrains displaces weathered materials, thereby constraining fluoride levels in superficial groundwater relative to deeper aquifers situated within the rift valley.

Cordona et al., (2018) found that the primary source of elevated fluoride concentrations in groundwater around San Luis Potosí is the thermal water–rock interaction with regional rhyolites. Natural controls on fluoride mobilization include fluorite precipitation, which reduces fluoride concentrations in the aqueous phase, and the solubility control by CaF_2 when water travels through Ca-rich sediments. Additionally, mixing of thermal and cold water end-members influences fluoride levels, with geochemical variations indicating the presence of multiple flow systems contributing to fluoride mobilization.

Mukherjee and Singh (2018) opine that fluoride originates from various sources in the groundwater, including fluoride-bearing aquifers, geological factors, and subsurface contamination. The principal factors influencing its mobilization encompass the rate of weathering processes, ion-exchange dynamics, duration of water residence and the rate of leaching. These processes indicate the geochemical dynamics of an area, contributing to the presence of high fluoride concentrations. Understanding these factors is crucial for addressing groundwater quality issues, particularly in regions like Rajasthan, Andhra Pradesh, and Tamil Nadu, where contamination is prevalent.

Younas et al., (2019) observed that the mobilization of fluoride in groundwater is primarily dominated by the weathering of silicate minerals, particularly granitic rocks, and the exchange of hydroxyl ions (OH^-) on clay surfaces under alkaline conditions. High pH facilitates the leaching and mobility of fluoride, with significant correlations observed between fluoride concentrations and bicarbonate (HCO_3^-).



Dubey et al. (2021) opine that major sources of fluoride mobilization in groundwater in central India include granite gneisses, limestones, sandstones, and basalts, with maximum concentrations reaching up to 4.9 mg/L. Key controls on fluoride mobilization are water-rock interactions, particularly in alkaline environments, and low-temperature hydrothermal mineralization of fluorite in limestone aquifers. The presence of fluor-apatite in granite gneiss aquifers, with high F^- content, also substantially influence the concentrations of fluoride present in groundwater, indicating geogenic enrichment as the primary factor.

Mandal et al., (2021) suggest that the sources of fluoride mobilization in groundwater include water-rock interaction with fluoride-bearing minerals found in granites and gneisses, which significantly contributes to high fluoride levels. Additionally, phosphate fertilizers can add approximately 0.46 mg/L of fluoride to groundwater, particularly affecting low fluoride samples. Controls on fluoride levels are influenced by factors such as high pH, sodium, alkalinity, and low calcium concentrations, with calcite precipitation playing a crucial role in the solubility of fluoride-bearing minerals.

Aind et al., (2022) suggest that the mobilization of fluoride (F^-) in groundwater is primarily controlled by geotectonic factors, climate, and anthropogenic activities such as land use and groundwater pumping. The study indicates that unsaturated zone mineralogy, particularly the presence of clay minerals, calcite, and Fe, Al hydroxides, significantly influences F^- retention and mobilization. Areas underlain by granitic-gneissic complexes exhibit the highest unsaturated zone F^- inventory, while the absence of these minerals in Pleistocene alluvial deposits leads to enhanced leaching of fluoride into groundwater.

Ali et al. (2023) assert that the mobilization of fluoride (F^-) within groundwater is predominantly governed by alkalinity, which is instrumental in facilitating the release of fluoride from geological substrates. The research reveals that elevated concentrations of fluoride are more commonly observed in arid and semi-arid alluvial plains in contrast to hard rock formations. Furthermore, a positive association exists between increased fluoride concentrations and geogenic sources associated with the weathering of fluorine-containing silicates, particularly in relation to SiO_2 and K^+ . Collectively, these elements significantly regulate fluoride mobilization 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.

2.2.1 Geogenic Sources

2.2.1.1 Rocks and minerals

Rao et al. (2003) assert that geological origins of fluoride pollution in the groundwater of Anantapur District, Andhra Pradesh, are predominantly attributed to the local lithology, notably the Peninsular Gneisses dating back to the Archaean era. Fluorine exhibits a strong affinity for adsorption within soils that are abundant in clay minerals, while the processes of weathering promote the leaching of fluoride into the subterranean water. Furthermore, the dissolution of fluorine-containing minerals is augmented by the alkaline conditions prevalent in the region, extended residence periods of water, and rigorous irrigation practices, which collectively result in heightened concentrations of fluoride in the groundwater.

Chae et al., (2008) opines that the geological sources of fluoride contamination in groundwater in the Samseung area of South Korea are primarily linked to the presence of fluoride-rich minerals in granite terrain, particularly biotite granite. The study indicates that fluoride ion in groundwater has a geogenic origin, with high concentrations correlated to local



heterogeneity of these minerals. Additionally, the distribution of permeable structures, such as lineaments and faults, facilitates the discharge of deep bedrock groundwater, contributing to the fluoride levels observed in the area.

Vasak et al.,(2010) opine that contamination of fluoride in groundwater can originate from geological sources like minerals rich in fluoride and volcanic gases. These natural sources contribute to elevated fluoride concentrations in water supplies, particularly in regions with specific geological formations like Precambrian Basement areas and volcanic zones of the African Rift system. Comprehending the geochemical dynamics of fluorine within these contexts is imperative for evaluating the potential hazards associated with elevated fluoride concentrations in groundwater, as well as for the strategizing of efficient water supply infrastructures.

Chakraborty and Sarma (2011) in their study in the Kamrup district, Assam, found that The geological sources of fluoride in groundwater include the presence of fluoride-containing minerals such as hornblende diorite and amphibolites within the granitic gneiss formations. These minerals contribute to higher fluoride concentrations due to their dissolution in groundwater. Additionally, the area's geological composition, characterized by igneous and metamorphic rocks, facilitates the release of fluoride ions, leading to significant contamination levels exceeding the maximum contaminant level (MCL) of 1.5 mg/L.

Arveti et al.,(2011) opine that Fluoride contamination in groundwater is primarily sourced from fluoride-bearing minerals in granite aquifers, particularly in arid regions like Talupula, Andhra Pradesh. The alkaline pH and high bicarbonate levels facilitate the release of fluoride from these minerals. Additionally, the weathering of silicate rocks by carbonic acid contributes to fluoride dissolution. Geological conditions, coupled with low freshwater exchange due to droughts, exacerbate fluoride concentration in groundwater, posing health risks to local populations reliant on these water sources.

Özmen et al.,(2011) suggest that the geological sources of fluoride contamination in groundwater primarily include minerals enriched in fluoride such as apatite, fluorite, tourmaline, and mica, commonly seen in granite, syenite, nepheline syenite, and gneiss. In the Kaman region, hydrothermal fluorite mineralization occurs in fractures of syenite and nepheline-syenites, with fluoride concentrations in these rocks ranging from 480 to 11,990 ppm, leading to significant contamination.

Gupta et al.,(2012) found that the Fluoride contamination in groundwater within the Raniganj coal field is primarily attributed to the dissolution of fluoride-bearing minerals in sandstone-dominant aquifers. The hydrolysis of alumino-silicate minerals produces bicarbonate ions, enhancing fluorite dissolution. Additionally, ion-exchange processes and evaporation contribute to fluoride levels. The groundwater is generally unsaturated with respect to fluorite, and high fluoride concentrations correlate with low calcium and high bicarbonate ion content, indicating the influence of geological factors on fluoride presence.



Srinivasamoorthy et al., (2012) point out that contamination of fluoride in groundwater in Mettur region primarily originates from geological sources, particularly by minerals rich in fluoride like apatite, hornblende, biotite etc. found in charnockites and peninsular gneiss. The higher degree of weathering in charnockites facilitates the accessibility of these minerals, enhancing fluoride concentration. Additionally, the region's crystalline metamorphic complexes and the chemical weathering processes expedite the leaching of fluoride, exacerbated by the area's dry and semi-arid climatic conditions.

Vikas et al., (2013) suggest that fluoride contamination primarily originates from the weathering of minerals enriched in fluoride present in hard rocks and alluvial formations. In the areas geologically characterized like granite gneiss and schist, with higher fluoride concentrations observed in granite gneissic terrains. The alkaline environment in arid to semi-arid conditions, along with chemical weathering processes, facilitates the dissolution of fluoride into groundwater, contributing to elevated fluoride levels in the aquifers.

Jha et al. (2013) assert that the presence of fluoride in groundwater chiefly stems from the weathering and leaching processes of fluoride-containing minerals located in rocks and sediments. Elevated fluoride concentrations are frequently linked to sodium bicarbonate-dominant water that lacks adequate calcium. The water's alkalinity further promotes the release of fluoride from minerals such as fluorite (CaF_2). These geological mechanisms play a crucial role in the prevalence of fluoride in groundwater, presenting a toxicological threat to human health.

Satpathy et al., (2014) suggest that fluoride contamination in groundwater can originate from diverse geological environments, including sedimentary rocks, crystalline rocks, and volcanic aquifers. The study highlights that these geological sources contribute to fluoride contamination, which is a significant public health concern, particularly in regions like India where groundwater is a primary drinking water source. Monitoring fluoride levels in these geological contexts is essential to assess water quality and prevent health issues related to fluoride exposure.

Singaraja et al., (2014) observed that groundwater fluoride contamination in the Thoothukudi District primarily originates from the weathering of fluoride rich minerals present in the bedrock, which includes hornblende biotite gneiss, charnockite, and granite. The geological composition, characterized by hard rock terrain and alluvial plains, contributes to elevated fluoride concentrations, particularly in the northern and central parts of the study area. Additionally, geogenic sources such as apatite, biotite, and clays, along with human induced factors, further influence fluoride levels in groundwater.

Vithanage and Bhattacharya (2015) suggest that the geological sources of fluoride contamination in groundwater primarily include rocks containing fluoride-rich minerals, such as gneisses and granites, which can have concentrations exceeding 5000 mg/kg. Other sources include volcanic ash and hydro-geothermal sources. The dissolution of fluoride from these rocks is influenced by factors like alkalinity, specific conductivity, and evaporation.



Additionally, weathering processes and the presence of secondary minerals contribute to fluoride release into groundwater, particularly in arid and semi-arid regions.

Banerjee (2015) is of the opinion that the primary geological sources of groundwater fluoride contamination are the weathering of fluorapatite (FAP) $[\text{Ca}_5(\text{PO}_4)_3\text{F}]$ and fluorite (CaF_2). These minerals release fluoride ions into the groundwater, particularly influenced by the precipitation of calcite, which significantly slows down the dissolution of FAP. The interaction time between rock and water must be extensive, on the order of 10^6 years, for substantial fluoride contamination to occur, highlighting the importance of geological processes in this context.

Sivasankar et al., (2016) opine that contamination of fluoride in groundwater primarily originates from the solubility of fluorapatite and other fluoride bearing minerals. Determinants affecting fluoride concentrations encompass litho-chemical properties, the depth and duration of water residence, as well as the preferential conduits facilitating deep groundwater flow. Furthermore, the hydrological dynamics of these conduits, alongside the geological framework, substantially influence the gradients of fluoride concentration. The interplay between aqueous solutions and sedimentary carbonates similarly plays a pivotal role in the overall fluoride content within groundwater systems.

Jha and Mishra (2016) postulate that fluoride contamination in groundwater primarily originates from natural geological sources, including the weathering of fluoride-rich minerals such as fluorite and apatite. The leaching and percolation processes through these minerals, influenced by local and regional geological settings, contribute significantly to the mobilization of fluoride into groundwater. Additionally, hydro-geochemical conditions play a crucial role in facilitating the dissolution of fluoride from rocks and minerals, leading to elevated concentrations in affected areas across various countries.

Dharmagunawardhane et al., (2016) point out that geological sources of fluoride contamination in groundwater in the study area of Polonnaruwa, Sri Lanka, primarily include the charnockitic gneiss bedrock, specifically minerals such as apatite, biotite, titanite (sphene), and hornblende. Apatite serves as a steady fluoride donor due to its high fluoride content and uniform distribution, in regions where hornblende and biotite are prevalent, they have the potential to induce significant fluoride concentrations. Weathering processes further release fluoride into the groundwater system, contributing to fluorosis.

Keesari et al., (2016) observed that the geological sources of fluoride contamination in groundwater in the Talchir region of Odisha, India, primarily include granitic rocks that contain fluoride-bearing minerals such as amphibole, biotite, and fluorite. The area's geology, dominated by these minerals, contributes to higher fluoride levels due to rock weathering processes. Additionally, groundwater under unsaturated conditions with respect to fluorite can lead to increased fluoride contamination, as indicated by the study's geochemical and isotopic investigations.



Patolia et al., (2017) found that the geological sources of fluoride contamination in groundwater in Gharbar Village are primarily linked to the geochemical composition of local rocks, which contribute to high fluoride concentrations. The study indicates that weathering of these rocks, along with alkaline environmental conditions and ion exchange processes, play significant roles in fluoride mobilization. The correlation of fluoride with pH and sodium, and its negative correlation with calcium, further supports the influence of rock-water interactions in the area's groundwater chemistry.

Narsimha and Sudarshan (2017) in their research work in Siddipet, Telangana, found that Fluoride contamination in groundwater is primarily sourced from the weathering and leaching of fluoride-bearing minerals, particularly fluorite (CaF_2), found in granitic gneiss and other rock formations. The study indicates that prolonged water-rock interactions, influenced by climatic conditions, facilitate the release of fluoride into groundwater. Additionally, the deficiency of calcium ions in the aquifers promotes fluorite dissolution, leading to elevated fluoride concentrations, particularly in areas with granite and granite gneiss geology.

Dubey et al., (2018) suggest that groundwater fluoride contamination in the Warora area is primarily sourced from the leaching of fluoride-bearing minerals found in the shales and limestones of the Lameta Formation, as well as from basaltic lava flows. The geological setting includes mixed rock types ranging from Archean to Cretaceous, with the highest fluoride concentrations recorded in shallow aquifers. The deeper gneissic aquifers are ruled out as potential sources, indicating that the shallower lithostratigraphic horizons are responsible for the elevated fluoride levels.

Haji et al., (2018) suggest that groundwater fluoride contamination is primarily geogenic, influenced by various rock types such as sedimentary, igneous, and metamorphic rocks. Fluorine-bearing minerals like topaz, fluorite, tourmaline, muscovite, biotite, hornblende, and villianmite release fluoride through weathering and water-rock interactions. Additionally, volcanic emissions and geothermal water contribute to fluoride levels. The study indicates that the interplay of silicate hydrolysis and ion exchange mechanisms within stagnant flow environments is instrumental in the augmentation of fluoride concentrations in aquifers.

Mukherjee and Singh (2018) in their detailed review on Fluoride contamination in the Indian context, suggest that the fluoride contamination in groundwater primarily originates from fluoride-bearing aquifers. The intensity of weathering of fluoride-rich minerals, ion-exchange reactions, and the leaching of subsurface contaminants also contribute significantly to fluoride availability. The geochemical mechanisms, shaped by the surrounding geological and hydrological conditions, significantly contribute to the establishment of fluoride concentrations in groundwater, especially within the arid and semiarid zones of India, where elevated fluoride concentrations have been documented.

Kumar et al., (2019) observed that fluoride contamination in groundwater primarily originates from geogenic sources, specifically the weathering and leaching of fluoride-bearing



minerals such as biotite, apatite, quartz, sphene, and hornblende found in igneous and metamorphic rocks. The interaction of groundwater with these rock types under alkaline conditions, coupled with prolonged residence time and ion exchange processes, significantly contributes to elevated fluoride concentrations in the aquifer.

Younas et al.,(2019) found that groundwater fluoride contamination is primarily attributed to the weathering of minerals rich in fluoride, particularly fluorite (CaF_2), found in granitic and alkaline rocks. The study indicates that the leaching and mobility of fluoride are facilitated by alkaline groundwater conditions, that enhances the breakdown of fluoride minerals. Additionally, the presence of silicate minerals contributes to fluoride release through hydrolysis processes, augmenting the levels of fluoride present in the groundwater of the semi-arid alluvial aquifers located in Pakistan.

Mondal and Sanyal (2019) observed that fluoride contamination in groundwater is primarily geogenic in origin, often resulting from the dissolution of fluoride-rich minerals and rocks in the sub-surface. In the Puruliya District, the alkaline characteristics of the water, coupled with prolonged residence time within fractured aquifers, and the area's semi-arid climate contribute to fluoride enrichment. Additionally, the geological features and topography play a crucial role, as areas with high evaporation rates and limited groundwater recharge contamination of fluoride.

Dubey et al.,(2021) observed that the geological sources of fluoride contamination in groundwater in central India include granite gneisses, limestones, sandstones, and basalts. The study identified fluor-apatite in granite gneiss aquifers as a significant contributor, with fluoride content ranging from 2.5 to 4.2 wt%. Additionally, low-temperature hydrothermal mineralization of fluorite in limestone aquifers leads to higher fluoride concentrations, with values reaching up to 4.9 mg/L. Water-rock interactions, particularly in alkaline environments, further enhance fluoride dissolution in groundwater.

Mandal et al.,(2021) observed that geogenic sources of fluoride contamination in the study are primarily due to interaction of water and rocks having fluoride-bearing minerals such as in granites and gneisses. This interaction leads to high fluoride concentrations, with levels between 0.3 to 12 mg/L. Additionally, phosphate fertilizers contribute up to approximately 0.46 mg/L of fluoride in groundwater, particularly affecting samples with initially low fluoride concentrations. These factors significantly influence the spatial variability of fluoride levels in the region.

Maitra et al.,(2021) identified in their study that the geological sources of groundwater fluoride contamination include the weathering and disintegration of minerals enriched in fluoride from the rocks in the area. The hydrochemistry is influenced by the lithological characteristics, leading to high fluoride concentrations. Additionally, processes such as evaporation, the mixing of cold groundwater with fluoride-rich hot spring water and anthropogenic influences contribute to the elevated fluoride levels observed in the groundwater samples from the selected geothermal sites in Odisha, India.



Arredondo et al.,(2022) observed that Fluoride contamination in groundwater in the southeastern El Bajío region of Guanajuato, Mexico, primarily originates from volcanic rocks, particularly felsic types, which contain disseminated fluoride. The release of fluoride into groundwater is ascribed to the dissolution of volcanic glass, the alkaline desorption from minerals containing fluoride, and the ion exchange mechanisms occurring within minerals and clays. Additionally, the geothermal characteristics of the groundwater may accelerate these processes, leading to higher fluoride concentrations in the aquifers utilized by the local population.

Aind et al.,(2022) opine that the geological sources of fluoride in groundwater include the presence of fluoride-bearing minerals such as fluorite (CaF_2) and the mineralogy of the unsaturated zone. In the study area, the granitic–gneissic complex, residual soils, and Pleistocene alluvial deposits exhibit varying fluoride inventories, with the granitic–gneissic complex showing the highest. The mineral composition, particularly clay minerals, calcite, and Fe, Al hydroxides, influences fluoride retention and mobilization into groundwater, affecting fluoride levels in different geological terrains.

Nakayama et al.,(2022) are of the opinion that Fluoride contamination in groundwater is primarily sourced from the weathering of minerals containing fluoride within granitic rocks. In the Tabora region of Tanzania, the extent of weathering enhances fluoride leaching into groundwater. Additionally, in fractured zones, the direction of faults influences fluoride levels, with deeper water strikes and higher well yield potential correlating with lower fluoride concentrations. This heterogeneity in fluoride distribution poses challenges for groundwater development and necessitates careful assessment of hydrogeological structures.

Ghosh et al.,(2023) found that contamination of fluoride in groundwater may be principally attributed to the weathering and dissolution of fluoride-containing minerals, such as muscovite and fluorite, present in the subsurface lithology of the Sedimentary Alluvial Plain of Bankura District, West Bengal, India. The study indicates that rock-water interactions significantly influence major ion chemistry, with fluoride being leached from host materials in an alkaline-dominated environment. This process is exacerbated in elevated regions where rainwater interacts with fluoride-bearing minerals during infiltration and percolation.

Mustafa et al.,(2023) found that the primary sources of fluoride (F^-) contamination in groundwater within the Kurdistan Region of Iraq are geogenic, influenced by geological formations such as metamorphic rocks, which contain fluoride concentrations ranging from 100 to 5000 ppm. Factors affecting fluoride levels include temperature, pH, water-rock interaction, and the solubility of fluorine-bearing minerals. Additionally, the presence of complexing ions and the geological formations that water flows through play significant roles in controlling fluoride concentrations in groundwater.

Sulaiman et al.,(2023) suggest that the geological source of fluoride contamination in groundwater in the Indo-Gangetic Plains primarily stems from Quaternary alluvial sediment deposits. These geological formations contribute significantly to the fluoride (F^-) concentration in the groundwater. Additionally, anthropogenic activities further exacerbate



the fluoride levels. The study highlights that the severity of fluoride toxicity is particularly pronounced in the northern and lower regions of the Indo-Gangetic Plains, influenced by factors such as water type, pH, and evaporation processes.

Beg et al., (2023) found that high fluoride (F^-) concentration in groundwater in the Tamnar area is primarily associated with the Barakar Formation, which consists of feldspathic sandstones, shales, and coal. Micas and clay minerals in these formations may also contribute to fluoride release. The geochemical processes involved include feldspar dissolution and cation exchange, particularly with Na^+ and Ca^{2+} . Additionally, the higher residence time and temperature of groundwater in deeper aquifers enhance the dissolution of fluorine-bearing minerals, leading to increased fluoride levels.

Shaji et al. (2023) propose that the geological origins of fluoride pollution in groundwater predominantly consist of high-grade metamorphic terranes characterized by granitoid or alkaline intrusions, geothermal hot springs, and volcanic areas. These geological structures play a significant role in increasing fluoride concentrations in potable water, especially in arid or semi-arid climatic environments. The study highlights that fluoride contamination is often geogenic, meaning it originates from natural geological processes rather than anthropogenic sources, which also include forage, grasses, grains, and tea.

Rashid et al., (2024) suggest that fluoride contamination in groundwater is primarily linked to the presence of F-bearing minerals such as biotite and muscovite, as indicated by photomicrographs of granite rocks. The study found that the enrichment of fluoride (F^-) is associated with higher pH levels, $NaHCO_3$, $NaCl$, and depleted Ca^{+2} aquifers. Additionally, thermodynamic considerations of fluorite minerals showed undersaturation, suggesting that other geological sources contribute to the fluoride levels in the groundwater of the semiarid region of Gilgit, Pakistan.

Ning et al., (2024) suggest that Geogenic fluoride contamination in groundwater primarily arises from the dissolution of fluoride-bearing minerals in geological formations, particularly in cold Mollisol regions. The study highlights that biogenic dissolution-precipitation equilibria of calcium-containing minerals contribute to the seasonal variation of fluoride concentration in groundwater. This process, influenced by the infiltration of dissolved organic matter from Mollisols, alters the hydrochemical types of groundwater, leading to elevated fluoride levels that pose health risks to local communities.

Wei et al., (2024) are of the opinion that the geological sources of fluoride contamination in groundwater primarily include the dissolution of fluoride-containing minerals such as fluorite and apatite. These natural processes contribute to the enrichment of fluoride in aquifers. Additionally, cation exchange and competitive adsorption of bicarbonate (HCO_3^-) and hydroxide (OH^-) with fluoride (F^-) in an alkaline environment further influence fluoride levels. The study highlights that these natural factors play a significant role in the genesis of high fluoride groundwater in the investigated area.



Chaudhuri et al.,(2024) are of the opinion that natural sources of fluoride contamination in groundwater primarily include the weathering of rocks that contain fluoride-rich minerals and volcanic eruptions. These geological processes release fluoride into the water, contributing to elevated concentrations. Additionally, the type of rock, tectonics, and the physico-chemical properties of the water play significant roles in determining fluoride levels.

2.2.1.2 Geothermal Sources

A study conducted by **Lottermoser and Cleverly (2007)** in Queensland, Australia, indicate that The study indicates that fluoride contamination in groundwater at Innot Hot Springs is primarily controlled by fluid-rock interactions with fluorite-bearing granitic rocks at temperatures between 150 and 200°C. The thermal water, which is meteoric in origin, contributes significant fluoride to local surface waters, particularly during the dry season, leading to elevated fluoride concentrations (up to 18 mg/L) in Nettle Creek. This contamination poses risks to water quality, making it unsuitable for livestock consumption.

Ayenaw (2008) opine that fluoride contamination in groundwater is often associated with geothermal sources, particularly in regions with active and sub-active thermal fields and acidic volcanics. The study indicates that high-temperature geothermal systems contribute significantly to fluoride mineralization, with deep wells and springs near these geothermal waters exhibiting high fluoride levels. Moreover, meteoric waters that replenish volcanic aquifers tend to accumulate fluoride as they traverse from elevated recharge zones to rift discharge zones, thereby exacerbating the contamination of groundwater resources.

Vasak et al.,(2010) suggest that Geothermal sources of fluoride contamination in groundwater primarily arise from volcanic gases and the leaching of fluoride-bearing minerals. In volcanic regions, such as the African Rift system, geothermal processes can elevate fluoride concentrations in groundwater. This natural occurrence, combined with anthropogenic factors, contributes to the prevalence of high fluoride levels, often exceeding the WHO guideline of 1.5 mg/L, leading to health issues like fluorosis.

Bhattacharya and Chakrabarti (2011) in their study in Purulia district, West Bengal, found that groundwater fluoride contamination is primarily attributed to geological factors, particularly the presence of fluoride-bearing minerals such as apatite, fluorite, biotite mica, and hornblende within the Pre-Cambrian metamorphic rocks of the Purulia District. Hydrothermal fluids can adsorb fluoride into the structure of these silicate minerals, which may leach into groundwater under favorable conditions. Additionally, structural weaknesses like shear zones, joints, and contacts in the host rock facilitate fluoride mineralization, contributing to elevated fluoride levels in the groundwater.

Cakin et al.,(2012) suggest that Geothermal sources of fluoride contamination in groundwater primarily arise from the interaction of geothermal fluids with geological formations. In the Balçova Geothermal Field, high concentrations of fluoride were detected in groundwater, indicating the influence of geothermal fluid. The study found that the shallow aquifer has been affected by geothermal fluid, leading to elevated fluoride levels,



which exceeded drinking water standards. This contamination poses risks to agricultural activities, as the groundwater is extensively used for irrigation.

Atasoy et al., (2013) are of the opinion that Geothermal sources of fluoride contamination in groundwater are linked to volcanic rocks and geothermal resources, as observed in certain regions of Turkey. These natural geological formations can leach fluoride into the water supply, leading to endemic fluorosis among populations relying on this contaminated water for drinking. The study highlights the significance of addressing fluoride levels in such areas to mitigate health risks associated with fluorosis.

Silva et al., (2014) suggest that geothermal sources of fluoride contamination in groundwater may be associated with saline, thermal waters in confined areas. It indicates that the origin of fluoride could be linked to pre-SGA formations containing salts and sulfated minerals. Additionally, the most widely accepted hypothesis points to mixtures with saline deep waters, where vertical flows predominate, enhancing the ion exchange capacity of clay minerals, which may contribute to anomalous fluoride concentrations in groundwater.

Satpathy et al., (2014) notes that Geothermal sources of fluoride contamination in groundwater can be associated with volcanic aquifers. The occurrence of high fluoride content in groundwater is linked to diverse geological environments, including sedimentary rocks and crystalline rocks. These geological formations can release fluoride into the groundwater, contributing to contamination.

Vithanage and Bhattacharya (2015) point out that Geothermal sources contribute to fluoride contamination in groundwater, particularly in areas with hydrothermal activity. Acidic geothermal waters can contain high fluoride concentrations under low pH conditions. Additionally, high fluoride levels are often found in closed-basin alkaline lakes due to rift valleys with hyperalkaline volcanic rocks. The dissolution of fluoride from minerals in these geothermal environments is influenced by factors such as evaporation, soil pH, and the presence of specific minerals that enhance fluoride solubility.

Ali et al. (2016) assert that the contamination of groundwater by fluoride is significantly affected by geothermal parameters, notably temperature and alkalinity. In geothermal springs, the levels of fluoride can attain concentrations as elevated as 2800 mg/L. Elevated temperatures promote the leaching of fluoride from minerals containing fluorine, while alkaline environments facilitate the mobilization of fluoride. This phenomenon is particularly evident in arid and semi-arid areas, where high evaporation rates lead to heightened fluoride levels in groundwater, a consequence of the chemical weathering of alkaline volcanic formations and their associated minerals.

Atasoy and Yesilnacar (2017) discovered that the geothermal origins of fluoride pollution in groundwater predominantly stem from volcanic formations and specific geological conditions. Within the region of Sanliurfa, Turkey, elevated fluoride levels in groundwater are linked to the volcanic soil types and phosphate deposits found near Mazi Mountain. These geological characteristics result in heightened fluoride concentrations, ranging between 1 to 4 mg/L,



surpassing the allowable thresholds established by national standards and the WHO, consequently leading to health complications like dental fluorosis.

Chunhui et al.,(2018) found that the geothermal waters of Tibet, where the presence of fluoride (F⁻) poses a considerable risk. Geothermal features have the ability to leach fluoride from the minerals found in the earth's crust, resulting in heightened concentrations in groundwater. This investigation emphasizes the use of transformed yak dung biochar as a means to effectively extract both fluoride and arsenic (As) from this tainted geothermal water, underlining the ecological repercussions of geothermal activities on the quality of water.

Ameur et al.,(2019) found that Geothermal sources of fluoride contamination in groundwater in the Oued Rmel aquifer are primarily linked to discharges from thermal springs, specifically Hammam Zriba and Hammam Djedidi. These hydrothermal sources contribute to elevated fluoride concentrations, which range from 4 to 22 mg/L in the aquifer. The study indicates that these geothermal activities, along with potential leachate from nearby fluorite mines, are significant contributors to the high fluoride levels observed in the groundwater, posing health risks to the local population.

Bianchini et al.,(2020) identified that geothermal sources of fluoride contamination in groundwater as primarily geogenic, stemming from the weathering of volcanic glass and minerals such as apatites and clays. The interaction of CO₂-bearing alkaline water with these materials facilitates the mobilization of fluoride into the liquid phase. Hot spring water is particularly contaminated, with leaching processes enhanced by the presence of fluvio-lacustrine sediments, indicating that geothermal activity significantly contributes to fluoride levels in the Main Ethiopian Rift waters.

Addison et al.,(2021) propose that concealed geothermal springs are a major contributor to fluoride pollution in groundwater, especially within the Rift Valley of Malawi. These springs release an excessive fluoride in dissolved state into local water sources, resulting in widespread and severe dental fluorosis. The study emphasizes the difficulty in forecasting the presence of these hot springs due to irregular groundwater data. A groundbreaking technique utilizing proxy indicators was created to locate these hidden springs, thereby improving the comprehension of groundwater fluoride origins and their effects on public health.

Kaur et al.,(2021) suggest that Geothermal controls on fluoride contamination in groundwater are influenced by tectonicity, including the aquifer capacity and rock-water interactions. The occurrence of fluoride in groundwater is mainly attributed to natural sources like granite and biotite, which emit fluoride via chemical processes such as precipitation and evaporation. These geological traits, coupled with fluctuations in temperature, significantly influence the movement and accumulation of fluoride in groundwater supplies, especially in arid and semi-arid areas.



Arredondo et al.,(2022) found that groundwater fluoride contamination in the study area is controlled by geothermal factors, as the geothermal characteristics of the groundwater can accelerate the mobilization of fluoride. This process involves volcanic glass dissolution, alkaline desorption from fluoride-bearing minerals, ionic exchange in clay minerals. The interaction of these processes, particularly in the fractured volcanic environment, contributes to the high concentrations of fluoride found in the groundwater, posing health risks to the local population.

Suyarko et al.,(2022) identified that Geothermal sources of fluoride contamination in groundwater are primarily linked to the influx of endogenous fluids that discharge along fault structures during the post-hydrothermal stage of tectonic activation. These fluids mix with formation waters, leading to the formation of hydrogeochemical anomalies. Additionally, hypergenic physicochemical destruction of fluorite (CaF_2) by gravitational infiltration waters contributes to elevated fluoride levels, particularly in areas with significant geothermal activity, such as the Pokrovo-Kyreevsky fluorite deposit and the Mykytiv mercury ore field.

Kundu et al.,(2022) opine that Geothermal controls on fluoride contamination in groundwater are evident from the venting of high fluoride-rich thermal water into the regional aquifer system through fractured and weathered rocks. The study indicates that the mixing of this thermal water with surrounding groundwater leads to elevated fluoride concentrations, particularly around the hot spring and nearby villages. The spatial distribution of fluoride correlates inversely with apparent resistivity, highlighting the influence of geothermal activity on groundwater quality in the area.

Podgorsky and Berg (2022) suggest that Geothermal conditions influence fluoride contamination in groundwater by enhancing chemical weathering and increasing groundwater temperatures, which promote the desorption of fluoride from minerals. High temperatures can lead to longer groundwater residence times, allowing more time for fluoride to dissolve into the water. Additionally, geothermal waters often exhibit higher pH and alkalinity, conditions that are associated with increased fluoride concentrations. Thus, geothermal activity can significantly contribute to amplified fluoride concentrations in groundwater resources.

Hu et al.,(2022) indicate in their study that Geothermal exploitation can lead to fluoride contamination in groundwater due to the release of geothermal fluids enriched with dissolved species, including toxic elements like fluoride. These contaminants originate from magma degassing and water-rock interactions under high temperature and pressure conditions. The presence of fluoride in groundwater poses health risks to local populations, particularly through contaminated drinking water and food crops. Effective management and pollution control measures are essential to mitigate these risks associated with geothermal energy utilization.

Shoeb et al.,(2022) indicates a relationship between fluoride contamination in groundwater and geothermal factors, particularly the depth to water level and proximity to hot springs. In



80% of cases reviewed, fluoride concentration increased with greater depth to water level. Additionally, areas with hot springs may exhibit higher fluoride levels due to geothermal activity. The study highlights that regions with hard rock formations tend to have higher fluoride concentrations, suggesting a potential geothermal influence on fluoride leaching into groundwater.

Kumar et al., (2023) discusses that geothermal activity can influence fluoride contamination in groundwater through the leaching of fluoride-rich minerals from geological formations. High temperatures associated with geothermal systems can enhance the solubility of fluoride, leading to increased concentrations in groundwater. Additionally, the geochemistry of the surrounding rocks and the spatial distribution of geothermal resources play crucial roles in determining fluoride levels. This issue is particularly pronounced in arid and semiarid regions, such as those in India, where geothermal influences are significant.

Chaudhuri et al., (2024) opine that the Geothermal controls on fluoride contamination in groundwater are influenced by natural sources such as volcanic eruptions and the weathering of fluoride-rich minerals. These geological processes can release fluoride into groundwater systems, contributing to elevated fluoride concentrations. Additionally, tectonic activity can affect the movement and interaction of groundwater with fluoride-bearing rocks, further influencing fluoride levels. Understanding these geothermal factors is crucial for assessing and managing fluoride contamination in affected regions.

Wang et al., (2024) suggest that Geothermal activity significantly influences fluoride (F⁻) contamination in groundwater within the Guide basin's confined aquifers. The high pH and elevated Na/Ca molar ratios, combined with long groundwater residence times, enhance the dissolution of F⁻-containing minerals. This process, alongside competitive adsorption, is a primary mechanism for F⁻ enrichment. The study indicates that geothermal effects, along with other factors like high alkalinity and limited water circulation, contribute to the release and migration of F⁻ in groundwater.

2.2.2 Anthropogenic Sources

Farooqi et al., (2009) point out that the anthropogenic sources of fluoride contamination in groundwater identified in the study include fertilizers, combusted coal, and industrial waste. Among these, fertilizers with phosphates emerge as the primary contributor to the build-up of fluoride in the earth. The use of these fertilizers enhances soil alkalization, which facilitates the dissolution of fluoride adsorbed on the soil, ultimately leading to its release into the local groundwater. Additionally, air pollutants from coal combustion contribute to fluoride in the environment.

Brindha and Elango (2011) suggest that Anthropogenic sources of fluoride contamination in groundwater include agricultural fertilizers, particularly phosphate fertilizers, which contribute fluoride to irrigation lands. Additionally, the combustion of coal in various industries and brick kilns releases fluoride into the atmosphere. This gaseous fluoride can settle as particulate matter and, during rainfall, percolate into the groundwater. Improper



disposal of fly ash on the ground surface also adds to fluoride levels in groundwater, exacerbating the contamination issue.

Rao (2012) identifies anthropogenic sources of groundwater contamination, including the infiltration of pit toilet leachate, which is an emerging concern in the Kolar district of Karnataka. While the study primarily focuses on fluoride concentration, it highlights that common anthropogenic contaminants also include nitrate, metals, organics, and microbial contamination. However, in Mulbagal town, the groundwater is under saturated with respect to calcite, which suppresses the dissolution of fluorite, thereby affecting fluoride levels in the groundwater.

Singh et al., (2013) observed that Anthropogenic sources leading to groundwater fluoride contamination, include high changes in fluoride flux due to human activities. The elevated fluoride concentration at Koraon during the pre-monsoon season is attributed to these anthropogenic influences. Additionally, localized knowledge about groundwater quality indicates that untreated groundwater is still being used by local populations, which may exacerbate fluoride contamination levels, necessitating attention to protect human health.

Roy and Dass (2013) opine that human induced sources of groundwater fluoride contamination include the application of phosphate fertilizers, sewage sludges, and pesticides. These activities can lead to artificially high levels of fluoride in the soil, which subsequently leaches into groundwater. The fluoride compounds introduced through pollution are typically soluble, contributing to increased fluoride concentrations in drinking water. This contamination poses significant risk of fluorosis, particularly in regions with inadequate water quality management.

Dass (2014) suggest that human induced sources of groundwater fluoride contamination include the application of phosphate fertilizers, sewage sludges, and pesticides. These activities introduce fluoride into the environment, contributing to elevated levels in drinking water. Unlike naturally occurring fluoride, these artificial sources significantly impact groundwater quality and can lead to health issues.

Selvam (2015) indicate man-made sources of fluoride contamination in groundwater include the unwise use of potassium, nitrate, sulfate, and phosphate fertilizers, as well as emissions from burning coal, steel industries, and aluminum extraction. The study indicates that agricultural activities and unsewered rural and urban areas are significant contributors to fluoride levels. Additionally, industrial activities have influenced the geochemical characteristics of groundwater, leading to elevated fluoride concentrations, particularly in the Tuticorin coastal region of Tamil Nadu, India.

Vithanage and Bhattacharya (2015) point out that human-induced origins of fluoride pollution in subterranean water sources include emissions from industries such as steel, aluminum, glass, and phosphate fertilizers, which release gaseous and particulate fluoride. Additionally, the use of coal and fly ash, along with agricultural chemicals like fumigants and herbicides containing fluoride, contribute to groundwater pollution. Wet and dry



depositions from these industrial activities, as well as soil dust and crustal material, further exacerbate fluoride levels in affected areas.

Stogiera and Radlinska (2015) point out that Human-induced origins of fluoride pollution in groundwater primarily include emissions from industries such as chemical plants, particularly those producing phosphoric acid and phosphate fertilizers. These facilities release significant amounts of fluoride compounds, which can leach into groundwater. Additionally, coal combustion for industrial and municipal purposes contributes to fluoride levels. The disposal of phosphogypsum, a byproduct of phosphoric acid production, also poses a risk, as it contains various contaminants, including fluoride, which can infiltrate groundwater systems over time.

Ali et al.,(2016) suggest that human-induced origins of fluoride pollution in groundwater sources primarily include the improper applications fertilizers with phosphates, which is common in developing countries like India. Other significant contributors are industrial activities such as aluminum smelting, glass production, and emissions from brick industries and coal-based power stations. Additionally, irrigation with fluoride-enriched water further exacerbates the contamination. These activities lead to increased fluoride levels in groundwater, posing serious health risks to affected populations.

Sajil Kumar (2017) point out that Anthropogenic sources of fluoride contamination in groundwater primarily include industrial, domestic, and agricultural activities. These activities can lead to pollution that deteriorates groundwater quality. Additionally, saline intrusions in coastal areas contribute to the problem. While fluoride is mainly derived from natural sources such as aquifer materials and rock formations, human activities exacerbate its concentration, leading to fluoride enrichment in groundwater, which poses significant health risks to populations relying on this water source.

Mukherjee and Singh (2018) highlight that anthropogenic inputs contribute to fluoride contamination in groundwater through various pathways. These include industrial discharges, agricultural runoff containing fluoride-based fertilizers, and improper waste disposal. Additionally, urbanization and mining activities can exacerbate fluoride levels in aquifers. Understanding these human-induced factors is crucial for addressing the fluoride pollution problem, particularly in regions of India where groundwater is already affected by natural geological processes and contamination.

Colombani et al.,(2018) point out that anthropogenic sources of fluoride contamination in groundwater include unmanaged human excretions, particularly in urban areas. The study highlighted that urine-polluted soils can significantly increase fluoride concentrations in recharge waters. In the research conducted in Addis Ababa, fluoride levels in contaminated soil were found to be over ten times higher than in uncontaminated soil, demonstrating the impact of human activities on fluoride enrichment in groundwater, especially in regions with high fluoride intake among the population.



Rasool et al., (2018) indicate that human-induced origins of fluoride pollution in groundwater include industrial activities such as aluminum refining, glass and ceramic production, and phosphate fertilizer manufacturing. Additionally, coal combustion and waste from brick production contribute to elevated fluoride levels. These activities release fluoride into the environment, which can leach into groundwater supplies. In Pakistan, significant sources also include agricultural fertilizers and industrial wastes, particularly in areas with high agricultural and industrial activity, exacerbating the fluoride contamination issue.

Sahu (2019) suggest that human-induced origins of fluoride pollution in groundwater primarily include industrial activities such as smelting of aluminium, production of ceramic and brick, combustion of fossil fuel, and production of steel. These operations discharge fluorine into the atmosphere in a gaseous state (e.g., HF, SiF₄) or as particulates (e.g., CaF₂, NaF). Although natural sources contribute small amounts of fluoride, the major concern arises from these industrial processes, which significantly elevate fluoride levels in groundwater, posing health risks to affected populations.

Dutta et al., (2019) are of the opinion that human-induced origins of fluoride pollution in groundwater include the manufacturing of fertilizers, glass, and bricks, as well as thermal power stations that use coal. Calcium fluoride phosphate, commonly used in phosphate fertilizers, significantly contributes to fluoride levels in groundwater. Additionally, industrial activities and urbanization can exacerbate fluoride contamination, particularly in areas where natural fluoride sources are already present. These human activities, combined with natural geogenic factors, lead to elevated fluoride concentrations in groundwater, posing health risks to local populations.

Zhang et al., (2020) indicated in their research that anthropogenic contributors of fluoride contamination in groundwater primarily stem from industrial park sewage discharge, which affects the geographic dispositions of fluoride levels. The research highlights that the high-value areas of fluoride are mainly concentrated in the southeast of the studied area, suggesting a correlation between human activities and elevated fluoride levels in shallow groundwater. Natural factors also contribute, but the impact of industrial activities is significant in this context.

Onipe et al., (2020) discusses various anthropogenic sources of fluoride contamination in groundwater, including industrial discharges, agricultural runoff, and the use of fertilizers containing fluoride. Additionally, urbanization and mining activities contribute to elevated groundwater fluoride levels. These human activities can significantly impact the natural fluoride concentration, leading to health implications for populations relying on contaminated water sources. Understanding these sources is crucial for managing fluoride levels and protecting public health in Sub-Saharan Africa.

Mandal et al., (2021) identifies phosphate fertilizers as an anthropogenic source of fluoride contamination in groundwater, contributing up to approximately 0.46 mg L⁻¹ of fluoride in low fluoride samples. While the primary source of high fluoride levels is attributed to natural water-rock interactions with fluoride-bearing minerals in granites and gneisses, the use of



fertilizers represents a significant human influence on groundwater quality in the region. This highlights the need for awareness and management practices among farmers regarding fertilizer application.

Chaudhry and Sachdeva (2021) indicate that anthropogenic sources of fluoride contamination in groundwater include industrial and domestic wastewater discharge, the use of phosphate fertilizers, mining activities, and extreme irrigation practices. Additionally, brick kilns contribute to increased fluoride levels. These activities, combined with geogenic processes such as weathering of fluoride-bearing minerals, exacerbate fluoride contamination in the region, particularly in areas with less rainfall and limited surface water supplies, leading to significant public health concerns related to fluoride exposure.

Aind et al., (2022) identifies anthropogenic activities, such as land use and groundwater pumping, as significant factors influencing fluoride (F^-) contamination in groundwater. These activities can alter the natural balance of fluoride mobilization, particularly in semi-arid environments. The research emphasizes that while geotectonic and climatic factors are crucial, human actions play a vital role in the occurrence and distribution of fluoride in groundwater, potentially exacerbating health risks associated with elevated fluoride levels.

Podgorski and Berg (2022) determined that anthropogenic inputs to fluoride contamination in groundwater include the application of fertilizers, which can introduce fluoride into the soil and water systems. Additionally, coal combustion releases fluoride compounds that can be deposited through rainfall, further contaminating groundwater. Managed aquifer recharge practices may also lead to increased fluoride levels if the water used contains fluoride. These human-induced factors can exacerbate the natural geogenic fluoride presence in aquifers, particularly in areas already prone to high fluoride concentrations.

Sulaiman et al., (2023) opine that anthropogenic activities significantly contribute to fluoride (F^-) contamination in groundwater, particularly in the Indo-Gangetic Plains. These sources include industrial operations, agricultural practices, and improper waste management, which enhance fluoride levels in the groundwater. The geological deposits of Quaternary alluvial sediment also play a role, as they interact with these human activities, leading to increased fluoride dissolution. The study highlights the need for effective management strategies to mitigate these anthropogenic impacts on groundwater quality.

Chaudhuri et al., (2024) mentions that while natural sources like weathering of fluoride-rich rocks and volcanic eruptions are primary contributors to fluoride contamination in groundwater, anthropogenic sources also exist. These human-induced sources can include industrial discharges, agricultural runoff containing fluoride-based pesticides, and improper waste disposal. Such activities can exacerbate the fluoride levels in groundwater, leading to increased health risks associated with excessive fluoride consumption, particularly in vulnerable populations.

Wei et al., (2024) pointed in their research that human-driven sources of fluoride pollution in groundwater stem from the use of fertilizers and pesticides, irrigation methods, and



alterations in land use/land cover (LULC). These anthropogenic activities play a crucial role in the spatiotemporal fluctuations of fluoride levels in groundwater. The study emphasizes that these elements, in conjunction with natural phenomena, enhance the overall fluoride enrichment process in aquifers, showcasing the intricate relationship between human endeavors and groundwater quality.

Patel et al. (2024) identified that the human-induced origins of fluoride pollution in the groundwater of the Korba Basin stem from industrial processes, including coal extraction, thermal energy production, and aluminum manufacturing. These activities lead to the seepage of fluoride and various other pollutants into the groundwater sources. Additionally, waste disposal practices and industrial effluent seepage exacerbate the pollution levels. The study indicates that fluoride levels exceeded acceptable quality limits across all monitored locations, highlighting the significant impact of human activities on groundwater quality in the region.

2.3 Controls on mobilization of fluoride in groundwater

2.3.1 Geological and Geochemical controls

Saxena and Ahmed (2001) opine that mobilization of fluoride in groundwater is primarily controlled by specific chemical parameters such as pH, bicarbonate (HCO_3^-) concentration, and specific conductivity. An alkaline medium (pH 7.6 to 8.6), high HCO_3^- concentration (350–450 mg/l), and moderate specific conductivity (750–1,750 $\mu\text{S}/\text{cm}$) favor fluoride dissolution from minerals like fluorite. Additionally, the presence of minerals rich in calcite enhances fluoride dissociation, while the geological formation and weathering processes also play significant roles in controlling fluoride levels in groundwater.

Ayenaw et al., (2008) are of the opinion that mobilization of fluoride in groundwater is primarily dominated by geological and hydro-chemical factors. High F^- concentrations are often associated with active thermal fields and acidic volcanic rocks, particularly ignimbrite and rhyolites. The weathering and breakdown of fluoride-rich minerals and interactions with calcium-rich waters also influence F^- levels.

Li et al., (2012) opine that mobilization of fluoride in groundwater is primarily controlled by geothermal anomalies, as indicated by the positive correlation between fluoride concentration and temperature. The confined artesian thermal groundwater, with concentration of fluoride ranging from 0.32 to 4.57 mg/L, is influenced by geological structures, including transpression and tension-shear faults, which create abnormal centers for fluoride distribution. Additionally, the alkaline environment (pH > 8.0) facilitates the desorption of fluoride, further enhancing its mobilization in groundwater.

Padhi and Muralidharan (2012) suggest that the mobilization of fluoride in groundwater is controlled by several factors, including the availability of leachable fluoride in soils, the chemical characteristics of the groundwater, and the physico-chemical conditions of the soil, such as its alkaline nature and high Al_2O_3 content. Additionally, groundwater flow dynamics influence fluoride concentration, with an increase observed from upstream to downstream



areas. The presence of fluoride-bearing minerals and the degree of weathering also play significant roles in fluoride release into groundwater.

Jha et al., (2013) propose that the influx of fluoride into groundwater is shaped by numerous elements, such as the water's alkalinity, which promotes the extraction of fluoride from minerals such as fluorite (CaF_2). Moreover, the category of groundwater, especially sodium bicarbonate-rich water lacking in calcium, is linked to elevated fluoride levels. Additional factors encompass the fluoride content in drinking water, the length of exposure, and regional climate conditions, especially in warmer regions where water intake tends to rise.

Pandey et al., (2013) indicate that the controls on the mobilization of groundwater fluoride include the geochemical environment, particularly pH levels and the presence of calcium. Lower pH can dissolve calcium compounds, increasing fluoride mobility. The study found a negative correlation between sulphate and fluoride, suggesting that the absence of calcium as a binding agent allows free fluoride to persist. Additionally, the geological presence of fluoride and sulphur, along with coal mining activities, contributes to the deterioration of water quality in the region.

Dass (2014) discusses various control measures for fluoride mobilization in groundwater, emphasizing the use of inexpensive and effective adsorption media. These include clays, solid industrial wastes (like red mud and spent bleaching earths), activated alumina, carbonaceous materials, bone charcoal, and both natural and synthetic zeolites. These materials can effectively treat fluoride contamination, thereby reducing its concentration in groundwater and mitigating health impacts associated with fluoride exposure.

Dutta et al., (2014) opine that fluoride mobilization in groundwater is controlled primarily by the presence of cations and anions, particularly Na^+ and HCO_3^- . In silty-clay samples, the ion-exchange mechanism is significant, while in sand samples, the weathering of muscovite and biotite plays a crucial role. Additionally, a $\text{Na}^+/\text{Ca}^{2+}$ ratio greater than 1.0 enhances fluoride release, with solutions exhibiting this ratio releasing 25% more fluoride from silty-clay and 7% more from sand compared to deionized water.

Dong et al., (2015) suggest that the mobilization of fluoride in groundwater is primarily controlled by the alkaline environment, characterized by high levels of HCO_3^- , Na^+ , TDS, and EC, along with a deficiency of Ca^{2+} . In confined aquifers, lithology plays a significant role, with high fluoride concentrations observed in the lacustrine platform zone. Additionally, water-rock interactions, particularly the dissolution of fluoride-bearing minerals, contribute to fluoride release into groundwater, especially in areas with strong evaporation and slow groundwater flow.

Wei et al., (2015) suggest that the mobilization of fluoride in groundwater is controlled by several factors, including temperature, solution composition, pH, CO_2 partial pressure, and the presence of carbonate minerals in the aquifer. Fluorite solubility, which is the upper limit for fluoride concentration, increases with temperature and varies in different aqueous solutions. In acidic conditions, HF is dominant, while free fluoride prevails at higher pH



levels. Additionally, CO₂ affects fluoride concentration differently in calcite-bearing versus non-calcite-bearing aquifer systems.

Subba Rao et al., (2016) propose that the movement of fluoride within groundwater is chiefly influenced by the erosion of granitic formations housing F-rich minerals like fluorite, biotite, and hornblende. This process releases Na⁺ and HCO₃⁻ ions, enhancing ion solubility. The exchange of ions between Na⁺ and Ca²⁺, coupled with the formation of CaCO₃, diminishes the activity of Ca²⁺, thereby encouraging the release of CaF₂ from these geological formations. Additionally, spatial variations in fluoride concentration are influenced by the occurrence of F⁻ bearing minerals, rock weathering, fracturing, and water residence time.

Panner et al., (2017) are of the opinion that the mobilization of fluoride in groundwater is primarily controlled by the interaction of minerals such as Biotite and Hornblende with groundwater and carbon dioxide, which leach fluoride ions along with calcium and magnesium into the water. Additionally, reverse ion exchange processes replace calcium ions with sodium, leading to increased fluoride concentration. The geological composition, including fluoride-bearing minerals and the aquifer's depth, also significantly influences fluoride levels in the Morappur region's groundwater.

Dehbandi et al., (2017) suggest that the presence of fluoride in groundwater is mainly governed by the interactions between water and rock, alongside the role of clay minerals. Their research revealed that the levels of fluoride in groundwater were affected by the variety of fluoride-containing and clay minerals present within the soils and aquifer substrates. Furthermore, fluoride demonstrated an inverse correlation with pH and bicarbonate (HCO₃⁻), highlighting that these geochemical elements significantly influence the accumulation of fluoride in the groundwater of the fluorosis-endemic region in central Iran.

Puccia et al., (2018) suggest that the movement of fluoride within groundwater is mainly governed by the dissolution theory, which claims that the levels of fluoride are affected by the solubility of fluorite and calcite. The study found that fluorite and calcite are in equilibrium with their corresponding ions in solution, indicating that fluoride levels are not significantly affected by adsorption processes on mineral oxides. Additionally, positive correlations between fluoride, arsenate, and carbonate further support the dissolution mechanism as the main control on fluoride mobilization.

Mukherjee and Singh (2018) are of the opinion that mobilization the concentration of fluoride in subterranean water is influenced by a multitude of factors, such as the existence of fluoride-rich aquifers, geological characteristics, the pace of weathering processes, ion-exchange activities, the duration that water remains in the aquifer, and the leaching of contaminants from below the surface. These geochemical processes and subsurface contamination significantly influence the availability of fluoride in groundwater, particularly in arid and semiarid regions of India, where high concentrations pose health risks to the population. Understanding these controls is essential for addressing fluoride contamination issues.



Elango and Jagadishan (2018) suggest that mobilization of fluoride in groundwater is mainly influenced by environmental factors, pH, the composition of surrounding rocks, and hydrological characteristics. The weathering of fluoride-rich minerals from host rocks, such as granite and biotite, releases fluoride into groundwater. Additionally, prolonged residence time of water in aquifers with these rocks enhances fluoride levels.

Rasool et al., (2018) indicate that the controls on the mobilization of fluoride in groundwater include geological factors such as the presence of fluoride-bearing minerals, pH levels, and the concentration of calcium and sodium ions. Alkaline conditions favor fluoride dissolution, while prolonged water retention enhances fluoride concentration through ion exchange processes.

Liu (2019) emphasizes that understanding the mechanisms of fluoride occurrence in underground water chemistry is crucial for controlling fluoride mobilization. It highlights the importance of predicting high-risk areas using geographic information and remote sensing. Additionally, the use of alternative source water or blending is recommended as a priority option. Efforts should focus on developing efficient defluoridation reagents and innovative materials, alongside strengthening the design and operation of defluoridation facilities to ensure stable benefits.

Kechiched et al., (2020) emphasize that the release of fluoride into groundwater is largely governed by the leaching of evaporite minerals, as demonstrated by the Durov diagram and saturation indices (SI) in their investigation. Their findings reveal that fluoride levels rise with CaCO_3 precipitation, subsequently causing CaF_2 to dissolve. This phenomenon underscores the geochemical interactions that shape fluoride concentrations in the Complex Terminal aquifer, ultimately influencing water quality and public health concerns in the Hassi Messaoud region.

Mandal et al., (2021) suggest that the controls on the mobilization of fluoride in groundwater include water–rock interactions with fluoride-bearing minerals found in granites and gneisses, which significantly contribute to high fluoride levels. Additionally, the precipitation of calcite influences the solubility of these minerals. High pH, sodium, and alkalinity levels, along with low calcium concentrations, characterize high fluoride samples. Furthermore, evaporation processes enrich groundwater fluoride through kinetic fractionation of water isotopes (^{18}O and ^2H), further affecting fluoride mobilization in the region.

Dubey et al., (2021) suggest that the mobilization of fluoride in groundwater is primarily controlled by water-rock interactions, particularly in alkaline environments. The study identifies low-temperature hydrothermal mineralization of fluorite in limestone aquifers as a significant factor for fluoride dissolution, leading to high concentrations. Additionally, the presence of fluorapatite in granite gneiss aquifers contributes to fluoride levels, with concentrations ranging from 2.5 to 4.2 wt%. These geological factors, along with seasonal variations, significantly influence groundwater quality and fluoride enrichment.



Aind et al.,(2022) opine that the mobilization of fluoride (F^-) in groundwater is primarily controlled by unsaturated zone mineralogy, particularly the presence of clay minerals, calcite, and Fe, Al hydroxides, which retain F^- more effectively. In contrast, areas with Pleistocene alluvial deposits, lacking these minerals, experience enhanced leaching of F^- . Additionally, geotectonic factors, climate, and anthropogenic activities such as land use and groundwater pumping also influence F^- occurrence and mobilization in semi-arid environments, as indicated by the study's findings.

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 $Na-HCO_3-SO_4$ 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.

Ghosh et al.,(2022) in their research found that the mobilization of fluoride in groundwater is primarily controlled by hydraulic conductivity, as indicated by the sensitivity analysis of the calibrated model, which shows that fluoride migration is more susceptible to changes in this parameter than others. Additionally, the stratigraphic layers of the aquifer influence the rates of fluoride migration, with horizontal movement making surrounding areas unsafe for drinking water and irrigation. Common hydrologic phenomena in the subsurface environment also contribute to the enrichment and migration of fluoride.

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.

Shaji et al., (2023) assert that the release of fluoride into groundwater is mainly influenced by natural sources, geological characteristics, and climatic factors. Areas with high-grade metamorphic rocks featuring granitoid or alkaline intrusions, along with geothermal hot springs and volcanic landscapes, are especially vulnerable to fluoride contamination. Moreover, dry or semi-dry climates amplify this concern. Human activities, including excessive fluoride in drinking water and dental care products, also play a role in raising fluoride concentrations. Grasping these influences is crucial for formulating effective remediation methods and guaranteeing safe drinking water.

Li et al.,(2023) indicated in their research that the groundwater fluoride mobilization is principally regulated by the dissolution of fluoride laden minerals, including evaporites (~58.80%), silicates (~15.89%), and carbonates (~12.94%). Additionally, the dissolution equilibrium of CaF_2 plays a crucial role in F^- enrichment. Under alkaline conditions, the release of F^- is enhanced when Ca^{2+} and Mg^{2+} reach oversaturation. Competitive adsorption



of OH^- and HCO_3^- promotes F^- desorption, while cation exchange involving K^+ and Na^+ reduces F^- adsorption capacity, further influencing groundwater F^- levels.

Saha et al.,(2024) suggest in their research that the mobilization of fluoride in groundwater is controlled by a decisive hierarchy of lithology, geomorphology, soils, and lineaments. These geological and environmental factors interact with climatic conditions, which are pivotal in governing the controlling variables. In dry regions, fluoride contamination is significantly higher compared to humid areas, indicating that both geological characteristics and climate play crucial roles in and concentration of groundwater fluoride.

Gao et al.,(2024) identifies microbial activity and sediment lithology as key controls on fluoride mobilization in groundwater. Microbial processes significantly enhance fluoride release, particularly in silt loam sediments, by affecting carbonate-bound and Fe-Al-bound fluoride fractions through mineral dissolution and desorption. Additionally, the co-dissolution of fluoride with calcium illustrates the complex biogeochemical interactions that govern fluoride dynamics in sediments, highlighting the importance of microbial interactions in influencing groundwater fluoride concentrations in regions like the Yuncheng Basin.

Fowler et al.,(2024) indicate in their findings that the mobilization of fluoride in groundwater is primarily controlled by pH-dependent processes, including fluoride complexation at low pH and carbonate stability at high pH. Elevated fluoride concentrations are observed at pH extremes, while near-neutral conditions typically show fluoride levels in the tens of ppm range. However, uncertainties in thermochemical, kinetic rate, and adsorption/desorption data limit the quantitative assessment of fluoride mobility at industrial sites, highlighting the need for comprehensive geochemical models to understand these processes better.

2.3.2 Tectono-Structural Controls

Srinivasamoorthy et al.,(2008) indicates that tectonic controls on fluoride mobilization in groundwater are linked to the geological complexity resulting from recurring tectonic and magmatic activities during the Precambrian period. This has resulted in the emergence of extensively weathered, fractured rocks like Peninsular gneiss and charnockite, which are rich in fluoride-bearing minerals. The flow of circulating water through these fissures and joints aids in the leaching of fluoride into groundwater, leading to heightened fluoride levels in the studied region.

Nanni et al.,(2009) found that the Tectonic controls on fluoride mobilization in groundwater are linked to the density and orientation of fractures within the Serra Geral aquifer system. The study identifies four main fracture directions (NNE, E-W, ENE, and NW) that facilitate the ascension of fluoride and other ions from deeper aquifers. High fluoride content is associated with areas of medium to high fracture density, where the interaction of ascending and descending water recharge occurs, influencing the hydrochemical facies and fluoride distribution.

Li et al.,(2012) found that the distribution of fluoride rich groundwater in the Guide Basin is significantly controlled by tectonic structures, specifically the NNW striking transpression



fault and NEE striking tension-shear fault. These faults create two anomaly centers, with the anomaly area spreading around the NEE shear in an elliptical shape. This tectonic activity influences the confined groundwater's movement, contributing to the mobilization of fluoride through geological effects of thermal dynamics, which play a crucial role in fluoride enrichment and migration.

Mondal et al., (2013) does not specifically address tectonic controls on fluoride mobilization in groundwater. However, it highlights that fluoride concentration is influenced by geological formations, particularly the litho-assemblage of the saprolitic zone between fractured granite gneiss and weathered mantle. The breakdown of fluoride-bearing minerals like fluorite, along with cation exchange processes, plays a part in enriching fluoride contamination, suggesting that geological and hydrogeochemical factors are more critical than tectonic controls in this context.

Kotra et al., (2014) highlights that the local topographic nature and the sporadic presence of apatite traces are significant sources of fluoride in the groundwater of Srikakulam. The geological formations influence the leaching behavior of fluoride, suggesting that geological factors, which may include tectonic activity, could play a role in the mobilization of fluoride in groundwater, warranting further in-depth study in the area.

Panner et al., (2017) found that the tectonic controls on fluoride mobilization in groundwater in the Morappur region include the development of numerous vertical joints due to tectonic disturbances are highly mineralized. These geological features facilitate the interaction of groundwater with minerals like Biotite and Hornblende that are rich in fluoride, leading to the leaching of fluoride ions into the groundwater. The deeper aquifers, affected more significantly, exhibit higher fluoride concentrations due to prolonged contact with these minerals.

Pradhan and Biswal (2018) opine that the tectonic controls on fluoride mobilization in groundwater include the presence of fractured and deformed rock formations, such as granitoid-granulite suite rocks, which facilitate the development of potential aquifers. The fracture networks enhance rock-water interactions, allowing for prolonged leaching of fluoride-bearing minerals like fluorite and apatite.

Haji et al., (2018) found that the tectonic controls on fluoride mobilization in groundwater in the Bilate River basin are influenced by the volcanic geology, including basalts and felsic-volcanic rocks, which release fluoride during weathering. The hydrodynamic conditions, characterized by strong dynamic flow in highland areas, facilitate the flushing of weathered components, while stagnant flow environments promote fluoride accumulation. Additionally, the interaction of groundwater with these geological formations, along with cation exchange processes, significantly contributes to fluoride enrichment in deep aquifers.

Gevera and Mouri (2018) found that the primary tectonic factors contributing to contamination of fluoride in groundwater in Nakuru County are related to the geological features of the Rift Valley of Kenya. Extended fluoride concentrations are noted in the



aquifers located in the rift floor, where minerals dissolve and evaporative enrichment occurs due to high temperatures.

Wang et al.,(2021) discusses how tectonic activity influences fluoride contamination in groundwater by affecting the geological formations and hydrogeochemical processes. Tectonic movements can create fractures and faults that facilitate the migration of fluoride-rich minerals into aquifers. Additionally, these geological structures can alter groundwater flow patterns, enhancing the concentration of fluoride in certain areas. The interplay between tectonics and geothermal conditions further contributes to the mobilization of fluoride.

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.

Shaji et al., (2023) assert that the key tectonic elements influencing fluoride pollution encompass the existence of high-grade rocks of metamorphic origin, granitoid or alkaline intrusions, geothermal hot springs, and volcanic zones. These geological characteristics frequently coincide with arid or semi-arid climates, which enhance the geogenic fluoride sources found in drinking water. The research underscores that these tectonic and geological elements are crucial in determining the distribution and concentration of fluoride in groundwater across various impacted regions worldwide.

Chaudhuri et al.,(2024) suggests that the tectonic controls incorporate the geological structures and movements that influence the distribution of fluoride-rich minerals. Tectonic activities can lead to the exposure of these minerals through processes such as faulting and folding, facilitating the release of fluoride into groundwater. Additionally, tectonic settings can affect the hydrology and flow patterns of groundwater, further impacting the concentration of fluoride. Understanding these tectonic influences is crucial for assessing and managing fluoride contamination in affected regions.

Ayub et al.,(2024) evaluates the hydrogeochemical properties and identifies tectonic factors influencing fluoride contamination in groundwater. It highlights that geological formations, fault lines, and tectonic activity can enhance the leaching of fluoride from minerals into groundwater. Additionally, the study discusses how tectonic uplift and subsidence can affect groundwater flow patterns, leading to increased fluoride concentrations in certain areas. Understanding these tectonic influences is crucial for assessing fluoride sources and mitigating health risks associated with high fluoride levels in drinking water.

2.4 Global perspectives on Fluoride contamination

Smedley et al.,(2002) opine that naturally high fluoride contamination is a global concern, particularly in arid regions where water scarcity is prevalent. In Africa, significant fluoride



problems have been identified, with studies showing extreme concentrations exceeding WHO guidelines. For instance, in central Tanzania, fluoride levels surpassed 20 mg/L, while northern Ghana recorded levels over 4.0 mg/L. Chronic ingestion can lead to fluorosis impacting teeth and bones and therefore reducing health and quality of life, especially in rural communities.

Amini et al., (2008) in their extensive study found that the global scenario of groundwater fluoride contamination indicates a major health threat, affecting millions. The study modeled fluoride concentrations using a large database and environmental factors, dividing the world into eight "process regions." The models explain 60-70% of fluoride variation in six regions, while only 30% in two. A global probability map was created, aligning well with known fluorotic areas, providing initial indications of contamination to aid in planning new drinking water projects.

Guan et al. (2011) assert that the issue of fluoride pollution in groundwater is a widespread issue, impacting nations like China, Mexico, Argentina, and Pakistan. Elevated levels of fluoride have been detected across various regions, such as Shanxi, Inner Mongolia, Xinjiang, Qinghai, and Jilin. The existence of fluoride in groundwater presents considerable health hazards, especially in rural communities that depend on this water supply.

Ibrahim et al., (2011) indicate that the presence of fluoride in groundwater poses a critical worldwide challenge, with concentrations surpassing the acceptable threshold of 1.0 to 1.5 mg/L in various areas. This problem is especially acute in nations like India, where high fluoride consumption results in health complications such as dental and skeletal fluorosis. Groundwater, being the primary source of freshwater, is affected by natural fluoride constituents and anthropogenic activities, necessitating urgent measures for defluorination and improved groundwater quality management worldwide.

Ghosh et al., (2013) highlight that the issue of fluoride pollution in groundwater is a pressing global concern, particularly in South and Southeast Asia, where alarming concentrations are increasingly observed. WHO has set a safe limit for fluoride in drinking water at 1.5 mg/L, yet numerous areas surpass this standard, resulting in widespread health dangers such as fluorosis. Elements that contribute to elevated fluoride concentrations include volcanic formations, granite, and marine deposits, which compromise groundwater quality and pose significant health threats to the impacted communities.

Satpathy et al. (2014) opine that the issue of fluoride contamination in groundwater is a pressing global concern, with an alarming 80% of illnesses linked to inadequate drinking water quality. In fact, fluoride present in drinking water accounts for 65% of the global cases of endemic fluorosis. In India, a staggering 90% of rural communities depend on groundwater, with half of these sources tainted by fluoride, impacting over 40 million individuals. Elevated fluoride concentrations can emerge from diverse geological settings, making it essential to conduct thorough monitoring to guarantee the safety of water for drinking.



Vithanage and Bhattacharya (2015) point out that concentration of fluoride in groundwater is a major global issue, affecting over 200 million people across 25 nations, particularly in regions like India, Sri Lanka, Pakistan, Ethiopia, Ghana, Kenya, and China. High fluoride levels primarily stem from geogenic sources, such as rocks containing fluoride-rich minerals, and are exacerbated by anthropogenic activities.

Kut et al., (2016) believed that nearly 200 million individuals worldwide rely on groundwater containing fluoride levels that surpass the WHO recommended limit of 1.5 mg/L. In the region of Sub-Saharan Africa, about 40% of the 680 million inhabitants do not have access to reliable sources of safe drinking water. Water with high fluoride levels often found in regions like the East Africa Rift Valley.

Bibi et al., (2017) contends that the pollution of groundwater with fluoride has repercussions for over 300 million individuals across the planet. The culprits behind this fluoride pollution stem from both natural earth formations and industrial operations. Elevated levels of fluoride in potable water can result in serious health complications, including dental and skeletal fluorosis, along with bone malformations. The spread of fluoride pollution is not uniform globally, with specific areas facing more drastic consequences due to local geological circumstances and insufficient water purification practices.

Kannaujia et al., (2018) highlight that the pollution of groundwater with fluoride poses a serious global challenge, leading to health issues like tooth decay and skeletal fluorosis. Nearly 80% of illnesses around the globe are associated with subpar drinking water quality, with fluoride contamination accounting for 65% of cases of endemic fluorosis. Both geological and human-induced factors, including industrial growth and urban expansion, intensify this dilemma, especially in developing nations. The World Health Organization establishes the acceptable fluoride concentration in drinking water at 1.5 mg/L to protect community health.

Haji et al., (2018) assert that fluoride pollution in groundwater poses a serious health threat around the globe, impacting more than eight million individuals in the Ethiopian Rift Valley and nearly 200 million in various areas across the planet. Elevated fluoride concentrations in drinking water can result in dental issues, skeletal deformities, and debilitating fluorosis.

Rasool et al., (2018) estimate that worldwide, millions are impacted by fluoride pollution in groundwater, with roughly 200 million individuals across 25 nations facing the threat of fluorosis. The most elevated levels are noted in India and China, while nations such as Tanzania, Germany, and Argentina also indicate considerable amounts. Numerous areas, especially those that are arid or semi-arid, show heightened fluoride concentrations surpassing the WHO's safe threshold of 1.5 mg/L, which presents significant health hazards.

Sahu (2019) indicates that fluoride contamination in groundwater is a significant global issue, with high concentrations reported in various regions. In South Asia, countries like India, Afghanistan, and Bangladesh experience elevated fluoride levels, often exceeding the WHO limit of 1.5 mg/L. Geochemical processes, groundwater alkalinity, and climatic



conditions further influence fluoride mobilization, leading to widespread health concerns caused by fluorosis.

Dutta et al., (2019) indicate that elevated concentrations of fluoride in groundwater is a global concern, affecting over 260 million people, particularly in 23 countries, including India. In India alone, around 100,000 villages face serious health issues due to fluoride contamination, with 230 districts across 20 states reporting high fluoride levels. The World Health Organization has set a permissible limit of 1.5 mg/L, reaffirmed in 1993 and 2004, highlighting the widespread nature of this issue and the associated health implications which may lead to fluorosis of the teeth and bones.

Onipe et al., (2020) primarily focuses on fluoride contamination in groundwater within Sub-Saharan Africa, highlighting that over 400 million people in Africa rely on groundwater as their main water source. While it does not provide a comprehensive global scenario, it indicates that fluoride is a persistent groundwater contaminant, which poses health risks. The implications of fluoride exposure can vary significantly based on geographic and environmental factors, necessitating further research to understand its global prevalence and health impacts.

Saeed et al., (2020) opine that groundwater fluoride contamination is a major global issue, exacerbated by increasing anthropogenic activities. It is the principal source of fluoride exposure for many populations, leading to various health problems, including neurotoxicity and cognitive impairments in children. The magnitude of this contamination varies across endemic areas, with limited research primarily focused on a few countries.

Robledo-Piralta et al., (2021) opine groundwater fluoride contamination is a persistent global issue affecting over 300 million people across more than 100 countries. It is considered one of the most serious contaminants in drinking water, necessitating effective removal strategies.

Kaur et al., (2021) point out to the fact that approximately 200 million people across 28 nations face health issues due to the consumption of water contaminated by fluoride, primarily in arid and semiarid regions. Heightened fluoride concentrations, frequently surpassing 1.5 mg/L, make water unsuitable for drinking, resulting in dental and bone fluorosis, along with various other health hazards.

Islam and Mostafa (2021) identified that the contamination of fluoride in groundwater reveals a pooled concentration of 2.1267 mg/L across 20 countries, surpassing the standards set by WHO of 1.5 mg/L. The study identified significant positive correlations between fluoride levels and factors such as pH, sodium, bicarbonate, and rainfall. Regions with semi-arid and arid climates are particularly affected, with children being more vulnerable to fluorosis than adults. The findings underscore the need for measures to ensure safe water supply in impacted areas.

Rehman et al., (2022) point out that groundwater fluoride contamination is becoming a significant challenge, with serious health implications. The research highlights that elevated



levels of fluoride in drinking water can cause fluorosis at alarming rates. In the specific case of Isa Khel, Punjab, Pakistan, over 50% of the water samples collected were deemed unsuitable for consumption due to excessive fluoride concentrations, indicating a broader concern regarding groundwater quality and public health globally.

Kalsido et al., (2022) project that worldwide, more than 200 million individuals depend on groundwater containing fluoride levels that surpass the safe threshold of 1.5 mg/L, creating serious health hazards such as both skeletal and nonskeletal fluorosis. This concern is especially widespread in areas like Ethiopia, where groundwater is often the only economically option of drinking water.

Shaji et al., (2023) assert that fluoride pollution in groundwater affects upwards of 100 nations, impacting over 200 million individuals, predominantly in Africa (38 nations), Asia (28), and Europe (24). This contamination frequently surpasses the World Health Organization's threshold of 1.5 mg/L. Contributing factors include natural geogenic elements, human activities, and dietary sources. The most affected regions are typically located in high-grade metamorphic belts, geothermal hotspots, and dry climates. Children are especially at risk, underscoring the critical necessity for effective remediation measures.

Tiwari et al., (2023) report that excessive fluoride concentration in groundwater has been reported in over 20 countries, both developing and developed, including India, where 19 states face serious fluorosis issues. Groundwater, a crucial water source for human consumption, can contain fluoride levels exceeding safe limits due to natural processes like rock dissolution and human activities such as industrial operations. In uncontaminated surface water, fluoride levels typically do not exceed 0.3 mg/L, highlighting the significant risk posed by contaminated groundwater sources.

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

Singh et al., (2013) are of the opinion that in India, particularly in Northern regions like Allahabad, groundwater fluoride contamination is a significant problem, with several areas exceeding WHO and BIS standards. The study indicates that post-monsoon samples show higher fluoride concentrations than pre-monsoon, stemming from a blend of natural and human-induced factors. Hydro-geological implications, such as mineral saturation and weathering processes, contribute to this contamination, impacting human health as untreated groundwater is often used for drinking. Localized knowledge of groundwater quality is crucial for addressing these issues.

Chakrabarti and Bhattacharya (2013) discovered a notable presence of fluoride in the Bankura district of West Bengal, with 612 out of 3617 examined tube wells surpassing the acceptable threshold of 1 mg/l. Their investigation indicated that around 75% of rock chip samples and 62% of sub-surface water samples exhibited fluoride concentrations of 4000 mg/kg and 1 mg/l, respectively. This pollution is associated with various geological formations and granitic intrusions, leading to health complications such as dental and skeletal fluorosis among the local populace.

Singaraja et al., (2014) argue that the contamination of fluoride in groundwater poses a critical challenge in India, notably within the Thoothukudi District of Tamil Nadu, where geological conditions lead to elevated fluoride concentrations. Their research reveals that fluoride levels surpass safe thresholds, resulting in health hazards like dental and skeletal fluorosis. Seasonal fluctuations indicate that fluoride concentration peaks during the pre-monsoon period due to diminished dilution, significantly impacting the northern and central areas. The existence of fluoride-rich minerals in the bedrock intensifies this contamination.

Patel et al., (2014) indicate that in eastern India, particularly in the tribal belts of Jharkhand and Odisha, groundwater contamination with fluoride exceeds safe levels (>1.5 mg/L), with



maximum concentrations exceeding 10.3 mg/L. The groundwater is mildly alkaline, and fluoride levels correlate positively with pH, electrical conductivity, and sulfate. The pollution largely stems from the breakdown of biotite and fluorapatite within quartzo-feldspathic gneiss, presenting considerable health hazards to the surrounding communities.

Naaz et al., (2015) found that in India, fluoride contamination in groundwater is prevalent, particularly in arid and semi-arid regions, often linked to geological formations like granites and gneisses. High fluoride concentrations exceed permissible limits, causing health issues such as skin, mouth, and stomach problems among local populations. The study in Sidhi District highlights spatial variations, with urban areas showing the highest fluoride levels, influenced by weathering of fluoride-bearing minerals and seasonal fluctuations in groundwater levels, exacerbated by limited irrigation and rainfall patterns.

Pandey et al., (2016) contend that the contamination of fluoride in groundwater poses a major challenge in India, especially in regions such as Uttar Pradesh, Andhra Pradesh, and Tamil Nadu. Elevated levels of fluoride in drinking water result in dental and skeletal fluorosis, impacting millions of individuals. The research conducted in Sonbhadra district reveals that out of 22 villages, eight surpassed the allowable fluoride threshold of 1.5 ppm. Factors contributing to this issue include the weathering of minerals containing fluoride, high rates of evaporation, and extended water retention periods in aquifers, increasing health risks for the local communities.

Das et al., (2016) highlighted that the presence of fluoride in groundwater poses a critical challenge in India, especially in areas rich in fluoride-bearing minerals. The solubility dynamics of fluorite and calcite play a crucial role in determining fluoride concentrations, resulting in elevated levels in specific locales. In a research endeavor within the Simlapal block of Bankura district, West Bengal, a startling 58% of water samples surpassed the WHO's recommended threshold of 1.5 mg/L. Overconsumption of fluoride can lead to various health complications, such as dental and skeletal fluorosis, underscoring the urgent necessity for vigilant monitoring and effective management of groundwater quality.

Sahu et al., (2017) indicate that fluoride contamination in groundwater in India, particularly in Chhattisgarh, has led to endemic fluorosis in humans and domestic animals. High concentrations of fluoride, between the ranges of 4.6 to 62 mg/L in urine samples, indicate significant health risks.

Tiwari et al., (2017) opine that in India, particularly in regions like Uttar Pradesh, contamination of fluoride in the groundwater is a significant problem. The Pratapgarh district study revealed fluoride in the ranges of 0.41 to 3.99 mg/L, with 78% of samples exceeding the statutory levels of 1.0 mg/L. Fluoride contamination is often attributed to geogenic sources and agricultural runoff from phosphatic fertilizers. The alkaline nature of groundwater enhances fluoride mobilization from minerals, posing health risks, especially in areas with limited industrial activities.



Batabyal and Gupta (2017) opine that fluoride contamination in West Bengal, particularly in the Birbhum district, has been a significant concern, with concentrations ranging from 0.01 to 19 mg/L. The majority of groundwater samples show excess fluoride, leading to health issues like fluorosis among residents. Local authorities have closed many tube wells due to high fluoride levels. The contamination is primarily attributed to chemical weathering and ion exchange processes, with the groundwater being unsuitable for drinking in about 81% of sampling sites.

Shubhangi et al., (2018) point out that fluoride contamination in groundwater in India, particularly in regions like Jaisalmer, Pokhran, and Bhatinda, is significant, with levels exceeding WHO guidelines. In the city of Jaisalmer, fluoride levels fluctuate between 1.9 to 4.5 mg/L, while the regions of Pokhran and Bhatinda reveal concentrations ranging from 1.1 to 6.1 mg/L and 0.8 to 4.0 mg/L, respectively. Alarming, about 60% of the samples from Bhatinda, all samples from Jaisalmer, and 90% of those from Pokhran surpass the threshold of 1.5 mg/L, highlighting a pressing public health issue.

Podgorski et al., (2018), in their comprehensive study centered on machine learning, have identified elevated levels of naturally occurring fluoride in groundwater across different regions of India for nearly eighty years, resulting in dental and skeletal fluorosis. The study identified 12,600 fluoride measurements, revealing that 2,895 exceed the local guideline of 1.0 mg/L, with significant contamination in northwestern states like Gujarat, Delhi, Punjab, Rajasthan and Haryana as well as southern states such as Karnataka, Andhra Pradesh, Telangana and Tamil Nadu, posing a risk to public health.

Mukherjee and Singh (2018) assert that the presence of fluoride in West Bengal is a critical concern, with the region being recognized as one of the areas exhibiting notably elevated fluoride concentrations in its groundwater. The groundwater fluoride contamination in the region is attributed to various geochemical processes, geological factors, and subsurface contamination. Chronic exposure to fluoride-rich water poses health risks, including fluorosis, affecting a large portion of the population. Urgent attention is needed to address the quality issues of groundwater and understand the contributing factors to fluoride pollution in West Bengal.

Arumugam et al., (2019) contend that in India, especially in rural areas where the groundwater remains the primary source of potable water, thereby making populations vulnerable to fluoride contamination. Excessive intake of fluoride contaminated water can lead to dental and skeletal fluorosis, with significant health impacts. The study in Palghat District, Kerala, highlighted that 11 samples exceeded permissible fluoride limits, emphasizing the need for remedial measures like defluoridation and rainwater harvesting. The geological and climatic conditions contribute to fluoride levels, necessitating government intervention for public health management.

Kumar et al., (2019) find that in the Indian context, groundwater fluoride contamination, particularly in the Indo-Gangetic Alluvial Plains, poses significant health risks, especially to children. The study indicates that 44% of pre-monsoon and 38% of post-monsoon



groundwater samples exceed safe fluoride levels. Health implications include mottling of teeth and bone deformities, attributed to prolonged exposure. The contamination primarily arises from weathering of fluoride-bearing minerals in crystalline rocks, necessitating urgent remedial measures like solar energy-driven de-fluoridation and rainwater harvesting.

Mandal and Sanyal (2019) point out that contamination of fluoride in the groundwater of West Bengal is a significant problem, with 43 blocks across 7 districts noted to be severely affected. Puruliya district is the worst affected, with 18 out of 20 blocks showing elevated concentrations of fluoride ranging from 0.126 to 8.16 ppm. Approximately 7.5 million people in rural areas of the district are at high risk of fluorosis, highlighting the severe health implications associated with prolonged exposure to fluoride-rich groundwater.

Sahu (2019) asserts that in India, the presence of fluoride in groundwater poses a crucial health concern, with more than 184 districts in 19 states indicating fluoride concentrations surpassing the allowable threshold of 1.5 mg/L. Since 1937, endemic fluorosis has been widespread, impacting millions of lives. The natural origins of fluoride stem from the breakdown of minerals such as fluorite and the effects of alkaline environments. Elements like elevated alkalinity, evaporation, and the occurrence of calcium also play a role in the mobilization of fluoride within groundwater, worsening the contamination dilemma.

Prajapati et al., (2020) underscore that the presence of fluoride in groundwater poses a major issue in India, especially within rural locales such as Surat district in Gujarat. Elevated fluoride concentrations can negatively impact human health, resulting in dental and skeletal fluorosis. The research stresses the importance of employing multivariate statistical analysis to evaluate groundwater quality and pinpoint contamination sources, which is essential for crafting effective management strategies to alleviate fluoride-related health hazards in the impacted communities.

Singh et al., (2020) emphasize that in India, the issue of fluoride contamination in groundwater has been a prominent concern since its initial discovery in Andhra Pradesh back in 1937. At present, nineteen states are gravely impacted by fluoride pollution, mainly stemming from natural origins such as fluoride-rich rocks, the application of phosphate fertilizers, and discharges from smelting operations. Although fluoride is crucial in small quantities, levels exceeding 1.5 mg/L are exceedingly harmful, underscoring the pressing need to address this ecological challenge.

Kisku and Sahu (2020) reveal that in India, the presence of fluoride in groundwater is mainly of geological origin, with noteworthy concentrations found in several states. High fluoride levels present significant health hazards, including dental and skeletal fluorosis, neurotoxic repercussions, and effects on the digestive and reproductive systems, especially in children. Additionally, industrial processes, such as those involving phosphate fertilizers and coal-fired power stations, further elevate fluoride concentrations in water.

Aravinthasamy et al., (2020) assert that within the Indian landscape, the presence of fluoride in groundwater, especially in locales like the Shanmuganadhi River basin, presents



considerable health hazards, notably dental fluorosis. Their investigation revealed elevated fluoride concentrations associated with natural sources such as fluoride-rich minerals found in granitic and gneissic formations, alongside contributions from artificial fertilizers. The study underscored the vulnerability of 26 villages and stressed the importance of treating fluoride-laden groundwater, particularly in regions possessing hornblende-biotite gneiss, to alleviate health risks.

Thapa et al., (2020) reveal in their research that fluoride pollution in Birbhum, especially within the Dwarka River Basin, is quite pronounced, with fluoride concentrations in groundwater soaring to 14.0 mg/L, far surpassing the allowable threshold of 1.5 mg/L. The investigation pinpointed fluorapatite in sediment samples as the major contributor to fluoride levels. Around 62.5% of the water samples exceeded the safe fluoride thresholds, presenting a grave public health risk linked to fluorosis in the area, which calls for immediate water management interventions to address this pressing challenge.

Singh and Singh (2021) highlight that in India, the contamination of groundwater with fluoride presents a major challenge, impacting more than 66 million individuals afflicted by fluorosis. This dilemma has surged from just four states in 1930 to a staggering 21 states now grappling with high fluoride concentrations. Groundwater, which is mainly utilized for drinking purposes, suffers from severe pollution due to the leaching of fluoride minerals from geological formations and unregulated extraction practices. The acceptable range for fluoride levels in drinking water is established between 0.6 to 1.2 mg/l, with a ceiling of 1.5 mg/l when alternatives are not available.

Hossain et al. (2021) reveal that the fluoride pollution in West Bengal, particularly within the Birbhum region, is alarming, as groundwater assessments demonstrate fluoride levels fluctuating between 0.3 to 17.6 mg/L. Around 70% of the examined samples surpassed the adjusted ideal fluoride threshold of 0.7 mg/L, resulting in drinking water quality deemed poor to unsuitable in 50% of the sites. The research underscores non-carcinogenic health hazards, especially for children, stemming from elevated fluoride concentrations caused by the weathering of fluoride-rich minerals and interactions between water and rock.

Chowdhury et al.,(2021) point out that groundwater fluoride contamination in India, particularly in Purulia district, poses significant health risks, especially to vulnerable populations such as infants. The study indicates fluoride levels ranging from 1.30 to 7.0 mg/l, averaging at 4.06 mg/L, leading to serious health issues from prolonged exposure. The study underscores that infants between 6 and 12 months face heightened vulnerability from ingesting tainted water, stressing the immediate necessity for robust water quality oversight and health initiatives for the community.

Maitra et al., (2021) express that the issue of fluoride pollution in groundwater is a pressing concern in India, especially in areas such as Odisha, where elevated fluoride concentrations have been identified in hot springs. Approximately 39% of groundwater samples surpassed the WHO's recommended threshold of 1 mg/L. This pollution is associated with various geochemical phenomena, such as the leaching of fluoride-rich minerals and agricultural



practices. This situation poses health hazards, particularly for children, resulting in ailments like dental fluorosis. Viable remediation techniques encompass membrane defluoridation and the Nalgonda method.

Dubey et al.,(2021) in their study in central India, found that groundwater fluoride contamination in central India poses a significant public health concern, with about 90% of sampled groundwater exceeding the permissible limit of 1.5 mg/L. The contamination is linked to lithological sources, particularly granite gneisses, limestones, sandstones, and basalts, with maximum fluoride concentrations reaching 4.9 mg/L. Geogenic enrichment, influenced by water-rock interactions and low-temperature hydrothermal mineralization of fluorite, is a primary factor in fluoride dissolution, necessitating effective management of drinking water sources in affected areas.

Nizam et al., (2022) suggest that within the Indian landscape, especially in the Northern Indo-Gangetic Plain, the presence of fluoride in groundwater poses a major health threat, with 98% of testing sites surpassing the safe drinking water threshold. The research reveals that deeper aquifers exhibit a 27% increase in fluoride levels. At-risk populations, notably children, are exposed to grave health dangers, such as dental and skeletal fluorosis. These outcomes emphasize the pressing necessity for efficient water management strategies and corrective actions to alleviate the long-term health hazards linked to elevated fluoride consumption in the area.

Kashyap et al.,(2022) assert that the contamination of groundwater with fluoride poses a serious challenge in India, chiefly attributed to the leaching of fluoride-rich minerals from geological formations and sediments. Numerous areas, such as the Pondi-Uproda block in Chhattisgarh, exhibit fluoride concentrations that exceed the limits set by WHO, resulting in dental and skeletal fluorosis within the community. Around 66.66% of groundwater samples from the research region exceeded the allowable fluoride level of 1.5 mg/l, underscoring the pressing necessity for efficient water purification and preventive strategies in regions plagued by fluorosis.

Shoeb et al.,(2022) point out that fluoride contamination in India's groundwater has been a significant issue for decades, with concentrations often exceeding the WHO permissible limit of 0.6-1.5 mg/L and the BIS range of 1-1.5 mg/L. The study indicates that fluoride levels increase with depth to water level in 80% of cases. Regions like Guwahati show higher fluoride concentrations compared to areas like Nalbari. Notably, fluoride levels have fluctuated in various districts, with some areas experiencing significant increases or decreases over the past two decades.

De et al., (2022) draw attention to alarming levels of fluoride pollution in the groundwater of the lower Gangetic plain in West Bengal, India. They indicate that fluoride concentrations vary widely, with certain regions surpassing the acceptable thresholds established by health officials. The presence of fluoride in potable water sources presents grave health hazards, notably leading to dental and skeletal fluorosis. The research underscores the critical



necessity for monitoring and intervention strategies to effectively tackle this pressing public health issue.

Sulaiman et al., (2023) reveal that in the context of India, especially within the Gangetic Plains, there is a substantial issue with fluoride (F^-) pollution in groundwater, impacting more than 700 million individuals. The geological makeup of the Quaternary alluvial sediments is a major factor contributing to elevated fluoride concentrations, further intensified by human activities. The northern and lower regions face greater levels of toxicity, influenced by the $Na-HCO_3$ water type, alkaline pH, water depth, and heightened evaporation rates. This pollution presents non-carcinogenic health threats, highlighting the urgent need for effective measures to ensure sustainable groundwater management.

Ghosh et al., (2023) emphasize that fluoride pollution in India's groundwater is a pressing concern, especially in underdeveloped areas. Their findings reveal that 37% of groundwater samples from Bankura District surpassed the WHO's threshold of 1.5 ppm during the pre-monsoon season, which decreased to 30% afterward due to dilution effects. This contamination largely arises from the weathering and dissolution of fluoride-rich minerals, driven by alkaline conditions and seasonal rainfall that promotes fluoride leaching as rainwater interacts with these minerals in the soil zone.

Nandi et al., (2023) discovered that fluoride pollution in groundwater presents a serious environmental challenge in India, especially in areas such as Dhanbad. The research reveals that 67 out of 283 groundwater samples surpassed the World Health Organization's acceptable threshold of 1.5 ppm, classifying them as hazardous. Elements contributing to this pollution include alkaline pH, elevated levels of Na^+ and HCO_3^- ions, extended rock-water interactions, and silicate weathering. These circumstances promote fluoride proliferation, endangering public health.

Beg et al. (2023) assert that in India, the presence of fluoride in groundwater poses a major public health challenge, especially in areas such as Raigarh, Chhattisgarh. Excessive concentrations of fluoride are often linked to geological formations, such as the Barakar Formation, which contains feldspathic sandstones and coal. The study indicates that groundwater with elevated fluoride levels is associated with specific hydrogeochemical types and processes, including feldspar dissolution and ion exchange. Systematic investigations are essential to address the health risks posed by fluoride contamination in similar geological settings across India.

Ali et al., (2023) emphasizes a troubling issue of fluoride contamination in groundwater across Agra, India, where levels surpass the WHO's advisable threshold of 1.5 mg/L in both rural and urban settings. Pachgain Kheda stands out with the highest recorded average fluoride level of 5.20 mg/L, signifying dire repercussions for public health. The assessment of health risks unveiled heightened non-carcinogenic threats, especially affecting children and adolescents, underscoring the urgent necessity for regulatory actions and increased public consciousness regarding fluoride presence in drinking water throughout India.



Ruidas et al., (2023) reveal that nearly 55% of the groundwater in the Indo-Bangladesh delta area, encompassing West Bengal, is unsuitable for consumption due to heightened levels of fluoride and arsenic pollution. This alarming level of contamination presents grave health dangers and environmental challenges, particularly throughout both dry and wet periods. The research underscores the pressing necessity for ongoing surveillance and sustainable strategies to reduce fluoride contamination in drinking water supplies to guarantee safe and clean water availability for the community.

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.

Rajan et al., (2024) assert that the presence of fluoride in groundwater presents serious health hazards, especially in regions susceptible to drought such as the Nagavathi River basin in southern India. The study found that 16.17% of samples are above the WHO guideline of 4 mg/l, categorizing them as extreme risk. The Total Hazard Index (THI) indicated that all age groups, especially infants and children, are adversely affected by fluoride exposure, necessitating urgent geochemical investigations and water treatment before consumption.

2.5 Health Risk Assessment

Chen et al.,(2017) in their study in the Zhongning area, Northwestern China, found that fluoride levels of Zhongning area range from 0.11 to 6.33 mg/L, with four samples exceeding the WHO acceptable limit of 1.5 mg/L. Infants are identified as the most vulnerable group through ingestion pathways, with 60% of samples posing potential adverse effects. The study emphasizes the urgent need for interventions to mitigate fluoride exposure among rural residents, particularly for sensitive populations like infants and children.

Aghapour et al.,(2018) indicate that health risk assessment related to fluoride contamination in groundwater involves evaluating non-carcinogenic risks using the hazard quotient (HQ). An HQ greater than 1 indicates potential health effects. In Isfahan, 51% of children, 17% of teens, and varying percentages of adults faced health hazards due to fluoride levels exceeding safe limits. Areas like Nayin, Natanz, and Ardestan showed significant risks, particularly for children, necessitating measures to reduce fluoride levels to prevent endemic fluorosis and protect vulnerable populations.

Francisca et al.,(2018) point out that assessment of health risks related to the consumption of groundwater contaminated by fluoride involves evaluating the potential adverse effects due to fluoride exposure. In the Makindu District study, groundwater from boreholes contained fluoride concentrations exceeding the WHO maximum allowable value, posing health risks to the population. The presence of mottled enamel in 38.4% and 33.3% of respondents indicated the adverse effect of fluoride on the health of teeth.

Narasimha and Rajitha (2018) assert that conducting health risk assessments is vital for understanding the potential negative impacts of ingesting fluoride-rich groundwater. Their research computed the hazard quotient for fluoride (HQ_{Fluoride}) to evaluate non-carcinogenic health threats, especially for children, who are particularly vulnerable to dental fluorosis. When fluoride levels in groundwater surpass the WHO's recommended threshold of 1.5 mg/L, they present considerable health dangers. Continuous monitoring and evaluation of fluoride



concentrations in drinking water are imperative to alleviate these threats and safeguard public well-being.

Qasemi et al., (2019) evaluated the potential adverse health effects of consuming fluoride-enriched groundwater by estimating exposure levels and comparing them to established safety thresholds. In the study, the hazard quotient (HQ) were calculated for fluoride exposure through drinking water. The findings indicated that certain populations, particularly children and infants, faced significant health risks due to fluoride levels exceeding acceptable limits, necessitating remedial measures to protect public health in Bardaskan County, Iran.

Hanse et al., (2019) point out that health risk assessment for fluoride-enriched groundwater involves evaluating potential non-cancer risks through the hazard quotient (HQ), which compares daily fluoride intake to a reference dose. In the study, HQ values indicated significant health risks, particularly for children, with many sampled sites exceeding safe limits ($HQ > 1$). The assessment highlighted that elevated fluoride levels, primarily from geological sources, pose serious health threats, necessitating urgent attention to safeguard local populations in Karbi Anglong district, Assam.

Ahada and Suthar (2019) in their study of southern Punjab, undertook a health risk evaluation regarding fluoride-laden groundwater by measuring chronic daily intake (CDI) and hazard quotient (HQ_{Fluoride}) to assess non-carcinogenic health risks. Their findings revealed fluoride levels surpassing the WHO's acceptable threshold, signaling serious health dangers, especially for young ones. The HQ_{Fluoride} figures varied between 0.29 to 2.41 for adults and 0.67 to 5.63 for children, indicating a considerable likelihood of dental and skeletal fluorosis, thus highlighting the urgent need for public health measures to reduce fluoride exposure.

Karunanidhi et al., (2020) in their investigation conducted in a semi-arid area of southern India, revealed that evaluating health risks associated with fluoride-laden groundwater involves analyzing potential health effects across various age demographics, especially infants. The research discovered that 79% of the samples of groundwater present a health threat to infants aged 5–12 months, contrasting with only 36% being potentially dangerous for adults older than 23 years. The analysis employed hazard quotients and total hazard indices based on both ingestion and skin contact with fluoride-rich groundwater, emphasizing the heightened susceptibility of younger individuals to fluoride exposure.

Singh et al., (2020) in their investigation conducted in the semi-arid landscapes of Northern India, expressed that evaluating health risks associated with fluoride (F^-) pollution in groundwater reveals that children are especially at risk, with a hazard index (HI) fluctuating between 0.12 and 3.35, and around 68 samples surpassing $HI > 1$. This suggests a significant non-carcinogenic health risk, as high fluoride levels can lead to dental fluorosis, osteoporosis, and thyroid dysfunction. The study emphasizes the urgent need for measures to mitigate fluoride contamination to protect the health of the local population, especially children.



Fernández-Macias et al., (2020) reveals that the health risk evaluation in the research scrutinizes the possible health consequences of ingesting fluoride-laden groundwater in San Luis Potosí, Mexico. The fluoride concentrations in the water varied from 0.20 to 3.50 mg/L, and the probabilistic health risk evaluation uncovered a mean cumulative hazardous index (HI) surpassing 1, signaling a significant non-carcinogenic risk (NCR) for both children and adults. This highlights the urgent need for campaigns aimed at safeguarding exposure to alleviate health hazards linked to fluoride ingestion.

Zhang et al. (2020) elucidate that the evaluation of health hazards assesses the possible non-carcinogenic dangers linked to fluoride intake from groundwater sources. The investigation measured fluoride levels in superficial groundwater, uncovering an average of 0.35 mg/L. The health risk indices for both children and adults were determined to be 0.27 and 0.15, respectively, both remaining beneath the permissible threshold of 1.0. This suggests that while fluoride exposure is mainly through ingestion, the overall risk stays within acceptable bounds, underscoring the significance of overseeing groundwater quality.

Liu et al., (2021) emphasize that assessing health risks related to fluoride-rich groundwater requires examining the possible health consequences of fluoride ingestion via drinking water. The study found that fluoride (F^-) significantly contributes to health risks, particularly for children, with average risks of 4.59 for children and 0.62 for adults. The Monte Carlo stochastic simulation method used in the research highlights the importance of considering uncertainties in model parameters, indicating that the health risks from fluoride consumption cannot be overlooked, especially for vulnerable populations.

Haji et al., (2021) opine that conducting a Health Risk Assessment (HRA) is vital for understanding the possible health effects of ingesting fluoride-laden groundwater. In the study, noncarcinogenic health risks were quantified, revealing that children faced the highest risk (0.75 to 8.44), followed by women (0.34–3.84) and men (0.27–3.01). The evaluation reveals that 59% of groundwater samples surpassed the safe fluoride threshold of 1.5 mg/L, underscoring considerable health hazards linked to excessive fluoride consumption, especially for at-risk groups such as children.

Raja and Neelakantan (2021) are of the opinion that the health risk assessment related to the consumption of fluoride-enriched groundwater is crucial as it evaluates the potential non-carcinogenic risks posed by fluoride exposure. In the study, 61% of water samples exceeded the permissible fluoride limits, with a calculated non-carcinogenic risk ranging from 0.1 to 12, averaging 1.8. Notably, 63% of samples surpassed the acceptable non-carcinogenicity limit set by the United States Environmental Protection Agency (USEPA), indicating significant health risks associated with fluoride consumption.

Das et al., (2022) opine that health risk assessment related to fluoride-enriched groundwater involves evaluating the non-carcinogenic health risks posed by fluoride (F^-) exposure. The study found that the health risk index for fluoride exceeded unity in infants, children, and adults, indicating potential health concerns. Factors influencing these risks included fluoride concentration, ingestion rate, and exposure duration. Monte Carlo simulations highlighted



these parameters as critical in assessing the health risks associated with fluoride consumption from groundwater, particularly in vulnerable populations like children.

Mukate et al., (2022) indicate that health risk assessment related to fluoride-enriched groundwater involves evaluating the potential adverse health effects on different age groups due to elevated fluoride levels. In the Bhokardan tehsil study, 77% of dug well samples exceeded the permissible fluoride limit, with children showing the highest health risk (THQ value of 2.42). This assessment helps identify vulnerable populations, guiding policymakers to implement strategies for monitoring and mitigating health risks associated with fluoride consumption in drinking water.

Husnejinovic et al., (2022) assert that evaluating health risks is essential for grasping the effects of ingesting fluoride-laden groundwater, as illustrated in their investigation. The findings indicated that fluoride levels in groundwater surpassed the WHO's acceptable limits, resulting in heightened daily fluoride consumption. By employing both deterministic and probabilistic methods, the research assessed health risks, revealing that a notable portion of both adults and children exceeded the permissible limit. This highlights the need for continuous monitoring and risk-benefit analysis to manage fluoride levels effectively.

Podgorski and Berg (2022) emphasize that evaluating health hazards associated with fluoride-laden groundwater is vital because prolonged exposure to high fluoride concentrations can result in health complications like dental discoloration and skeletal fluorosis. The World Health Organization establishes a maximum recommended limit of 1.5 mg/L for fluoride in potable water. The global fluoride hazard map developed in the study identifies areas at risk, allowing for targeted assessments and interventions to mitigate health risks for affected populations.

Rehman et al., (2022) in their research at Isa Khel, Punjab, Pakistan, executed a Health Risk Assessment (HRA) that entails scrutinizing chronic daily intake (CDI) and hazard quotient (HQ) to gauge possible health repercussions. Within the investigation, adults exhibited CDI and HQ values ranging from 0.001–0.15 mg/kg/day and 0.001–2.55, respectively, while children presented even higher figures of 0.001–0.29 mg/kg/day and 0.02–4.84. The evaluation unveiled that 40.25% of adult samples and a striking 66.95% of children's samples surpassed the safe HQ limit, highlighting considerable health threats, especially for the younger population.

Garcia-Montiel et al., (2023) emphasize that assessing health risks is vital for analyzing the non-cancerous dangers linked to consuming groundwater infused with fluoride. In the study, it was found that 90% of sampled wells exceeded the maximum fluoride limit, leading to a significant hazard quotient (HQ) for the adult population, with over 70% of wells showing HQs greater than 1. This indicates a substantial risk of fluoride-related health issues, particularly dental fluorosis, highlighting the importance of assessing health risks from contaminated drinking water sources.



Karabulut et al., (2023) suggest that a Health Risk Assessment assesses the possible health consequences of drinking fluoridated groundwater. The research found that typical fluoride levels varied between 0.26 and 3.62 mg/L., with the highest health risks identified in children, who exhibited a strong correlation with dental fluorosis. The HRA considered exposure through oral and dermal routes, highlighting that elevated fluoride levels pose significant health risks, particularly in vulnerable populations like children, emphasizing the need for monitoring and management of fluoride in drinking water sources.

Alharbi and El-Sorogy (2023) found that fluoride concentrations in groundwater exceeded WHO recommendations in 30.55% of samples, posing risks such as dental and skeletal fluorosis. The hazard index (HI) values indicated that infants and children are particularly vulnerable, with HI values surpassing the safety level of 1. This assessment highlights the need for immediate remedial measures to protect public health from fluoride exposure in drinking water.

Liu et al., (2023) highlights that evaluating the health risks linked to fluoride-rich groundwater entails analyzing the possible non-carcinogenic dangers tied to fluoride consumption via drinking water. This research employed the model from the U.S. Environmental Protection Agency to evaluate these hazards, concentrating on the routes of exposure through drinking water. Elevated fluoride levels can result in widespread health issues, especially dental fluorosis, with children being more vulnerable to these dangers. The evaluation underscores the necessity for groundwater purification to lower fluoride concentrations to acceptable drinking water standards.

Zhang et al.,(2023) point out that the risk assessment in the study indicates that fluoride-enriched groundwater poses significant health threats, particularly to children. The investigation uncovers that 66.67% of the groundwater samples surpass allowable fluoride thresholds, potentially resulting in negative health consequences. The research underscores the importance of overseeing and regulating fluoride concentrations in groundwater to protect community well-being, especially in areas with high concentrations, thereby providing a scientific basis for ensuring safe groundwater supply in Tongzhou District.

Krishanppa et al., (2024) assert that evaluating health risks linked to fluoride-laden groundwater requires an analysis of the potential hazards of non-carcinogenic nature stemming from fluoride exposure. Their research revealed that groundwater samples from Chikkaballapur surpassed safe fluoride thresholds, resulting in threats of fluorosis of the bones and teeth, in addition to neurotoxic repercussions. The total hazard index (THI) computations showcased notable health dangers, especially for children, underscoring the necessity of monitoring fluoride concentrations in drinking water to protect community health.

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.

Saha et al., (2024) suggest that the evaluation of health risks associated with fluoride pollution in groundwater reveals that the hazard quotient (HQ) for elevated fluoride concentrations presents more significant dangers to children compared to adults. Nationally, 8.65% and 7.10% of pre- and post-monsoon sites exceed the safe limit of 1.50 mg/L. The study highlights a potential for very high-risk skeletal fluorosis at around $\leq 2\%$ and a significant prevalence of dental caries due to fluoride deficiency, estimated at approximately 40%.

2.6 Remedial Methods

Rao et al., (2010) discusses the IISc method, which utilizes magnesium oxide for fluoride removal from groundwater through precipitation-sedimentation-filtration techniques. This method effectively reduces fluoride concentrations by converting fluoride ions into a brucite lattice and adjusting pH with sodium bisulfate. Other traditional methods include the addition of an aluminum sulfate-lime mixture or passing water through activated alumina columns. The IISc method is highlighted for its non-toxic nature and cost-effectiveness compared to aluminum-based methods.

Brindha and Elango (2011) are of the opinion that Rainwater Harvesting (RWH) serves as an effective remedial method for excess fluoride in groundwater by diluting contaminated water. By capturing and storing rainwater through existing wells or artificial recharging



structures, the concentration of fluoride can be reduced. This method not only helps in decreasing fluoride levels but also enhances the overall quality of groundwater. Implementing rainwater harvesting can provide a sustainable solution to mitigate fluoride contamination, ensuring safer drinking water for communities affected by high fluoride concentrations.

Ajaneyulu (2012) rainwater harvesting serves as a remedial method for excess fluoride in groundwater by providing an alternative source of water that is typically free from fluoride contamination. In regions like Yellampalli village, harvested rainwater is used for cooking and drinking, especially during the rainy season. Nevertheless, owing to restricted storage capabilities, it frequently incorporates solar distillation to guarantee access to potable water year-round, adeptly tackling the health hazards linked to extended fluoride exposure.

Lu et al., (2013) outlines the application of surface water as a remedial method for excess fluoride in groundwater by implementing a centralized water supply mode. This approach harnesses surface water as the main source for drinking and household needs, significantly lessening dependence on fluoride-rich groundwater. By incorporating surface water into the water distribution framework, communities can alleviate the health hazards tied to fluoride consumption, guaranteeing safer drinking water for inhabitants in the high-fluoride regions of southwest Shandong Province.

Perrera et al., (2013) are of the opinion that rainwater harvesting serves as an effective remedial method for excess fluoride in groundwater by providing a low-fluoride alternative for drinking and cooking. In the rural village of Inginimitiya, Sri Lanka, the implementation of 5,000-liter rainwater collection tanks significantly reduced fluoride exposure, with collected rainwater showing mean fluoride levels of 0.272 ppm compared to 1.27 ppm in groundwater. This method not only mitigates dental fluorosis but also enjoys widespread community acceptance, enhancing public health outcomes.

Othman et al., (2014) discusses the use of activated red clay soil from Kiteto District, Tanzania, as a remedial method for excess fluoride in groundwater. The clay soil is activated by calcination at 700 °C for 3 hours, and a minimum of 10 g of this activated clay is required to reduce fluoride levels in 100 mL of water from 4.59 mg/L to ≤ 1.1 mg/L. The activated clay can be reused effectively for defluoridation up to four times.

Kayira et al., (2014) primarily focuses on the use of raw bauxite as a defluoridating agent for groundwater, achieving up to 96.1% fluoride removal. Other conventional methods mentioned include various domestic water treatment solutions, though they are often inefficient or costly. The study emphasizes local defluoridating agents, like bauxite, as viable alternatives for developing countries facing high fluoride concentrations in drinking water, thereby addressing the issue of fluorosis effectively.

Jayarathne et al., (2015) point out to remedial methods for excess fluoride in groundwater include adsorption techniques using materials like natural apatite, which is inexpensive and environmentally friendly. Other methods involve precipitation, reverse osmosis,



electrodialysis, ion exchange, and nanofiltration. However, many of these methods are costly and not suitable for low socioeconomic communities. Therefore, utilizing locally available geological materials, such as apatite, is highlighted as a practical solution for defluoridation at the domestic level, particularly in rural areas with high fluoride levels.

Masquetti da Conceição et al., (2015) explores the extraction of surplus fluoride from ground water through coagulation techniques. with *Moringa oleifera* Lam seeds combined with microfiltration. The process involves adjusting the fluoride concentration and pH, followed by coagulation/flocculation tests and microfiltration. The optimal conditions identified were 5 g/L of *Moringa oleifera* coagulant and 2 bar pressure during microfiltration, resulting in significant reductions of fluoride, color, and turbidity, thus providing an effective remedial method for excess fluoride in groundwater.

Chakraborty et al., (2016) presents a nano-membrane based hybrid treatment system that effectively separates fluoride from contaminated groundwater, achieving a removal efficiency of 99%. This system utilizes a continuous flat-sheet cross-flow nano-filtration membrane and a chemical coagulation–precipitation process for stabilization. The optimized conditions for fluoride stabilization involve adjusting calcium chloride concentration, pH, and stirring time, ensuring safe disposal of fluoride in a solid matrix. This approach offers a low-cost solution, producing safe drinking water at approximately \$1.4 per 1000 liters.

Mbugua et al., (2017) discusses a novel method for mitigating excess fluoride in groundwater by using triethylamine modified waste polythene material. This approach is affordable, environmentally friendly, and sustainable, addressing the limitations of previous methods that were expensive and ineffective. The modified polythene material facilitates complexation with fluoride ions, effectively removing them from water. The study highlights the potential application of this material in point-of-use systems to improve water quality in areas affected by natural fluoride contamination.

Marwa et al., (2018) are of the opinion that rainwater harvesting serves as a remedial method for excess fluoride in groundwater by providing a source of fluoride-free water. This harvested rainwater can be blended with contaminated groundwater in calculated proportions to create safe drinking water. Additionally, the use of low-cost treatment methods, such as metallic iron-based filters, can address other pollutants, including pathogens, present in the blended water. This approach not only mitigates fluorosis but also offers a sustainable solution for water supply in affected regions.

Rawat and Patel (2018) suggest that surface water can serve as an alternative water resource for areas with excess fluoride in groundwater. It can be utilized for drinking and irrigation, helping to dilute fluoride concentrations in potable water supplies. However, relying solely on surface water may not meet the high demand for drinking water due to its insufficiency. Therefore, while it is a viable option, it should be part of a broader strategy that includes defluoridation techniques to effectively manage fluoride contamination.



Masindi et al., (2018) focuses on the use of mechano-chemically activated aluminosilicate clay soil as a remedial method for excess fluoride in groundwater. This method involves activating the clay soil through mechanical processes to enhance its adsorption capacity. The study achieved a maximum fluoride removal of 41% using a dosage of 0.6 g/100 mL of activated clay on water spiked with 9 mg-F/L at low pH, demonstrating the effectiveness of this approach in fluoride remediation.

Valentukeviciene et al., (2019) proposes that remedial methods for excess fluoride in groundwater include sorption techniques and membrane separation processes such as nano-filtration, reverse osmosis, and electro-dialysis. Other methods include coagulation-precipitation and ion exchange. Among these, sorption and membrane separation are the most commonly used due to their effectiveness and cost efficiency. The combination of these methods can lead to optimal treatment outcomes, particularly using materials like opoka sorbent, which has shown effective fluoride removal capabilities.

Gadgill et al., (2019) suggest that remedial methods for excess fluoride in groundwater include bauxite-based de-fluoridation, which utilizes mildly processed bauxite to effectively remove fluoride. Other methods include electrolytic de-fluoridation (EDF), which generates aluminum hydroxide in situ, and precipitation methods that involve adding aluminum, calcium, or magnesium salts to form flocculent precipitates. The process of acidifying contaminated groundwater with fluoride through the use of mineral acids or carbon dioxide can significantly improve the efficacy of fluoride extraction. Each method has its own challenges regarding cost, maintenance, and community acceptance.

Senthil et al., (2019) render the suggestion that surface water can be treated using technologies like reverse osmosis, which effectively retains fluoride ions with a retention factor over 98%, particularly at pH levels between 3-5. This method is advantageous due to its ability to work across a wide pH range and treat surface water with minimal maintenance.

Qi et al., (2019) opines that Rainwater Harvesting (RWH) serves as a remedial method for excess fluoride in groundwater by providing a clean, fluoride-free water source. It can be used directly for drinking or blended with contaminated groundwater to meet safety guidelines. RWH systems also recharge groundwater, mitigating the adverse effects of excessive groundwater abstraction. The Kilimanjaro Concept, initially developed to address fluoride issues in Tanzania, exemplifies the adaptability of RWH to regions facing similar geogenic contamination challenges, promoting sustainable water management.

Patrocino et al., (2019) focuses on electrodialysis reversal (EDR) technology as a remedial method for excess fluoride in groundwater. EDR was applied to both synthetic solutions and natural water samples, achieving an average fluoride removal of 90% for synthetic samples and around 80% for a natural water sample with an initial fluoride concentration of 7.49 mg F-/L. This method effectively reduces fluoride contamination, making the water suitable for drinking at a feasible cost, demonstrating its viability for treating fluoride-rich water.



Katiyar et al., (2020) discusses biological approaches for fluoride remediation, emphasizing bioremediation using bacteria, fungi, algae, and higher plants as effective methods for managing fluoride pollution in groundwater. These biological processes are eco-friendly, cost-effective, and sustainable alternatives to conventional methods, which are often labor-intensive and expensive. The review highlights the potential of enhancing indigenous natural agents and employing modern biotechnological techniques, such as gene editing, to improve plant-microbe interactions for more efficient fluoride degradation in contaminated environments.

Singh et al., (2020) focuses on the use of synthetic un-calcined hydroxyapatite (HAP) as a powerful technique for eliminating fluoride from groundwater. It demonstrates that un-calcined HAP can reduce fluoride levels significantly, achieving a fluoride uptake capacity of 4.38 mg F⁻/g HAP. The study suggests using a HAP dose of around 2.5 g/L to lower fluoride concentrations from 10 mg/L to below 1 mg/L. Continuous flow column studies indicate that HAP can be utilized in packed bed reactor systems for practical applications.

Mohan et al., (2020) explore a variety of solutions to tackle the issue of excessive fluoride in groundwater, such as reverse osmosis, electro-coagulation, nano-filtration, coagulation-precipitation, ion exchange, and adsorption methods. It specifically highlights the Fluoride Nilogon method, which utilizes a precipitation-adsorption mechanism involving pre-acidified water and crushed limestone to effectively remove fluoride. This method has shown consistent results over five and a half years, providing a safe, environment-friendly, and low-cost solution for defluoridation in affected communities.

Karunanidhi et al., (2020) recommends implementing managed aquifer recharge using check dams as a remedial method for excess fluoride in groundwater. This strategy has demonstrated its effectiveness in reducing fluoride levels, as highlighted by the study conducted near the current check dam in Kaldurai village, where fluoride concentrations were found to be beneath the permissible threshold of 1.5 mg/l in proximity to the dam. The technique seeks to enhance both the availability and usability of groundwater, rendering it more secure for drinking in areas impacted by fluoride.

Gilhotra et al., (2020) proposes electrocoagulation as an effective method for reducing excess fluoride in groundwater. This process optimizes parameters such as pH, current density, and treatment time, achieving permissible fluoride levels (1.5 mg/L) at pH 7.4, treatment time of 37 minutes, and current density of 40 A/m² using aluminum electrodes. The mechanism involves the formation of boehmite (AlO(OH)), which enhances fluoride adsorption, while also examining the interference of arsenic in the removal process.

Singh et al., (2020) discusses the complexity of remediating contamination of fluoride in groundwater, particularly due to its co-occurrence with arsenic. It emphasizes the need for a multi-model technique that combines statistical assessment with natural remediation methods. Various adsorption materials are explored to reduce fluoride concentrations to permissible levels, although specific remedial methods are not detailed. The integration of



machine learning classification algorithms is suggested to predict fluoride concentrations effectively, aiding in the development of targeted remediation strategies.

Richards et al., (2021) discusses rainwater harvesting as a sustainable method to mitigate excess fluoride in groundwater. By collecting and utilizing rainwater, communities can reduce reliance on fluoride-contaminated sources. This practice not only provides a clean water alternative but also helps in recharging aquifers, potentially diluting fluoride concentrations.

Fuoco et al., (2021) employed two innovative thin-film composite nano-filtration (NF) membranes, SPR 10113 and SPR 10114, to tackle the challenge of excessive fluoride in groundwater. Remarkably, the SPR 10114 membrane succeeded in lowering fluoride levels beneath the WHO benchmark of 1.5 mg/L in both treated water samples. Conversely, the SPR 10113 membrane fell short in achieving this for the Pc sample. The processed waters exhibited minimal ionic concentrations and were deemed suitable for agricultural irrigation without the need for additional re-mineralization.

Robledo-Peralta et al., (2021) evaluates two remedial methods for excess fluoride in groundwater: electrocoagulation and adsorption by biomaterials. The electrocoagulation process achieved over 90% fluoride removal, while biomaterials also demonstrated successful fluoride removal with efficiencies exceeding 80-83%. However, the operational conditions for fluoride removal must be prioritized, as they influence the effectiveness of the treatment processes. The study highlights the importance of these methods in addressing fluoride contamination in drinking water.

Tangitjaroenkit et al., (2021) presents an innovative approach to tackle the issue of excessive fluoride in groundwater through a hybrid cation exchanger infused with hydrated Al(III) oxide nanoparticles (HCIX-Al). This technique efficiently eliminates fluoride via a closed-loop regeneration mechanism, employing a polymeric macroporous cation exchanger. The HCIX-Al shows impressive fluoride absorption capacity, even under alkaline conditions, and facilitates material recycling with a 12% AlCl₃ solution, rendering it a sustainable and economical option for de-fluoridation.

Kromah et al., (2022) showcases the use of composite oxy-hydroxide mineral ores, especially bauxite, as a cheap and eco-friendly approach for the defluoridation of groundwater. Essential remedial strategies encompass refining the composition and pretreatment processes of bauxite, regulating pH levels and other contributing factors, alongside utilizing regeneration methods for the adsorbents. The research underscores the necessity of grasping the chemical properties of the ore and the adsorption dynamics to boost the efficiency of fluoride extraction from contaminated groundwater.

Kalsido et al., (2022) highlights various technologies for reducing excess fluoride in groundwater, with a focus on sorption-based processes. These methods are noted for their high removal efficiency, cost-effectiveness, ease of operation, and simplicity of design. Amidst the conventional methods for extraction, sustainable sorption innovations are highlighted as



exciting substitutes for adeptly reducing fluoride levels to acceptable standards, thus alleviating health hazards linked to elevated fluoride levels, including both skeletal and non-skeletal fluorosis.

Punia et al., (2022) indicates that remedial technologies for excess fluoride in groundwater include various processes such as Ultrafiltration, Electro-dialysis, Coagulation/Precipitation, Phytoremediation, Ion-exchange, and Reverse Osmosis. Among these, the Nalgonda procedure and adsorption techniques are widely used due to their cost-effectiveness and efficiency. The adsorption technique, in particular, is favored for its simplicity and acceptable results. It is crucial to adopt cost-effective and optimal techniques to effectively control fluoride contamination in water.

Maghanga et al., (2022) investigates the use of *Maerua subcordata* root powder (MSRP) as a plant-based remediation strategy for excess fluoride in groundwater. MSRP demonstrated approximately 68% fluoride ion removal efficiency, with optimal conditions being a dosage of 200 g/L and an equilibration time of 30 minutes. Although the treated borehole samples showed lower fluoride reduction levels than the standards, further modifications, such as doping with zero-valent iron nanoparticles, are anticipated to enhance its efficiency in fluoride removal.

Sahu and Debsarma (2023) opines that Rainwater Harvesting serves as a remedial method for excess fluoride in groundwater by providing an alternative source of safe drinking water. It reduces reliance on contaminated groundwater, thereby minimizing exposure to fluoride. Additionally, harvested rainwater can be treated to remove fluoride, ensuring its safety for consumption. Implementing rainwater harvesting techniques also promotes sustainable water management and can alleviate the health risks associated with fluoride-related disorders, contributing to public awareness and community health improvement.

Ou et al., (2023) developed magnesium oxide (MgO)-based adsorbents, specifically granulated MgO aggregates (GA-MgO) and surface-modified MgO powder (SM-MgO), as remedial methods for excess fluoride in groundwater. These adsorbents utilize chemical adsorption mechanisms, where magnesium hydroxide forms and fluoride ions replace hydroxyl groups to create magnesium fluoride precipitation. The GA-MgO system can contain and remediate fluoride-contaminated groundwater, while SM-MgO serves as a rapid removal alternative for emergency situations, achieving significant fluoride removal efficiencies.

Shaji et al., (2023) identifies several efficient fluoride removal techniques, including filters utilizing next-generation nanomaterials. However, it notes that no single technique has proven to be a practically robust solution for fluoride removal from drinking water. The study suggests developing advanced filters that can selectively retain essential minerals while removing harmful ones, and emphasizes the importance of choosing purification technologies based on specific needs, climate, geology, and geographic location to effectively address fluoride contamination in groundwater.



Sharma et al., (2023) point out that remedial methods for excess fluoride in groundwater include bioremediation, which utilizes living microorganisms to eliminate contaminants. This process can be categorized into in-situ techniques, performed at the contamination site, and ex-situ techniques, which involve treatment away from the site. Other methods mentioned are osmosis, nano-filtration, electro-dialysis, and adsorption. However, these conventional methods often face challenges like high investment and sludge generation, making bioremediation a more cost-effective and environmentally friendly option.

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 m², 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 defluorination 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 defluorination.

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)



Chapter 4: Geogenic controls on fluoride contamination in the groundwater

4.1 Preface

The presence of fluoride ions (F^-) in groundwater systems represents a pressing global public health challenge, with widespread implications for human health and well-being. At trace concentrations (0.5–1.5 mg/L), fluoride plays a beneficial role in preventing dental caries by strengthening tooth enamel. However, chronic ingestion of groundwater containing fluoride concentrations surpassing the permissible threshold of 1.5 mg/L, as delineated by the World Health Organization (*WHO, 2022*), is associated with severe and chronic health disorders. These include irreversible dental fluorosis, characterized by mottling and pitting of tooth surfaces; crippling skeletal fluorosis, marked by bone deformation and joint immobility; and emerging evidence of neurotoxic effects, particularly in vulnerable populations such as children (Podgorski & Berg, 2022). The gravity of this issue is amplified in regions like India, where groundwater constitutes the principal drinking water source for approximately 70% of rural inhabitants. Nationally, endemic fluoride contamination has been documented across 20 states, with West Bengal emerging as a critical area of concern due to its hydrogeological susceptibility (*Central Ground Water Board, 2023*). Within this context, Birbhum district, located along the transitional margin of West Bengal's Chotanagpur Plateau, has been identified as a hotspot for fluoride enrichment. Recent hydrochemical surveys have detected extreme fluoride concentrations exceeding the statutory values, in localized groundwater systems, particularly in regions underlain by fluoride-bearing granitic bedrock (*Mukherjee and Singh, 2020; Chaudhuri et al., 2024*).

In general, the occurrence and subsequent accumulation of fluoride ions within the drinking water primarily be ascribed to a variety of geogenic processes (*Chowdhury et al., 2019*). Among the key geogenic processes that significantly contribute to the fluoride contamination are the weathering processes associated with minerals that are inherently rich in fluoride content, the geological phenomena of volcanic eruptions, the dynamic activities tied to hydrothermal systems and also the substantial contributions made by marine aerosols that enter the hydrological cycle (*Edmunds and Smedley, 2005; Vithanage and Bhattacharya, 2015*). The principal sources of fluoride within the geological context consist of a variety of fluoride-rich rock formations which include, but are not limited to, alkali rhyolites, granitic group of rocks and mafic igneous formations. Minerals such as fluorite, fluorspar, cryolite, apatite, fluorapatite and mica that play a critical role in the environmental fluoride cycle (*Jha and Tripathi, 2021*). The concentrations of fluoride exhibit significant variability that is largely contingent upon their lithological composition, with empirical measurements revealing concentrations of 1300 mg/kg in marine shale deposits, 1000 mg/kg in alkaline igneous rock formations, and 100 mg/kg in ultramafic rock types, thus reflecting the diverse geochemical environments from which they originate (*Nagudi et al., 2003; Scaillet and Macdonald, 2004; Ozsvath, 2006*). Fluoride-bearing mineralogical components are frequently associated with the later stages of pegmatitic intrusions, hydrothermal vein deposits and the



igneous rock types that crystallize from highly differentiated magmas characterized by unique geochemical signatures. These specific mineral types are known to release fluoride ions (F^-) into the surrounding groundwater through a series of geochemical processes that include leaching, hydrolysis, and ion-exchange mechanisms that facilitate the mobilization of fluoride (*Aind et al., 2022; Rashid et al., 2024*). The contamination of groundwater by fluoride ions (F^-) is significantly controlled by the lithological composition of the aquifer host rocks, particularly in geographical regions that are underlain by granitic and granite-gneissic formations. These rock types, which are prevalent in cratonic shields and Precambrian basement complexes around the world, serve as major geogenic sources of fluoride due to their specific mineralogical makeup. Granitic rock formations exhibit a variety of fluoride-bearing minerals, encompassing both primary and accessory types, such as fluorite, apatite, fluor-apatite, and mica, which are known to release fluoride ions upon undergoing the process of weathering (*Chakrabarti et al., 2013; Dubey et al., 2021*). Additionally, hornblende and other iron-magnesium silicate minerals are also capable of releasing fluoride ions (F^-) as a result of oxidative weathering processes, particularly in areas characterized by fracture zones (*Mukherjee and Singh, 2020*).

A significant influence is exerted by the tectonic characteristics of a specific area in the process of augmenting the concentration of fluoride present within the groundwater resources of that region. Numerous studies have indicated that areas exhibiting elevated levels of fluoride within their groundwater are frequently correlated with the presence of particular tectonic zones that exhibit unique geological features. The highest number of recorded incidences of fluorosis in human populations, in conjunction with the maximum observed concentrations of fluoride in various water sources, are typically documented in regions characterized by intra-continental hotspots, failed rift systems, and magmatic belts reminiscent of the Andean geological formations (*Chowdhury et al., 2019*). The calc-alkaline volcanoes located within the East African Rift System (EARS) have been shown to produce lavas that are comparatively rich in fluorine, a phenomenon that is similarly observed in continental volcanic arcs such as the Andes, as well as in island arcs exemplified by the geological formations found in Japan (*Rosi et al., 2003*). Within the confines of these aquifers, the interplay of regional thermal fields, along with the presence of felsic volcanic rocks situated within areas of high geothermal activity, serves as a significant contributor to the elevated levels of fluoride contamination observed in groundwater resources (*Alemayehu et al., 2006; Furi et al., 2011*). The waters emanating from geothermal springs frequently exhibit concentrations of fluoride that far exceed the safety standards established by the World Health Organization (WHO), thereby raising substantial public health concerns. Thermal springs, which are known to be surface manifestations of geothermal energy, represent a crucial aspect of the hydrological cycle in areas of volcanic activity. The thermal energy associated with these springs is partly derived from the radioactive decay of naturally occurring elements such as uranium (U), thorium (Th), and potassium (K) that are present in granitic rocks that produce significant amounts of heat (*Karakus, 2015*). The thermal waters that traverse through the granitic formations of the Chotanagpur Granite Gneiss



Complex (CGGC) are reported to exhibit fluoride contamination levels that are considerably higher than the permissible limits set by health authorities (*Minissale et al., 2000; Chandrasekhar and Chandrasekharam, 2009; Singh et al., 2015*). The waters sourced from the Taptapani hot springs located in Odhisa, as well as those from the Bakreshwar hot springs in West Bengal, are noted for their exceptionally high fluoride content that reaches values of 16 mg/L, are a part of the Son- Narmada- Tapti (SONATA) geothermal province. In the eastern parts of the aforementioned geothermal province. In a similar note, the most prominent hot springs within the Cambay Geothermal Province are situated in Tuwa, which is part of the Godhra granitic formation, where the fluoride content has been observed to fluctuate between 2.5 to 4 mg/L (*Singh and Chandrasekharam, 2010*). Furthermore, neotectonic events alongside subsequent tectonic activities characterized by lineament formations may also play a significant role in contributing to the excessive fluoride contamination observed in various geological settings. In the Highland and Vijayan rock formations of Sri Lanka, it is suggested that numerous deep-seated lineaments and faults, which were generated by both Pre-Cambrian and neo-tectonic events, could serve as critical sources for the outgassing of fluorine, thereby exacerbating the issue of fluoride contamination in groundwater resources (*Vithanage, 1989*).

The various determinants that influence the enrichment of fluoride within groundwater systems can be attributed to a multitude of factors including, but not limited to, temperature variations, pH levels, the capacity for anion exchange specifically involving hydroxide ions (OH^-) being exchanged for fluoride ions (F^-), the duration of contact that water has with geological substrates, the solubility characteristics of minerals that contain fluoride, the specific geological formations that the water traverses, as well as the notable absence of precipitating ions and colloids in the water (*Liu et al., 2023; Wei et al., 2024*). In regions characterized by arid and semiarid climates, where annual precipitation levels are markedly low and evaporation rates are significantly elevated, it follows that the hydraulic conductivity of groundwater within these areas tends to be relatively low (*Su et al. 2006*). As a direct consequence of this low hydraulic conductivity, the rate at which groundwater is recharged is rendered quite minimal, which in turn leads to an extended period of interaction between water and the surrounding rock formations. This prolonged interaction is a critical factor that contributes to the observed increase in fluoride concentrations within groundwater sources. Empirical observations have indicated that areas located in low-lying plains tend to exhibit elevated concentrations of fluorides in their groundwater, while regions situated in higher elevations or highlands report significantly lower fluoride levels. This phenomenon can be attributed to the fact that in the plains, water remains in contact with the aquifer for a longer duration, resulting in a slower movement of groundwater through the geological strata (*Ali et al., 2023*). The retention time of water within an aquifer is a crucial determinant of the degree of interaction that occurs with geological materials; thus, it can be concluded that the concentration of fluoride in groundwater is directly proportional to this retention time (*Saxena and Ahmed, 2003*). The precipitation of minerals that exhibit lower solubility, such as calcium carbonate (CaCO_3), is often triggered by elevated evaporation rates, which subsequently leads to a reduction in the concentration of calcium ions present in



groundwater, thereby facilitating the dissolution of fluorite minerals (**Vithnage and Bhattacharya 2015**). Another significant factor influencing the fluoride concentration in groundwater is the pH value, which plays a vital role in determining the solubility and mobility of fluoride ions. The increase in the concentrations of sodium ions (Na^+) and bicarbonate ions (HCO_3^-) can lead to a rise in pH levels, which consequently promotes the further dissolution of fluoride-bearing minerals within the groundwater system (**Rango et al. 2009**). When pH levels are low, fluoride ions tend to form complexes with aluminum and iron present in the soil matrix. Specifically, when the pH falls below 4.0, fluoride ions are actively adsorbed by clay minerals such as illite, chlorite, and smectite, whereas at pH levels exceeding 6.5, the adsorption processes become markedly reduced. In alkaline conditions, specifically when the pH exceeds 7, anion exchange reactions occur where hydroxide ions (OH^-) substitute for fluoride ions (F^-) in minerals such as biotite, muscovite, and various clay minerals (**Li et al. 2014**).

Handa (1975) and **Saxena and Ahmed (2003)** suggest that mechanisms governing the mobilization of fluoride within groundwater systems are, in fact, rather complex and not fully understood. The process of anion exchange has been shown to elevate fluoride concentrations in water to levels upto 30 mg/L (**Rasool et al. 2017**). As previously elucidated, the similarity in ionic radii facilitates the substitution of fluoride ions (F^-) for hydroxide ions (OH^-) due to their comparable atomic sizes and the fact that both possess a single negative charge (**Farooqi et al. 2007; Sivasankar et al. 2016**). It has also been noted that under conditions of low pH, fluoride ions are prone to adsorption by various clay minerals. Hence, it can be argued that alkaline environments significantly enhance the accumulation of fluoride ions in subterranean water reserves (**Singh et al. 2015; Liu et al., 2023**). As pH values exceed 7, signifying alkaline states, the phenomenon of anion exchange is promoted, wherein fluoride ions (F^-) are swapped for hydroxide ions (OH^-) within fluoride rich minerals (**Li et al. 2014**). The prolonged retention of water in an aquifer causes the substitution of calcium ions (Ca^{2+}) with sodium ions (Na^+), culminating in the creation of soft water that boasts an abundance of Na^+ , a scenario that particularly supports the leaching of fluoride from groundwater sources. Furthermore, the rate at which fluoride dissolves from fluorite (CaF_2) is significantly enhanced in the presence of elevated concentrations of bicarbonate ions (HCO_3^-) (**Handa 1988; Karro and Uppin, 2013**). Consequently, the pH level of water, in conjunction with other critical parameters for water quality regulation such as electrical conductivity (EC), total dissolved solids (TDS), and redox potential (Eh), experiences an increase. The elevation of fluoride levels in groundwater is facilitated by the presence of calcium ions (Ca^{2+}) and magnesium ions (Mg^{2+}) in minimal amounts, while sodium ions (Na^+) appear in higher concentrations (**Farooqi et al. 2007**). In acidic conditions, clay minerals have a tendency to capture fluoride ions, but in alkaline environments, fluoride ions (F^-) are liberated (**Sarma and Rao 1997**). However, the key chemical elements that influence fluoride pollution in groundwater include processes such as dissolution, hydrolysis, precipitation, adsorption, ion exchange, and biochemical interactions (**Saxena and Ahmed 2003, Chaudhuri et al., 2024**). The heightened fluoride concentrations in water extracted from dry and semi-dry areas can



be linked to the accumulation of soluble materials due to the processes of evapo-transpiration and evaporation (*Jacks et al. 2005*).

The comprehension of the mechanisms that exert a regulatory influence on the overarching dynamics of contamination of fluoride in subterranean water sources is of paramount importance. Given that fluoride contamination is predominantly governed by geogenic influences, the interaction among geological, geochemical, and tectonic factors is fundamentally responsible for the accumulation and subsequent mobilization of fluoride within the groundwater. Consequently, it is imperative to accurately identify the principal sources, elucidate the processes involved in the release and concentration of fluoride and understand its pathways of mobilization, to evaluate the possible effects on health. Most critically, remedial strategies must be formulated based on the insights derived from this knowledge.

4.2 Methodology

4.2.1 Study Area

The northernmost administrative division within the Burdwan region of the state of West Bengal is the district of Birbhum (**Fig. 1**). Geographically, this district is situated between the latitude coordinates of 23°32'30" N and 24° 35' 0" and longitudes of 88°1'40" N, extending down to 87°5'25" N. This area, which is referred to as the "Land of the Red Soil," holds immense cultural and historical significance, making it a highly esteemed locale within the broader context of West Bengal's diverse heritage. Encompassing an expansive area of approximately 4545 square kilometers, the district is characterized by a distinctive isosceles triangular shape, wherein the river Ajay functions as the base of the triangle, effectively delineating the geographical boundaries that separate the Burdwan and Birbhum districts from one another. To the west, the district shares its borders with the neighboring state of Jharkhand, while to the east, it is flanked by the districts of Murshidabad and Burdwan, thus highlighting its strategic location within the state. From the perspective of agro-climatic classification, Birbhum is situated in the lower Gangetic plain, a region known for its predominantly red laterite soils, which are interspersed with alluvial deposits and clay, thus contributing to the area's agricultural viability and ecological diversity. This unique combination of geographical and climatic attributes not only defines the physical landscape of Birbhum but also plays a critical role in shaping the socio-economic dynamics and cultural practices of its inhabitants.

The geographical landscape of Birbhum is predominantly influenced by the presence of lateritic soil, which plays a significant role in the development of the distinctive "khoai" region, a locale that is notably marked by its undulating topography and a variety of erosion phenomena such as rills and gullies that actively shape the land. In addition to these features, the district's topographical composition is further enriched by the presence of micro-relief forms, which include an array of natural formations such as ravines, waterfalls, and terraces; these are characteristic of lateritic terrains and bear a striking resemblance to the highland areas found in regions of Africa and Brazil, thereby underscoring the global



significance of Birbhum's geological characteristics. The climatic conditions prevalent in Birbhum are categorized as "dry sub-humid mega thermal," a classification that reflects the extreme temperature variations experienced throughout the year, with summer temperatures soaring to a staggering 44°C-46°C, while in stark contrast, winter temperatures can plummet to a chilling 6°C-7°C, illustrating the diverse climatic challenges that the region faces. Precipitation levels in the district are moderate, with the month of July witnessing the highest rainfall, which can reach up to 350 mm, a significant factor that

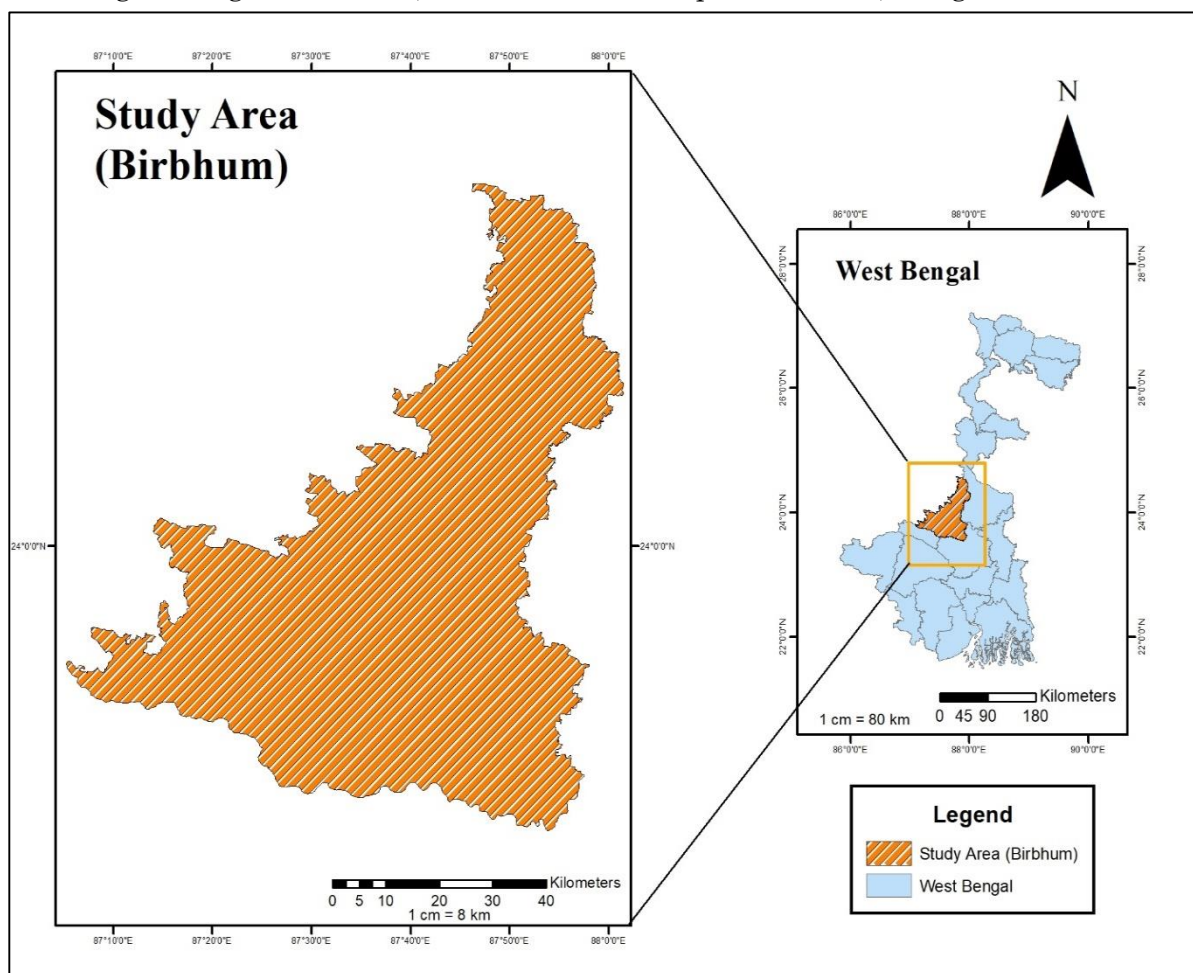


Figure 4.1: Study Area Map

contributes to the region's classification as drought-prone, thereby impacting the agricultural practices and water availability for its inhabitants. Furthermore, the district grapples with considerable challenges concerning groundwater quality, particularly with the contamination of water sources by fluoride, which poses serious health risks and affects the overall water quality in specific areas such as the Rampurhat-II block, as documented in various studies (*Sarkar et al., 2016; Das et al., 2020; Saha and Mondal, 2022*).



4.2.1.1 Geology of Birbhum

Birbhum exhibits a remarkable geological diversity. Exposures of Archean granitic rocks, the Rajmahal basaltic traps, deposits of Gondwana coal, as well as older and newer alluvial deposits, all contributing to a complex geological landscape. The Archean rocks, characterized predominantly by the Chotanagpur Granite Gneiss, are primarily visible in the southwestern region of the district, where they form a significant part of the geological framework. The Gondwana formations, can be found scattered in patches throughout the southern and southwestern areas, particularly along the banks of the Ajoy River (CGWB). In contrast, the Rajmahal basaltic traps are prominently exposed in the northern and northwestern sectors of the district. Additionally, Tertiary formations, which are represented in fragmented patches, consist chiefly of clay beds along with ferruginous and feldspathic sandstones, contributing to the intricate stratigraphic profile of the area (*Mukherjee et al., 1969*). Notably, the thickness of the alluvial deposits exhibits a significant gradient, increasing from the western to the eastern parts of the district, where it ranges from less than 20 meters to an impressive 80 meters below ground level (bgl), thereby highlighting the substantial accumulation of sediment over time (CGWB). The older alluvial deposits, dating from the Upper Tertiary to the Lower Quaternary periods, have extensively inundated the eastern and southeastern regions of the district, thus dominating the geomorphological features in these areas. Furthermore, the older alluvium is often overlain by layers of laterite and lateritic soil, which predominantly cover the upland regions. The recent alluvium, composed of alternating strata of sand, silt, and clay from the Upper Quaternary epoch, is found particularly in the extreme eastern sectors of the district, as well as along the major river courses.

Birbhum is geographically situated at the western extremities of the expansive Bengal Basin, which is distinctly separated from the ancient Precambrian Indian Shield to the west by a prominent fault zone that marks the margin of the basin, which is characterized by notable dislocation and cataclasis. The process of extensional tectonics has resulted in the formation of a complex system of grabens, which are characterized by tilted and/or downthrown blocks that emerged during the rifting events associated with the Gondwana supercontinent, a phenomenon that has been further complicated by the intersection of numerous normal faults. The geological composition of Birbhum is predominantly marked by the presence of the Rajmahal Trap, an extensive formation consisting of tholeiitic basalt flows that date back to the Late Cretaceous period, which were the result of significant igneous activity associated with the Kerguelen hotspot. This particular region is also influenced by the characteristics of the Stable Shelf, demonstrating extensional tectonics that have persisted from the Late Paleozoic era through to the Mid Mesozoic era, highlighting a prolonged period of geological evolution and transformation (*Hossain et al., 2019*). Furthermore, the structural integrity and geological history of Birbhum have been significantly shaped by the complex tectonic interactions that occur between the Indian Plate and the Eurasian Plate, which have played a crucial role in contributing to the region's overall structural complexity as well as its intricate sedimentary history.



Table 4.1 Generalized stratigraphic succession for the district of Birbhum (*Mukherjee et al., 1969; Sen et al., 1987*)

Horizon	Formation	Lithology
Recent		Alluvium
Quaternary/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

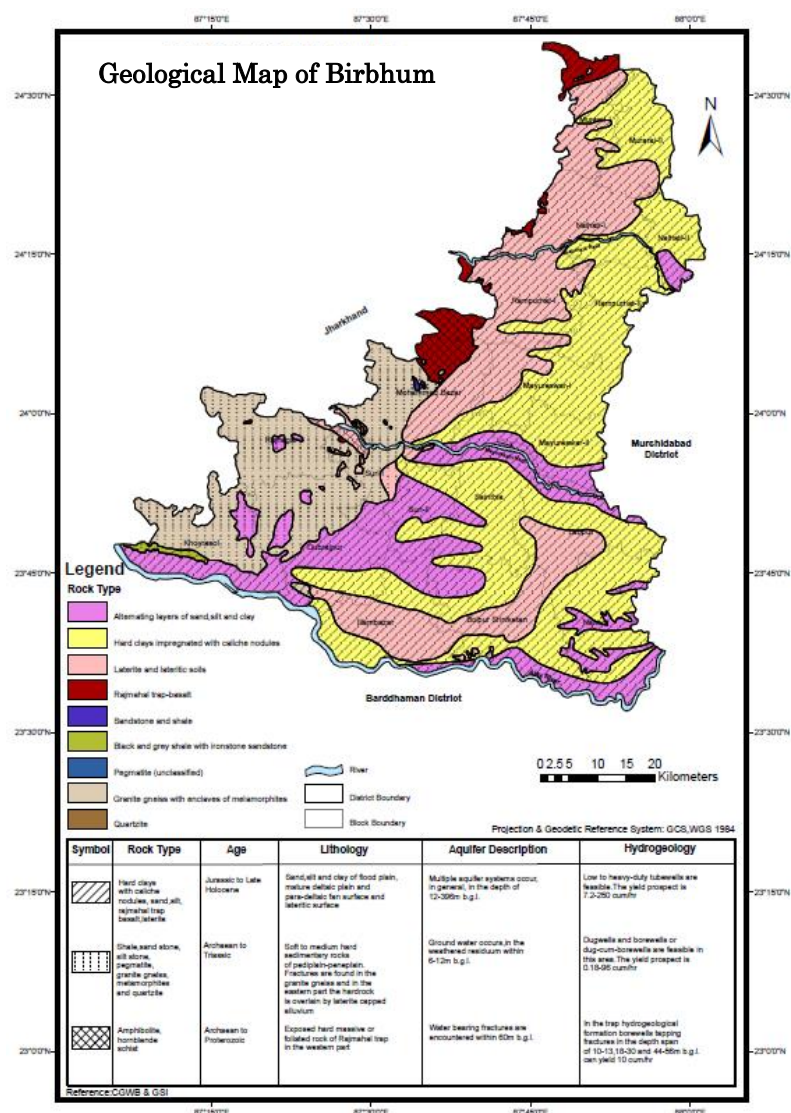


Figure 4.2 Geological map of Birbhum constructed through digitization of GSI maps

4.2.2 Petrographic analysis

Microscopic analyses were conducted on an array of rock samples that were systematically gathered from various locations throughout the district. Notably, the rock samples were chiefly gathered from targeted regions that displayed heightened levels of fluoride within the subterranean water sources, thereby providing a targeted approach to the investigation of fluoride dynamics. The aim was to achieve a lucid comprehension of the geological framework, emphasizing on the mineral assemblages and their associations, which are instrumental in contributing to the phenomenon of geo-genic fluoride contamination



observed within the groundwater resources. The coordinates of the locations from which rock samples have been collected are mentioned in **Table 4.2**.

Table 4.2: 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
Jhaptala 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 for the entire district, for the period of 2016 to 2019 were obtained from PHED, WB. Primary groundwater data, collected from around 50 wells in five fluoride affected blocks of Birbhum were also analyzed. Several analysis were conducted in order to comprehend the ionic character and understand the dominant processes that control the geochemistry of the groundwater of the region. The following analysis were conducted :

- **Gibbs Diagram:** Gibbs diagrams are a valuable tool in geochemical analysis of groundwater, primarily used to understand the interactions between water and geological formations. These diagrams help in identifying the dominant geochemical processes influencing groundwater chemistry, such as rock-water interaction, evaporation, and precipitation. By plotting the ratios of major ions, Gibbs diagrams provide insights into the sources and mechanisms controlling groundwater composition (*Makri et al., 2019; Changsheng et al., 2022*). This makes them essential for assessing water quality and understanding the hydrogeochemical evolution of aquifers
- **Piper Trilinear Diagrams:** The Piper diagram is a fundamental tool in geochemical analysis of groundwater, widely used to visualize and interpret the chemical characteristics of water samples. It provides a graphical representation of the major ionic species, facilitating the classification of water types and the understanding of hydrochemical processes. The utility of Piper diagrams extends to various applications, including the assessment of water quality for domestic and irrigation purposes, the identification of geochemical processes, and the visualization of large datasets. Piper diagrams are instrumental in classifying groundwater into different hydrochemical facies based on the relative concentrations of major cations and anions. This classification helps in understanding the chemical nature and origin of groundwater samples (*Darwesh et al., 2019; Arulnangai, 2020*). The diagrams allow for the identification of dominant water types, such as Na-Cl or Ca-Mg-HCO₃, which can indicate specific geochemical processes or sources of contamination (*Karmegam et al., 2011*).



4.2.4 Lineament Analysis

The term lineament can be defined as geological features that exhibit either linear or curvilinear patterns and can be discerned on the Earth's surface through advanced methodologies such as remote sensing technologies, aerial photography, or comprehensive topographic mapping techniques, holds significant importance in the realms of structural geology and tectonic analysis. These geological features frequently serve as indicators of underlying geological structures such as faults, fractures, joints, or contacts between different lithological units, thereby offering invaluable insights into the processes of crustal deformation, the regimes of stress that influence tectonic activities, and the broader narrative of tectonic evolution over geological time (*Gabrielsen et al., 2024*). Moreover, lineaments are not only essential for understanding the structural characteristics of the Earth's crust but also function as critical pathways for the movement and mobilization of hydrothermal fluids, which encompass geothermal waters, and they serve as efficient channels for the movement of groundwater within various geological settings (*Al Nahmi et al., 2016; Singh et al., 2020; Meles et al., 2024*). Thus, the study of lineaments is paramount for geoscientists, as it provides a deeper comprehension of both the physical properties of the Earth's crust and the dynamic systems that govern fluid movement beneath the surface, ultimately contributing to our understanding of geological processes and resource management.

Lineament maps were constructed for the district of Birbhum, along with the lineament density maps in order to gauge the presence, orientation, concentration and spatial extent of the lineaments, in order to understand the nuances and postulate the pathways for the mobilization of fluoride contaminated groundwater. GIS platforms were used for the generation of the aforementioned maps. The maps so created were compared with the lineament maps of the district that is available from the Bhuvan portal in order to correctly delineate the lineaments.

4.2.5 Statistical analysis

Statistical analysis plays a pivotal role in understanding the hydro-chemical dynamics of groundwater systems. It plays a crucial role in deciphering the geochemistry of groundwater, providing insights into the chemical characteristics, sources of contamination, and hydro-geochemical processes affecting groundwater quality. By employing various statistical techniques, researchers can interpret complex datasets, identify patterns, and make informed decisions for groundwater management. By quantifying relationships between ionic concentrations, these methods help in identify sources of contamination, natural geochemical processes, and anthropogenic influences.

Hydro-geochemical studies aim to unravel the intricate interactions between water, geological materials, and anthropogenic activities that shape the chemical composition of aquatic systems. These interactions are governed by a multitude of processes, including mineral weathering, ion exchange, redox reactions, and contamination, which collectively determine water quality and ecosystem health. To decode these complex relationships, researchers rely on robust statistical tools capable of quantifying associations between



variables. Among these tools, **Pearson's correlation coefficient (r)** stands as a cornerstone method for identifying linear relationships, offering insights into the drivers of hydro-geochemical dynamics.

The Pearson correlation analysis, which was executed on a variety of geochemical parameters associated with groundwater, aimed to establish a meaningful relationship between the concentration of fluoride and other quality indicators present in the groundwater system. The correlation coefficient, denoted by the symbol r and originally formulated by the eminent statistician Karl Pearson, serves as a quantifiable metric that gauges the strength and direction of the relationship that exists between two distinct variables, which in this context can be represented as λ and ξ , and is mathematically expressed through a specific equation as outlined in the scholarly work of *Suleiman et al. (2022)*.

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

The numerical value of the correlation coefficient, denoted by the symbol r , exhibits a range that spans from negative one to positive one, where the presence of positive values is indicative of a direct correlation between the variables under examination, whereas negative values suggest a weak or inverse correlation, thereby providing critical insights into the relationship dynamic between the two entities being analyzed. Furthermore, the specific value of zero serves as an important threshold, signifying a state of negligible correlation, which implies that there exists no discernible linear relationship between the two variables, thus highlighting the complexity of their interaction or lack thereof.

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

4.3.1 Petrographic analysis

The microscopic examination of various samples of granite-gneiss collected from across the district reveals an assemblage that comprises minerals such as Quartz, Microcline, Biotite, Apatite, sphene and a minor presence of Chlorite, among which Biotite and Apatite emerge as significant contributors of Fluorine when subjected to alkaline conditions. The mineralogical composition of the rock samples from the surface exposures located in the Birbhum region primarily reveals that apatite and biotite are the predominant fluoride-bearing minerals present, with the presence of hornblende being relatively minor in comparison. The data obtained from modal analysis illustrates that the granitic rock samples



comprise approximately 20–30% quartz, 40–45% feldspar, 5–10% apatite, and 20–25% biotite, alongside trace amounts of chlorite and sphene, thereby highlighting the intricate mineralogical diversity within these geological samples. The apatite grains manifest a euhedral to subhedral crystal morphology, displaying a range of variable grain sizes, with some elongated grains occasionally reaching lengths of up to 200 μm , and these grains are often found in close proximity to hydrous minerals, particularly at the interfaces between the coarse-grained feldspar and quartz present in the rock. With respect to their immediate mineralogical associations, the apatite grains exhibit a strong correlation with biotite, and in certain locations, there is also an observable association with chlorite, further emphasizing the complex interactions among these mineral phases.

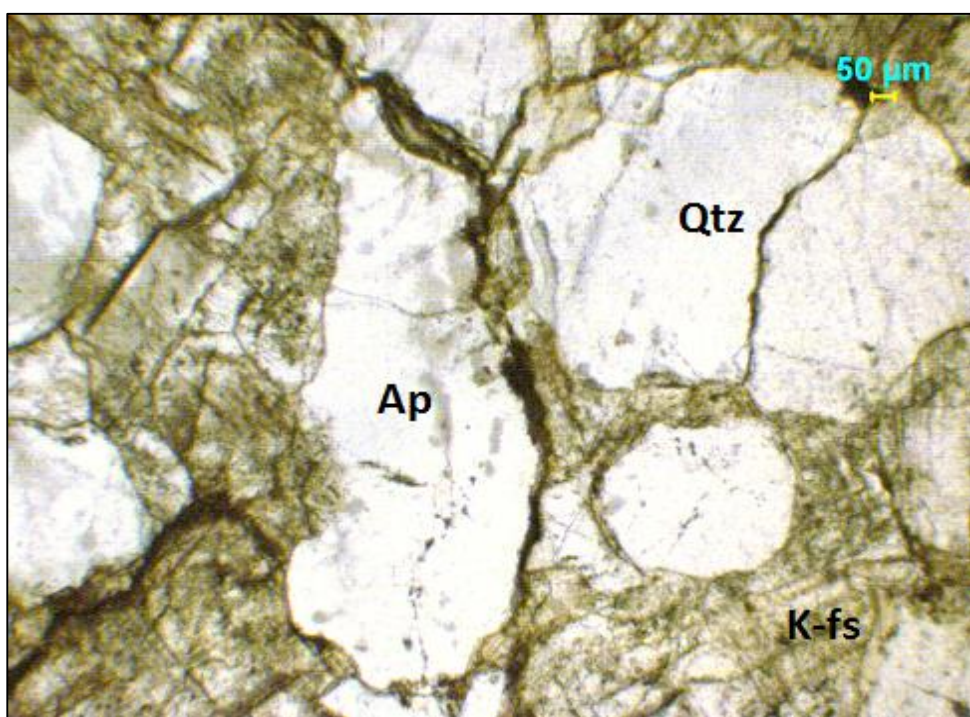


Figure 4.3 Tantipara granite showing an assemblage of Apatite, K-feldspar and Quartz under Plain Polarized Light (PPL).

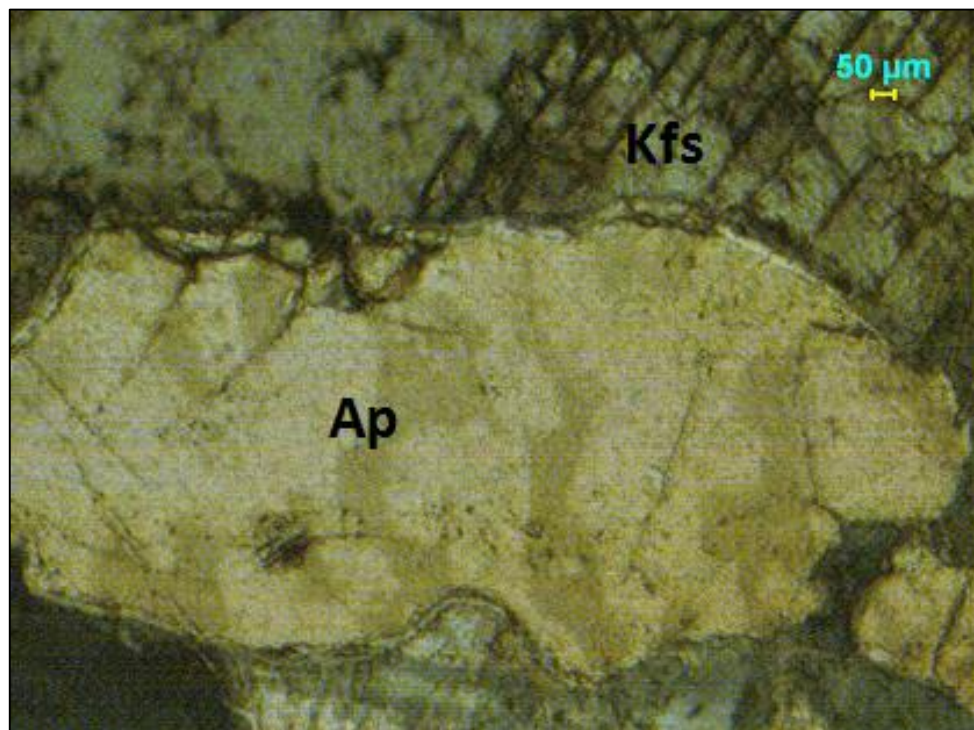


Figure 4.4 Same sample under Cross-Polarised Light (CPL)

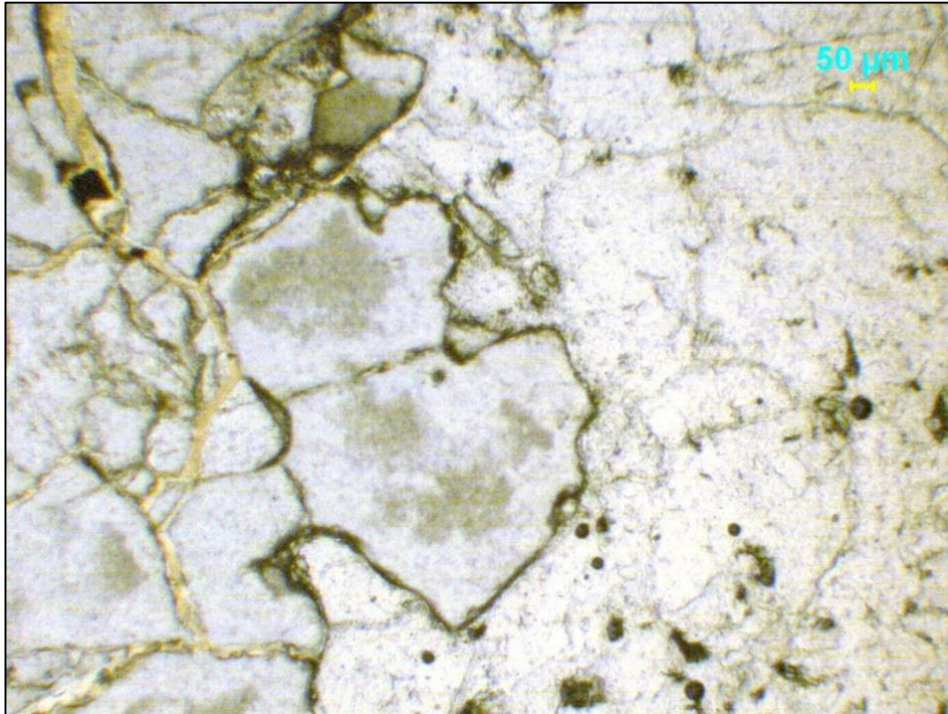


Figure 4.5 Elongated Apatite Grains, Bakreshwar river Gneiss under PPL

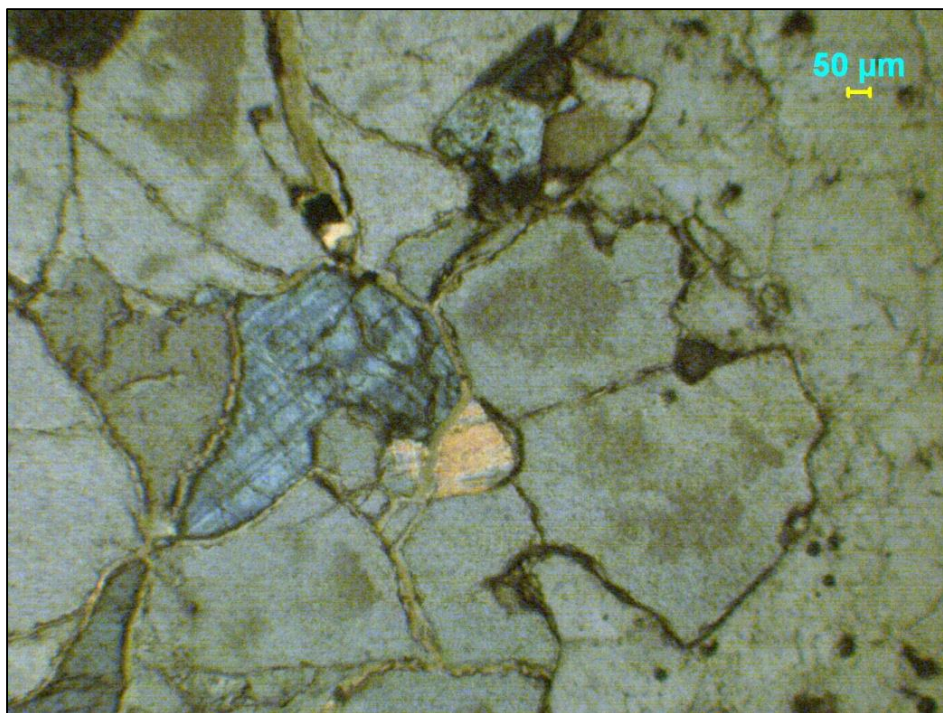


Figure 4.6 Elongated Apatite Grains, Bakreshwar river Gneiss under CPL

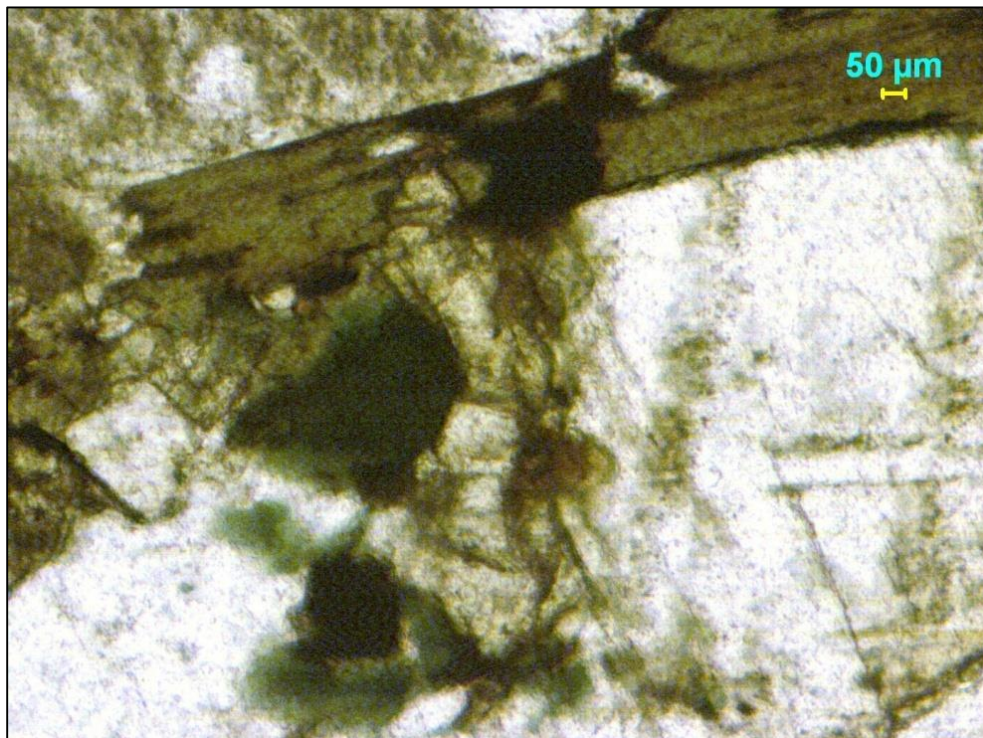


Figure 4.7 Sphene with biotite, Dubrajpur Granodiorite

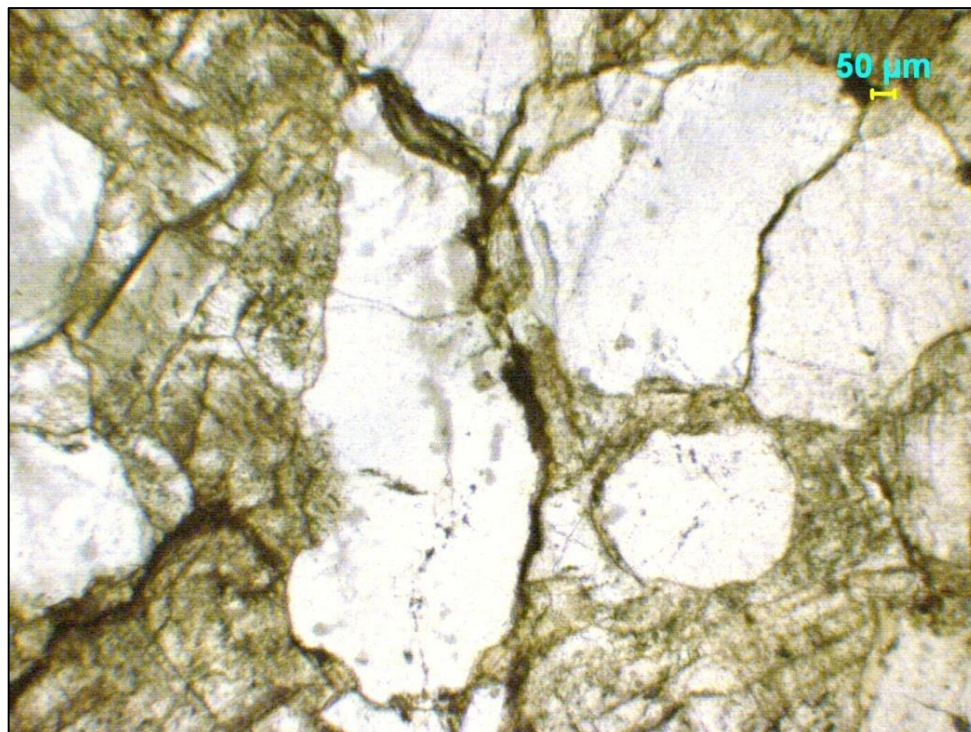


Figure 4.8 Apatite, K-feldspar and quartz assemblage observed in Jhaptala granite gneiss (PPL)

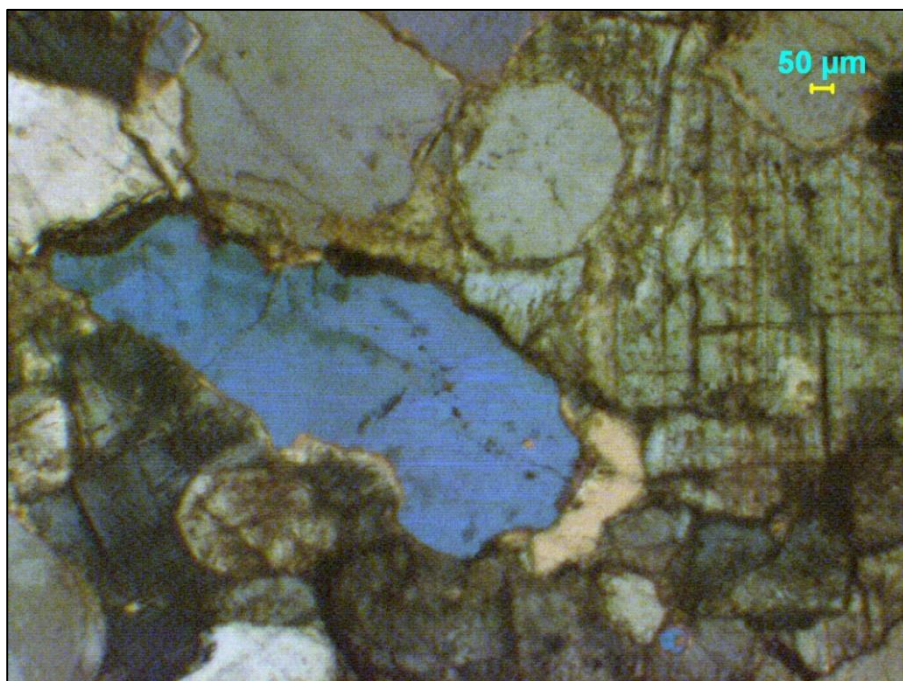


Figure 4.9 Jhapartala granite-gneiss under CPL

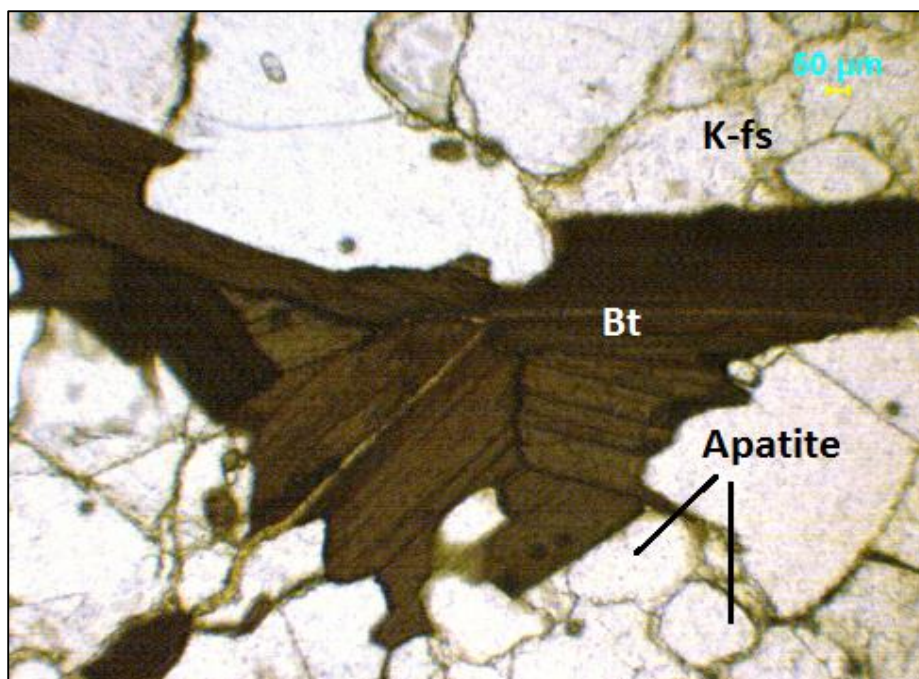


Figure 4.10 Apatite, Biotite and K-feldspar assemblage in Sukna pegmatite under PPL

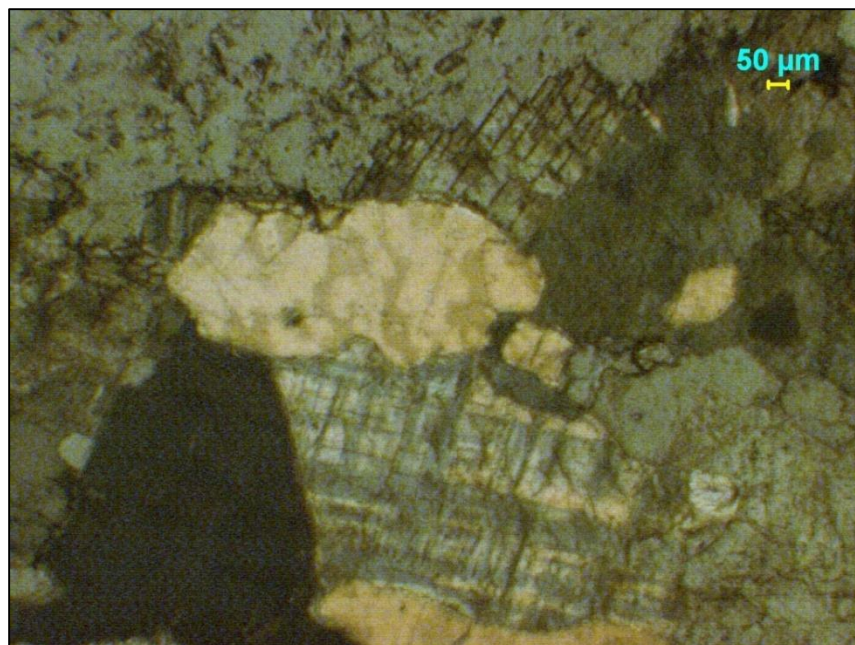


Figure 4.11 Apatite and K-feldspar in Sukna pegmatite under CPL



4.3.2 Geochemical analysis

The pH values recorded within the samples of the study area exhibit a noteworthy range that fluctuates from a minimum of 7.0 to a maximum of 7.7; however, it is crucial to acknowledge that under certain unique and specific circumstances, values falling below 7 or exceeding 8 can indeed be detected. Furthermore, a comprehensive analysis has revealed that an overwhelming majority, specifically 88%, of the electrical conductivity (EC) values are found to be below the threshold of 1000 mg/L, indicating a relatively low level of ionic content in the water samples. In addition, the total dissolved solids (TDS), which serve as a pivotal indicator of salinity levels, are observed to vary significantly within the range of 270 to 714 mg/L. Conversely, it is noteworthy that the bicarbonate content is impressively high, ranging from 152 to 396 mg/l, suggesting an elevated presence of this particular anion in the water. Moreover, when examining the concentrations of essential cations, it is evident that the levels of calcium are consistently found to be considerably lower than those of sodium across the majority of the water samples analyzed, a trend that is particularly pronounced in samples that are contaminated with fluoride.

4.3.2.1 Gibbs Diagram

In order to construct the Gibbs diagram, data acquired from PHED were segregated according to the fluoride content in an ascending order of concentration. For F^- content greater than 1.5 mg/L, that is for fluoride concentrations above the permissible limit, the data were represented by points in red colour in the diagram. In contrast, $F^- < 1.5$ mg/L, green colour was used to depict the points.

From an examination of the diagram presented (**Figure 4.12**), it becomes abundantly evident that the principal geochemical influence governing the chemistry of groundwater is predominantly attributed to the intricate interaction between rocks and water, notwithstanding the fact that evaporation contributes only a relatively minor role in this complex dynamic. It was observed that in instances where the concentration of fluoride (F^-) reaches levels of approximately 1.5 mg/L, nearly all of the analyzed samples exhibit the interaction between rock and water as the primary determinant influencing the hydro-geochemical characteristics, with the exception of a few notable anomalies that deviate from this trend. Moreover, in the case of samples characterized by fluoride concentrations below 1.5 mg/L, it was found that the vast majority of these samples displayed a clear predominance of rock dominance or the interaction between rock and water as the principal geochemical controlling factor. Nevertheless, for a subset of the aforementioned samples, it is important to note that evaporation emerges as the prevailing geochemical control, thereby highlighting the fact that evaporation is also a major factor influencing groundwater chemistry.



4.3.2.2 Piper Trilinear Diagram

For a systematic endeavor of constructing the Piper trilinear diagram, the available data was categorized and sorted into three distinct groups based on the concentration levels of fluoride, specifically delineating those samples with fluoride (F^-) content measuring less than 1 mg/L, those falling within the range of 1 to 3 mg/L, and those exhibiting concentrations greater than 3 mg/L. The graphical representation known as the Piper diagram was subsequently formulated utilizing an open-source software application developed by the United States Geological Survey (USGS), which is known as GW chart.

A notable and consistent observation derived from the analysis of the diagram is that the groundwater samples subjected to examination predominantly exhibit characteristics indicative of the $Na-HCO_3$ type, wherein Sodium (Na^+) is identified as the principal cation, while the predominant anion is recognized as bicarbonate (HCO_3^-). This particular observation holds particularly true for the samples categorized under the fluoride concentration greater than 3 mg/L, wherein all of the analyzed samples distinctly demonstrate the aforementioned ionic configurations. In instances where the fluoride concentration ranges between 1 and 3 mg/L, the majority of the samples predominantly exhibit $Na-HCO_3$ type ionic chemistry. However, it is worth noting that a smaller subset of samples, particularly those residing within the lower fluoride concentration ranges, display a $Ca-HCO_3$ type chemical profile, characterized by the dominance of Calcium (Ca^{2+}) as the principal cation, even though bicarbonate remains the predominant anion. Despite the observation of Ca^{2+} dominance in a significant number of samples reflecting fluoride concentrations below 1 mg/L, it is noteworthy that in the majority of these samples, Sodium (Na^+) and Calcium (Ca^{2+}) are present in nearly equivalent proportions. Across the spectrum of fluoride contamination observed in the analyzed samples, bicarbonate (HCO_3^-) emerges as the most dominant anion, significantly surpassing others in terms of prevalence.

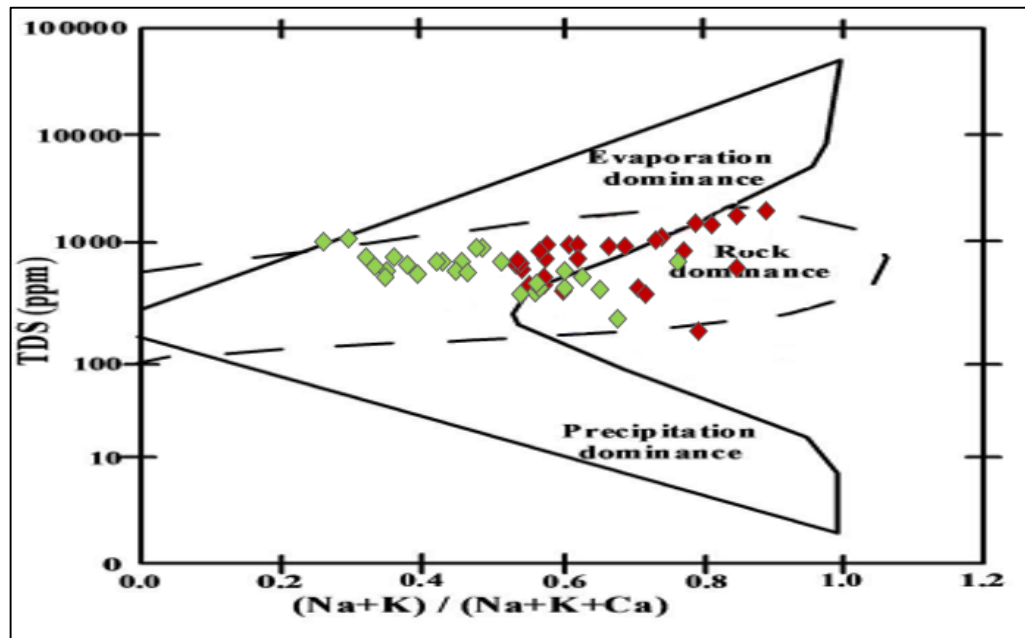


Figure 4.12 Gibbs diagram denoting major geochemical controls on groundwater chemistry. Green colour depict points with $F < 1.5$ mg/L, red depicting $F > 1.5$ mg/L

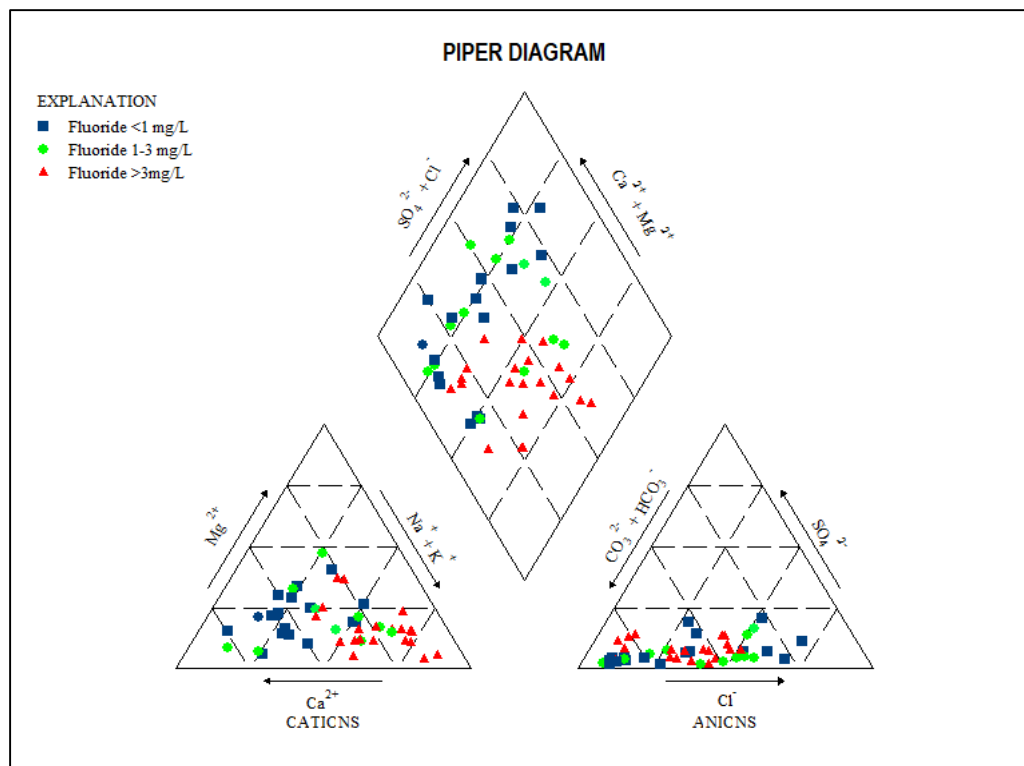


Figure 4.13 Piper trilinear diagram depicting ionic concentrations



4.3.3 Lineament Analysis

The comprehensive analysis of lineaments conducted within the context of the geographical features of the district reveals a notable prevalence of lineaments, particularly concentrated in the western and northwestern segments, as illustrated in Figure 4.14. The majority of these identified lineaments exhibit a predominant trend oriented from the Northwest to the Southeast; however, it is also crucial to note that several additional lineaments trending in the North-South and North-East to South-West orientations have been documented and analyzed. Furthermore, it has been observed that the lineaments trending in the North-South and Northwest-Southeast directions appear to converge in the vicinity of Dubrajpur, with a significant proximity to the renowned Bakreshwar hot springs, which are an integral part of the Son-Narmada-Tapi (SONATA) geothermal province. Substantial clusters of these major lineaments have been identified in several key localities, including Nalhati, Rampurhat, Md Bazar, Rajnagar, Suri, and Dubrajpur, where the concentration of these geological features is particularly pronounced. Additionally, the systematic analysis conducted in this study has revealed an intricate network of lineaments that delineate the locations of numerous wells within the district that have been adversely affected by elevated fluoride concentrations. It is noteworthy that the major lineaments are predominantly situated in regions characterized by geological formations consisting of Granite and Granite Gneiss, while only a limited number of such lineaments have been observed in areas composed of Basaltic terrain. Lastly, it is imperative to highlight that there was an almost complete absence of major lineaments detected in the Eastern and Southeastern regions of the district, which are predominantly characterized by alluvial deposits and lack significant geological structure.

Lineament density maps are analytical representations that illustrate intricate spatial patterns, which are indicative of the varying concentrations of geological lineaments across different regions. The map previously mentioned distinctly illustrates that there are clear groupings of dense lineaments, notably observable in the geological blocks denoted by Khoyrasole, Dubrajpur, Suri I, Rajnagar, Md Bazar, Nalhati I, as well as in certain portions of Rampurhat I, as represented in the visual document labeled Figure 4.15. It is of particular significance to note that an elevated lineament density is prominently recorded in the vicinity of the Bakreshwar hot springs, thereby substantiating the assertion that this particular area serves as a critical junction for lineaments exhibiting a variety of geological trends and orientations. In a broader context, it has been observed that higher density values are generally associated with the western blocks, which concurrently exhibit elevated fluoride concentrations in the groundwater, in stark contrast to the comparatively lower values recorded in the eastern blocks of the study area. Therefore, it can be inferred that the presence and arrangement of lineaments are instrumental in facilitating the mobilization and transport of groundwater that is contaminated with fluoride.

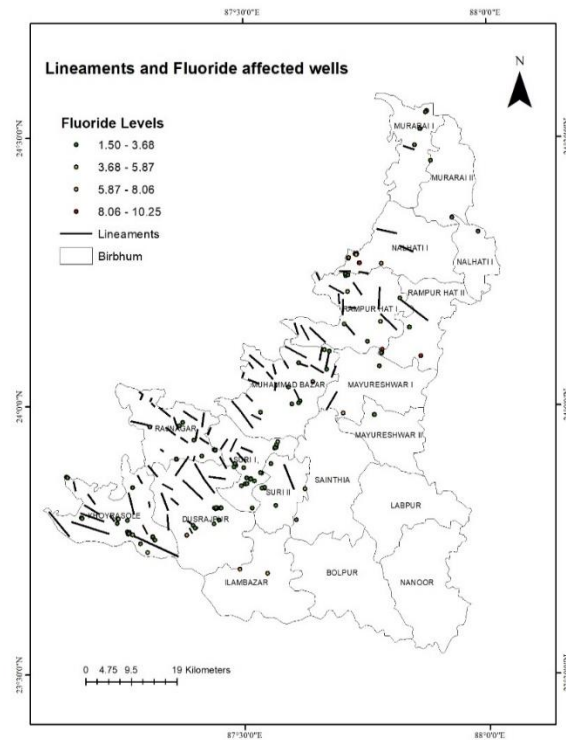


Figure 4.14 Spatial disposition map of lineaments along with fluoride affected wells

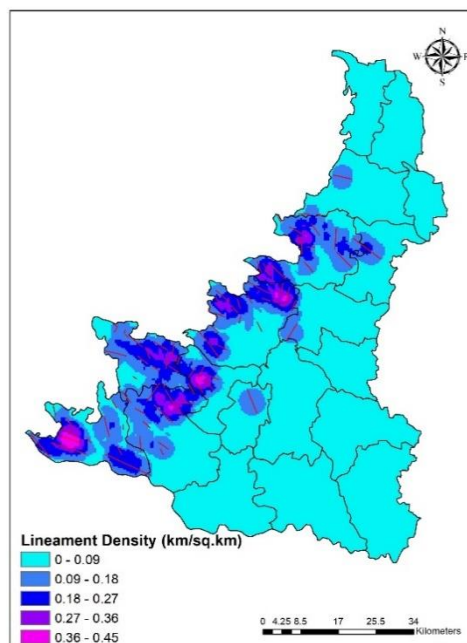


Figure 4.15 Lineament Density Map



4.3.4 Statistical Analysis

In the matrices presented in Tables 4.3 through 4.6, one can observe a comprehensive depiction of the correlations established between fluoride and various anions and cations, which are illustrated alongside their corresponding Pearson Correlation Coefficients, thereby facilitating a deeper understanding of the level of statistical significance inherent in these relationships.

It has been noted that for fluoride concentrations that are less than 1 mg/L, Fluoride (F⁻) exhibits a noteworthy positive correlation with Bicarbonate (HCO₃⁻), which is clearly delineated in **Table 4.3**. The correlation coefficient in this instance is calculated to be 0.368, which is deemed to be statistically significant at the 1% confidence level.

For fluoride concentrations that range between 1 and 3 mg/L, it has been determined that Fluoride (F⁻) demonstrates a positive correlation with Sulphate (SO₄²⁻), a finding that is visually represented in **Table 4.4**. The correlation coefficient in this context is noted to be 0.512, which is significant at the 1% confidence level. Moreover, a negative correlation has been identified with respect to Calcium (Ca²⁺) and Chloride (Cl⁻), with correlation coefficients of -0.363, which is significant at the 5% confidence level for Ca²⁺, and -0.441 for Cl⁻, which holds significance at the 1% confidence level, respectively.

In instances where fluoride concentration levels exceed 3.0 mg/L, it has been observed that no statistically significant correlation could be discerned between fluoride and the other variables under investigation (**Table 4.5**).

A comprehensive analysis (**Table 4.6**) encompassing the entire dataset reveals that Fluoride exhibits a positive correlation with both pH and Sodium (Na⁺). Specifically, for pH, the correlation coefficient has been observed to be 0.272, which is significant at the 1% confidence level, while for Sodium (Na⁺), the correlation coefficient is recorded at 0.536, which is also significant at the 1% confidence level, thereby highlighting the importance of these associations in the context of 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 Sig. (2-tailed) N	1 135										
DEPTH	Pearson Correlation Sig. (2-tailed) N	0.079047576 0.464122161 88	1 88									
pH	Pearson Correlation Sig. (2-tailed) N	0.091803379 0.289609729 135	0.091935 0.394268 88	1 135								
Ca	Pearson Correlation Sig. (2-tailed) N	0.088489278 0.307446143 135	-0.077972 0.470241 88	-0.063478 0.46452 135	1 135							
Mg	Pearson Correlation Sig. (2-tailed) N	0.097717056 0.259525829 135	0.021732 0.840718 88	-0.019552 0.821918 135	.701** 2.95383E-21 135	1 135						
SO4	Pearson Correlation Sig. (2-tailed) N	-0.023050271 0.827353927 92	-0.118867 0.278576 85	-0.155037 0.140033 92	.853** 3.44026E-27 92	.594** 4.285E-10 92	1 135					
NO3	Pearson Correlation Sig. (2-tailed) N	-0.097125246 0.262436296 135	0.088973 0.420391 88	-0.008589 0.921238 135	.579** 1.89479E-13 135	.470** 8.983E-09 135	.633** 1.2504E-11 92	1 135				
Na	Pearson Correlation Sig. (2-tailed) N	0.133336612 0.123142198 135	-0.089063 0.409267 88	-0.043759 0.614296 135	.741** 9.08131E-25 135	.555** 2.76E-12 135	.822** 1.05884E-23 92	.490** 1.61841E-09 135	1 135			
K	Pearson Correlation Sig. (2-tailed) N	-0.038926001 0.657664425 132	-0.068451 0.526282 88	0.065058 0.45881 132	0.060690429 0.489386097 132	0.0704313 0.4222668 132	0.140348206 0.182078683 92	0.032648973 0.710161265 132	.207** 0.017378051 132	1 132		
EC	Pearson Correlation Sig. (2-tailed) N	0.076664762 0.376813524 135	-0.143873 0.181118 88	-0.027078 0.755227 135	.945** 1.51544E-66 135	.705** 1.368E-21 135	.902** 1.59488E-34 92	.586** 8.1688E-14 135	.841** 2.90762E-37 135	.178* 0.041687 132	1 135	
HCO3	Pearson Correlation Sig. (2-tailed) N	.368** 1.18237E-05 134	-.239* 0.024674 88	0.15807 0.068132 134	.558** 2.40799E-12 134	.495** 1.201E-09 134	.450** 6.76453E-06 92	0.03943383 0.650995996 134	.574** 4.02814E-13 134	0.15624 0.074738 131	.623** 9.01401E-16 134	1 134
Cl	Pearson Correlation Sig. (2-tailed) N	-0.018890634 0.829127875 133	-0.100237 0.358477 86	-0.104408 0.231696 133	.913** 7.19293E-53 133	.649** 3.069E-17 133	.888** 3.4583E-32 92	.621** 1.50504E-15 133	.764** 1.05959E-26 133	0.129597 2.85481E-71 130	.955** 2.19019E-06 133	.399** 132 133



Table 4.4 Correlation matrix (Pearson correlation) when the value of Fluoride is between 1.0 mg/L and 3.0 mg/L

F:1-3 mg/L													
	FLUORIDE	DEPTH	pH	Ca	Mg	SO4	NO3	Na	K	EC	HCO3	Cl	
FLUORIDE	Pearson Correlation Sig. (2-tailed) N	1 35											
DEPTH	Pearson Correlation Sig. (2-tailed) N	-0.138939212 0.559091383 20	1 20										
pH	Pearson Correlation Sig. (2-tailed) N	-0.052757519 0.763420544 35	.462* 0.040368 20	1 35									
Ca	Pearson Correlation Sig. (2-tailed) N	-.363* 0.03221287 35	0.368843 0.109526 20	0.026883 0.879066 35	1 35								
Mg	Pearson Correlation Sig. (2-tailed) N	-0.224950907 0.193867937 35	0.333387 0.150881 20	0.006568 0.970132 35	.629** 5.21707E-05 35	1 35							
SO4	Pearson Correlation Sig. (2-tailed) N	.512** 0.008912894 25	0.154791 0.514647 20	0.001116 0.995777 25	0.179256418 0.391238592 25	.417* 0.0380035 25	1 25						
NO3	Pearson Correlation Sig. (2-tailed) N	-0.313941933 0.0662694 35	0.133713 0.574108 20	0.135057 0.439201 35	.348* 0.040664057 35	0.2892972 0.0918713 25	-0.057239538 0.785800344 35	1 35					
Na	Pearson Correlation Sig. (2-tailed) N	0.16676904 0.338307065 35	0.287654 0.218775 20	0.268288 0.119163 35	.506** 0.001915315 35	.406* 0.0154331 35	.424* 0.034532322 25	0.302464919 0.077387622 35	1 35				
K	Pearson Correlation Sig. (2-tailed) N	0.252857486 0.14277539 35	-.728** 0.000276 20	-0.161084 0.35526 35	-0.184576281 0.288478902 35	-0.157132 0.3673427 35	-0.019180939 0.927490364 25	-0.123005692 0.481455621 35	0.066596983 0.703866171 35	1 35			
EC	Pearson Correlation Sig. (2-tailed) N	-0.223871315 0.196072535 35	0.356229 0.123169 20	0.156171 0.370317 35	.907** 6.11358E-14 35	.699** 2.971E-06 35	0.3432483 0.092985386 25	.361* 0.033339548 35	.752** 1.94278E-07 35	-0.105663 0.5457 35	1 35		
HCO3	Pearson Correlation Sig. (2-tailed) N	-0.012208562 0.944507078 35	.461* 0.040592 20	0.138811 0.426465 35	.769** 6.59056E-08 35	.688** 4.928E-06 35	0.299004932 0.146517081 25	0.115391299 0.509201186 35	.633** 4.56568E-05 35	-0.1875 0.280775 35	.835** 4.53769E-10 35	1 35	
Cl	Pearson Correlation Sig. (2-tailed) N	-.441** 0.008026839 35	0.255276 0.277371 20	0.152247 0.382609 35	.877** 5.11442E-12 35	.558** 0.0004985 35	0.040635632 0.847072182 25	.425* 0.010876653 35	.644** 2.99368E-05 35	-0.06384 0.715604 35	.922** 3.52417E-15 35	.619** 7.42669E-05 35	1 35



Table 4.5 Correlation matrix (Pearson correlation) when the value of Fluoride is > 3.0 mg/L

F: >3mg/L													
		FLUORIDE	DEPTH	pH	Ca	Mg	SO4	NO3	Na	K	EC	HCO3	Cl
FLUORIDE	Pearson Correlation Sig. (2-tailed) N	1 8											
DEPTH	Pearson Correlation Sig. (2-tailed) N	-0.924510412 0.248948393 3	1 3										
pH	Pearson Correlation Sig. (2-tailed) N	0.554039981 0.154183806 8	0.327327 0.787704 3	1 8									
Ca	Pearson Correlation Sig. (2-tailed) N	-0.600234308 0.115660131 8	0.6302 0.565946 3	-0.503899 0.202941 8	1 8								
Mg	Pearson Correlation Sig. (2-tailed) N	-0.636616645 0.089642182 8	0.868232 0.330513 3	-0.408246 0.315337 8	.782* 0.021777544 8	1 8							
SO4	Pearson Correlation Sig. (2-tailed) N	0.976127075 0.139384903 3	-0.985227 0.109563 3	-0.160672 0.897268 3	-0.75385679 0.45638246 3	-0.940374 0.2209498 3	1 3						
NO3	Pearson Correlation Sig. (2-tailed) N	0.441860381 0.320904511 7	-0.029259 0.981371 3	-0.197966 0.67047 7	-0.097866975 0.834650379 7	0.0661309 0.887978 3	0.200006993 0.871807023 7	1 7					
Na	Pearson Correlation Sig. (2-tailed) N	0.380254468 0.400099957 7	-0.940553 0.220616 3	-0.526931 0.224284 7	0.307650058 0.502078728 7	-0.14481 0.7570608 3	0.98482382 0.111052191 7	-0.002939303 0.995010106 7	1 7				
K	Pearson Correlation Sig. (2-tailed) N	0.501993651 0.250976066 7	0.880155 0.314877 3	0.702765 0.078217 7	-0.27943792 0.543913895 7	-0.027946 0.9525757 3	-0.785860774 0.42444045 7	-0.131149302 0.779263851 7	0.012279633 0.979161808 7	1 7			
EC	Pearson Correlation Sig. (2-tailed) N	0.077861757 0.868218086 7	-0.964361 0.170474 3	-0.469919 0.287323 7	.762* 0.046650527 7	0.393574 0.3823709 3	0.995426303 0.060910827 7	0.069545714 0.882220837 7	.803* 0.029695743 7	0.018794 0.9681 7	1 7		
HCO3	Pearson Correlation Sig. (2-tailed) N	-0.298481915 0.51554858 7	0.595129 0.594202 3	-0.608065 0.147447 7	.921** 0.003253051 7	0.6509079 0.1133312 3	-0.723961495 0.484638612 7	0.007549843 0.987183354 7	0.607106889 0.148261797 7	-0.207766 0.654848 7	.913** 0.004098573 7	1 7	
Cl	Pearson Correlation Sig. (2-tailed) N	0.172379676 0.7116876 7	-0.939454 0.222665 3	-0.387917 0.389861 7	0.679560575 0.093085999 7	0.3126878 0.4947304 3	0.984259895 0.113101987 7	0.0181411 0.96920778 7	.843* 0.017238751 7	0.140796 0.76334 7	.988** 2.71339E-05 7	.856* 0.013954911 7	1 7



Table 4.6 Correlation matrix (Pearson correlation) including all the values of Fluoride

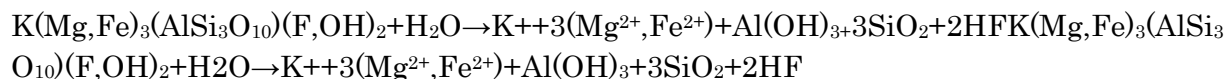
	FLUORIDE	DEPTH	pH	Ca	Mg	SO4	NO3	Na	K	EC	HCO3	Cl	
FLUORIDE	Pearson Correlation Sig. (2-tailed) N	1 178											
DEPTH	Pearson Correlation Sig. (2-tailed) N	0.020438684 0.832927809 109	1 109										
pH	Pearson Correlation Sig. (2-tailed) N	.272** 0.00024104 178	0.084208 0.383992 109	1 178									
Ca	Pearson Correlation Sig. (2-tailed) N	-.151* 0.044046765 178	-0.06313 0.514304 109	-0.094041 0.211816 178	1 178								
Mg	Pearson Correlation Sig. (2-tailed) N	-0.119122796 0.113252031 178	0.067208 0.487453 109	-0.052832 0.483681 178	.678** 2.52905E-25 178	1 178							
SO4	Pearson Correlation Sig. (2-tailed) N	0.118418349 0.197687518 120	-0.078939 0.4212 106	-0.119719 0.192775 120	.641** 3.09637E-15 120	.523** 9.283E-10 120	1 120						
NO3	Pearson Correlation Sig. (2-tailed) N	-0.124566591 0.098544888 177	0.076489 0.429225 109	-0.00934 0.901804 177	.536** 1.4527E-14 177	.414** 9.843E-09 177	.444** 3.82867E-07 120	1 177					
Na	Pearson Correlation Sig. (2-tailed) N	.536** 1.42161E-14 177	-0.038821 0.688578 109	0.063302 0.402567 177	.519** 1.33126E-13 177	.371** 3.832E-07 177	.677** 2.06033E-17 120	.309** 2.83555E-05 177	1 177				
K	Pearson Correlation Sig. (2-tailed) N	-0.014229329 0.85216693 174	-0.067289 0.486923 109	0.044633 0.558688 174	0.035695389 0.640063667 174	0.040126 0.599099 174	0.103836167 0.259059742 120	0.026114329 0.732315423 174	0.136564492 0.072358947 174	1 174			
EC	Pearson Correlation Sig. (2-tailed) N	0.091336711 0.22663393 177	-0.107435 0.266162 109	0.001505 0.984134 177	.915** 5.80375E-71 177	.673** 1.109E-24 177	.730** 2.86001E-21 120	.530** 3.25157E-14 177	.741** 4.87466E-32 174	0.145095 0.0561 174	1 177		
HCO3	Pearson Correlation Sig. (2-tailed) N	0.143970882 0.056608275 176	-.199* 0.037662 109	0.140876 0.062192 176	.593** 4.07056E-18 176	.526** 6.649E-14 176	.393** 9.02734E-06 120	0.030138311 0.691315042 176	.565** 3.33409E-16 176	0.10754 0.159043 173	.673** 1.47282E-24 176	1 176	
Cl	Pearson Correlation Sig. (2-tailed) N	0.028523788 0.707878861 175	-0.064966 0.506033 107	-0.066079 0.384941 175	.889** 1.50811E-60 175	.601** 1.566E-18 175	.649** 1.08773E-15 120	.579** 4.75989E-17 175	.653** 1.22347E-22 175	0.109765 0.151746 172	.950** 2.27968E-89 175	.451** 4.17018E-10 174	1 175

4.4 Discussions

Microscopic examination and analysis of various rock samples reveal an assemblage comprising several mineral constituents, including Quartz, Microcline, Biotite, Apatite, sphene, and a minor presence of Chlorite, wherein Biotite and Apatite emerge as significant contributors of Fluorine under alkaline conditions. It is noteworthy that, in the context of this particular type of rock formation, Biotite can contain Fluorine concentrations that reach as high as 0.91%, while Hornblende exhibits a relatively lower Fluorine concentration of approximately 0.17% while Fluorapatite showcases remarkable Fluorine concentrations that can ascend to a maximum of 3.72%. In terms of their immediate spatial association, it is observed that Apatite grains display a notable close relationship with Biotite in certain locations, as mentioned earlier, as well as with Chlorite, indicating a potential geochemical interaction among these minerals. The intimate association of hydrous phases with apatite and myrmekitic textures observed at the grain boundaries of feldspar megacrysts can be



attributed to the influence of late-stage fluid activity that is inherently linked to the processes of crystallization and the subsequent intrusions of pegmatitic materials. This fluid activity, which occurs during the later stages of geological formation, plays a critical role in facilitating the distribution and concentration of Fluorine within these mineral assemblages (*Demartis et al., 2014*). Hornblende and Biotite exhibit a markedly higher vulnerability to the processes of chemical degradation and leaching facilitated by groundwater compared to the more resilient mineral Fluorite. In hydrothermal systems (100–400°C), F^- partitions into fluids due to temperature-dependent mineral-fluid equilibria. For biotite:



HF dissociates into $H^+ + F^-$, contributing to fluoride in the system (*Zhu & Sverjensky, 1991*).

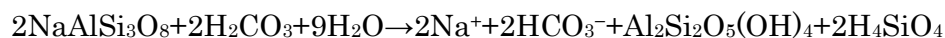
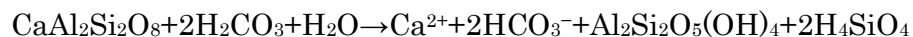
Given that the geographical region under study is characterized by significant rates of evapotranspiration and a humid subtropical climate, which is punctuated by extended periods of dryness, one can reasonably anticipate a pronounced degree of weathering that would consequently lead to a substantial influx of various ions into the circulating water. The observed lack of variability in the chemical composition of the water, pre and post monsoon indicator that these aquifers are not undergoing regular flushing with fresh water, which is a critical process for maintaining water quality. This particular hydrological situation has resulted in an extended residence time of water within the aquifers that are associated with fluoride minerals, thereby facilitating an increase in the ionic concentration of Fluoride within the groundwater system.

The observed pH of the groundwater varies from 7.0 to 7.7, denoting a predominantly alkaline condition. This favours solubility of Fluoride bearing minerals from rocks under elevated temperatures and facilitates the dissolution of fluoride from fluorite, biotite, and silicate clays. The breakdown of these minerals liberate fluoride ions into the aqueous environment, a process amplified by elevated pH levels (*Younas et al., 2019; Ali et al., 2023*). From the piper diagram (**Fig 4.13**), it is evident that the sodium (Na^+) and bicarbonate (HCO_3^-) are the dominant ions in the groundwater of Birbhum. It has been observed that the groundwater showing above the statutory levels of fluoride are mostly of $Na-HCO_3$ types.

Higher bi-carbonate (HCO_3^-) content (152-396 mg/L) suggests possible intense weathering of the granitic country rock, as the breakdown of these minerals liberates fluoride ions into the aquatic environment, a process that is amplified by elevated pH levels (*Subba Rao et al., 2016; Msengi et al., 2024*). Plagioclase feldspar, a major constituent of granite, undergoes chemical weathering in the presence of water and carbon dioxide (CO_2), releasing dissolved ions such as calcium (Ca^{2+}), sodium (Na^+), and bicarbonate (HCO_3^-). The breakdown of plagioclase is driven by hydrolysis, where acidic water (carbonic acid, H_2CO_3) reacts with the mineral structure. Anorthite ($CaAl_2Si_2O_8$) reacts with carbonic acid (H_2CO_3) to form kaolinite



(a clay mineral), calcium ions, and bicarbonate, whereas albite ($\text{NaAlSi}_3\text{O}_8$) weathers to form sodium ions and bicarbonate with the formation of kaolinite clay.



The elevated levels of sodium (Na^+) found in groundwater, in contrast to calcium (Ca^{2+}), suggest a heightened solubility of minerals that contain fluoride. Numerous investigations have shown a notable positive correlation between sodium (Na^+) and fluoride (F^-) concentrations in groundwater. This phenomenon is frequently linked to the breakdown of sodium-rich minerals, which can liberate fluoride ions into the aquatic environment. The weathering of sodium-rich silicate minerals plays a crucial role in facilitating the release of fluoride into groundwater. Additionally, the ion exchange processes, wherein sodium ions take the place of calcium ions, further boost the solubility of fluoride (*Sahoo et al., 2022; Machado et al., 2024*). The degradation of these minerals contributes to the introduction of fluoride ions into the water, a process that is further amplified by elevated pH levels.

The geothermal hot spring located in the Bakreshwar-Tantoloi region exhibits extraordinarily elevated concentrations of fluoride ions, reaching levels as high as 16 mg/L, while simultaneously displaying a high to very high pH range that varies between 8 and 9. The deep-seated thermal waters present in this area significantly enhance the leaching process of fluoride from the surrounding granitic country rock, thereby contributing to the elevated fluoride concentrations observed. Furthermore, the estimated geothermal temperature within this specific province approaches an impressive 200°C at a depth of approximately 3.0 kilometers, which plays a pivotal role in facilitating the dissolution of fluoride from the source minerals contained within the confined aquifers located at greater depths. Hence, it may be inferred with reasonable certainty that the fluoride present in the groundwater of Birbhum is primarily sourced from the geothermal phenomena associated with this particular geothermal province. It is also noteworthy to emphasize that at fluoride concentrations of approximately 3.0 mg/L, there appears to be no significant correlation between the fluoride levels and the concentrations of other ionic species, which strongly suggests a complex interaction involving the differential mixing of ascending deep-seated high-temperature water characterized by elevated sodium and pH levels with descending meteoric water that initially possesses lower pH and sodium concentrations.

In the western regions of the Birbhum district, numerous geological lineaments exhibiting various trends have been identified and analyzed, particularly noting that these lineaments manifest a higher density within the blocks of Dubrajpur, Khoyrasole, Md Bazar, and Rampurhat I. These identified areas are notably distinguished by their significant fluoride contamination in the groundwater sources, indicating a potential relationship between the geological features and the observed contamination. Moreover, there appears to be a notable convergence of several lineaments in the vicinity of the hot springs located at Bakreshwar, a phenomenon that is corroborated by the substantial lineament density surrounding these geothermal springs. It is well established in geological studies that deep-seated fault and



fracture networks serve as fundamental conduits for the transportation and movement of hydrothermal fluids through the subsurface. Consequently, it seems evident, upon initial examination, that the fluoride detected in the groundwater of Birbhum is likely to be derived from the thermal waters associated with the aforementioned hot springs, which subsequently migrate through the various aquifers distributed throughout the district via the dense fracture networks delineated by the identified lineaments.

It is posited that these fracture zones, which are of deep-seated geological origin and are intricately connected to the Bakreswar-Tantloi geothermal province, constitute the primary conduits for the subsurface flow of hot, alkaline groundwater that is characterized by high fluoride concentrations. The differential mixing process that occurs between the deep-seated geothermal waters and the percolating meteoric waters as they traverse through these fracture zones is believed to be the underlying mechanism responsible for the localized occurrence of elevated fluoride concentrations in the groundwater found within the constrained zones of Birbhum district.

Thus, the present comprehensive analysis has the potential to confirm with considerable certainty that within the majority of the affected blocks located in the Birbhum district, Chotanagpur Granite Gneiss, characterized by a significant presence fluoride rich mineral assemblage comprising Hornblende -Biotite -Apatite, serves as the predominant source contributing to the elevated levels of Fluoride found in the groundwater, particularly under conditions of alkalinity, coupled with higher concentrations of sodium, which facilitates the solubility of fluoride-bearing minerals, in conjunction with elevated temperatures that characterize the deep-seated thermal province encompassing Bakreswar and Rampurhat, alongside the prolonged residence time attributable to the confined aquifer conditions that prevail in this region.

Furthermore, the process of fluoride mobilization within the deeper aquifers is significantly enhanced by the migration of heated water originating from the Bakreswar-Rampurhat thermal province, which traverses through deep-seated fractures, thereby demonstrating the intricate interplay between geothermal activity and mineral dissolution. Additionally, the differential mixing of meteoric water with low fluoride concentrations contributes to the observed variability in fluoride concentrations across different locations, highlighting the complex hydrological dynamics at play in this geological setting.

4.5 Summary

In the present chapter, comprehensive and methodical investigations were carried out to ascertain the principal geogenic factors that exert control over the concentration and subsequent mobilization of fluoride within the groundwater system. Microscopic analyses were systematically performed on rock samples that were collected from various regions within the district to identify and elucidate the predominant mineralogical characteristics that are responsible for inducing the contamination of fluoride. Furthermore, thorough geochemical analyses were executed to not only comprehend the intricate chemical composition but also to discern the various geochemical parameters that contribute significantly to the



accumulation and persistence of fluoride in the groundwater. In addition, statistical analyses were conducted to facilitate a deeper understanding of the interrelationships between fluoride and other prevalent ionic species present in the groundwater. In order to effectively delineate the structural controls that influence the mobilization dynamics of fluoride within the groundwater, a detailed lineament analysis was undertaken. On the whole, this chapter converged on the multitude of geogenic factors that ultimately lead to the pervasive contamination of fluoride within the groundwater resources. In the next chapter, potential health hazards arising out of consumption of groundwater having fluoride above the statutory levels across different age groups, along with its spatio-temporal variations will be analyzed.



CHAPTER 5: Spatio - Temporal Variations of Fluoride Contamination and Estimation of Potential Health Hazards

5.1 Preface

Groundwater serves as the primary source of drinkable water for nearly 85% of India's citizens (*World Bank Report, 2012*). Fluoride is a vital trace mineral found within groundwater sources. While fluoride is crucial for bone mineralization and dental health (*Choi et al., 2012*), consuming water that contains fluoride levels surpassing the World Health Organization's recommended limit of 1.5 mg/L (*WHO 2017*) can lead to dental fluorosis, skeletal fluorosis, or even serious cases of fluorosis, and has the potential to adversely affect renal function (*Queste et al., 2001*). Fluoride is a ubiquitous element that neither adds colour, nor odour or taste to the water it contaminates. Hence, it becomes impossible to determine fluoride in groundwater without extensive laboratory testing. The occurrence of dental and skeletal fluorosis, stemming from heightened fluoride concentrations in groundwater, poses a considerable public health and economic hurdle for nations in the developing world (*Ali, 2016*). Approximately 200 million individuals globally, including 62 million from India—6 million of whom are children—experience fluorosis due to the consumption of water that is characterized by high fluoride concentrations (*Mukherjee and Singh, 2018; Nizam et al., 2022*). The presence of fluoride concentrations that exceed permissible limits constitutes one of the most critical concerns regarding the quality of natural groundwater. A considerable portion of India's arid and semiarid landscapes is adversely affected by this phenomenon. The Indian states that exhibit relatively elevated levels of fluoride contamination include Andhra Pradesh, Rajasthan, Gujarat, Tamil Nadu, Telangana, and West Bengal (*Mukherjee and Singh, 2018*). In the region of West Bengal, the western districts of Bankura, Purulia, and Birbhum, along with specific regions of the Raniganj coalfield, have shown fluoride concentrations that surpass statutory limit of 1.5 mg/l. In the year 1996, the village of Nasipur, located within the Nalhati block of Birbhum, recorded the first occurrence of fluorosis in West Bengal (*Patra et al., 2010*). This chronic non-communicable disease affects more than 50,000 individuals living in 78 villages and hamlets spread across 9 administrative blocks within the 4545 km² Birbhum district, including Nalhati I, Khoyrasol, Suri I & II, Rajnagar, Mayureshwar I, Sainthia, Dubrajpur, and Rampurhat (*Mondal et al., 2014; Mukherjee and Singh, 2018; Das et al., 2022*). Therefore, health risks associated with consumption of groundwater with excess fluoride in the study area need to be enumerated to understand the extent of its impact on public health.

Climate significantly impacts fluoride pollution, affecting the natural mechanisms that introduce fluoride into subterranean water sources and the necessity for water supplies in the communities impacted (*Vithanage and Bhattacharya, 2015; Kurella, 2023*). In dry and semi-dry areas like Birbhum, the process of evapo-transpiration is crucial in amplifying



fluoride levels, as elevated evaporation rates contribute to heightened mineral content in water supplies, worsening the pollution dilemma and increasing health hazards for the surrounding communities (*Ullah et al., 2022*). In contrast, regions experiencing abundant rainfall can facilitate water infiltration that replenishes aquifers, which may dilute fluoride levels and potentially mitigate health hazards linked to exposure (*Mukherjee et al., 2019*). Grasping these processes is vital for crafting efficient water management approaches that tackle both the ecological and health hurdles encountered by at-risk communities, ensuring they have access to clean drinking water while alleviating the consequences of fluoride pollution.

The acceptable fluoride concentration, as stipulated by the World Health Organization, is 1.5 mg/l (*WHO, 2006*). Notably, the Indian Council of Medical Research (ICMR) has established the optimal and maximum permissible fluoride levels at 1.0 and 1.5 mg/l, respectively (*ICMR, 1975*). However, fluoride concentrations ranging from 0.6 to 1.2 mg/L in potable water are deemed advantageous for the development of skeletal and dental health (*BIS, 2003; USEPA, 2010; Brindha and Elango, 2011*). Consumption of fluoride-contaminated groundwater leads, mostly, to non-carcinogenic health risks. Along with dental and skeletal fluorosis, renal problems, including renal failure, have also been reported in individuals who have consumed fluoride contaminated water for an extended period of time (*Brindha and Elango, 2011; Dharmaratne, 2015*).

Dental fluorosis represents a significant public health concern stemming from the consumption of drinking water with fluoride concentrations exceeding 1.5 mg/L. Usually, the first signs of dental fluorosis are marked by the emergence of white, opaque spots on the enamel, which may later evolve into brown or black stains on the tooth surfaces (*Shaji et al., 2024*). Moreover, dental fluorosis can trigger significant emotional turmoil in affected communities as a result of the deterioration of their dental appearance. In India, dental fluorosis is widespread in 14 states and affects around 150,000 villages (*Pillai and Stanley, 2002*), with particularly high incidence rates in the states of Bihar, Gujarat, Madhya Pradesh, Rajasthan, and Uttar Pradesh. Increased fluoride concentrations in drinking water surpassing 4–8 mg/L are linked to the development of skeletal fluorosis. The key symptoms encompass elevated bone density, discomfort in the joints resembling arthritis, stiffness and inflexibility in the joints, spinal curvature, and overproduction of bone tissue. Those afflicted with skeletal fluorosis often display muscular weakness, tingling sensations in the limbs, changes in bone structure, and a rigid spine. Abnormal growth may occur in various anatomical regions, potentially resulting in paralysis and neurological complications (*Srivastava and Flora, 2020*). When the levels of fluoride in drinking water exceed 10 mg/L, it can lead to the crippling condition known as skeletal fluorosis (*Boyle and Chagnon, 1995*). This ailment is classified into three distinct stages based on its intensity: mild, moderate, and severe skeletal fluorosis (*Mishra et al., 2020*). Additionally, fluoride levels that go beyond 8 mg/L in drinking water can also lead to the development of osteosclerosis. Scarcely, the fluoride concentration in groundwater can reach alarmingly elevated levels (>10 mg/L), as



observed in the waters of Bakreshwar hot spring complex, potentially leading to debilitating fluorosis. Such exposure can adversely impact various organs, including the nervous, hepatic, and renal systems. Instances of crippling fluorosis have been documented in certain regions across Asian nations and Africa (*Rasool et al., 2018*). Neurological problems have been reported among school-aged children globally, rendering this one of the most contentious consequences associated with fluoride exposure. It has been found to diminish growth hormone synthesis and the cognitive abilities of children. Numerous studies have investigated these concerns such as (*Grandjean and Landrigan, 2006; Choi et al., 2012; Agalakova and Nadei, 2020; Skórka-Majewicz et al., 2020; Onipe et al., 2020; Shaji et al., 2024*).

Numerous researchers have explored the health hazards linked to drinking water that contains fluoride levels exceeding the acceptable threshold (*Eminke et al., 2018; Yin et al., 2020*). Estimation of non carcinogenic risk (NCR) of fluoride on human health is generally conducted with the determination of Hazard Quotient (HQ) of fluoride by calculating potential hazards in humans through oral and dermal routes, the methodology of which has been standardized by USEPA in 2011. Further, the Total Hazard Quotient (THQ) is determined by the combination of individual Hazard Quotients (HQ) through Oral and Dermal routes. THQ values greater than 1 indicate that consumption of the water is potentially dangerous. For values less than 1, water is fit for consumption. Additionally, the aforementioned estimation has been segregated according to age, i.e. adult and children population have been analyzed separately, for better assessment of the impact across demographics.

The sustainable development goals proposed by the United Nations advocate for the equitable availability and sustainable management of water resources and sanitation services for all individuals. In this context, it is of paramount importance to comprehend the spatio-temporal fluctuations in fluoride concentrations within groundwater sources which, in turn, control the extent of severity of associated health hazards (*Podgorski and Berg, 2022*). A comprehensive understanding of the underlying mechanisms can facilitate the development of long-term strategies and interventions aimed at mitigating this potential health risk within an already socio-economically disadvantaged demographic.

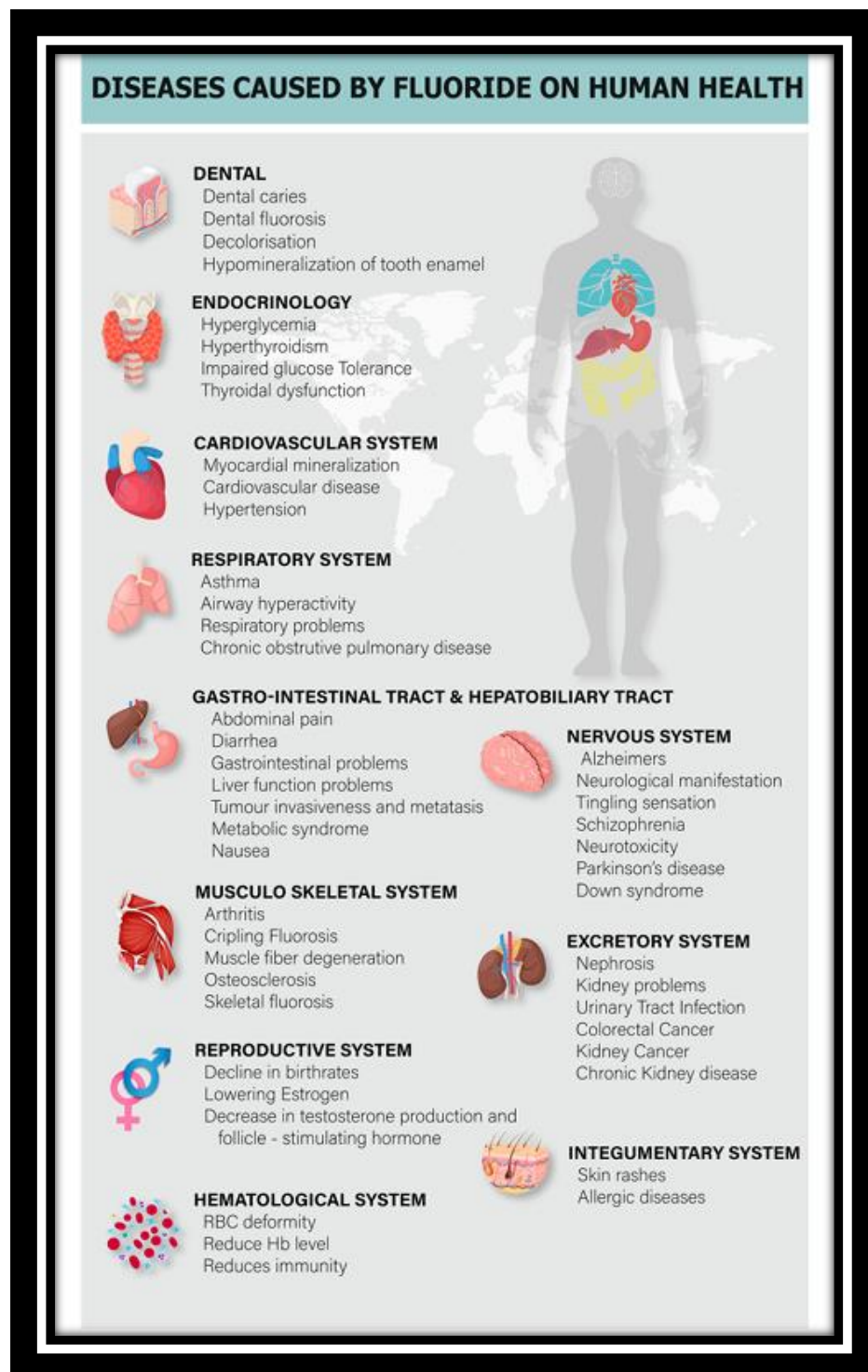


Figure 5.1: Depiction of different potential health risks associated with consumption of groundwater with excess fluoride (*Chakrabarti et al.,2016; Shaji et al.,2024*)



5.2 Methodology

5.2.1 General

In order to comprehend the spatio-temporal variations in fluoride contamination, secondary water quality data were obtained from the Public Health Engineering Department, Government of West Bengal, for the period of 2016 to 2019 (**Annexure A**). These data were further segregated into pre and post monsoon, depending on the date of collection. These were utilised to analyze trends in fluoride levels across the district of Birbhum using geo-spatial analysis tools. Rainfall data for the aforementioned period were collected from Climate Research Unit- Time Series (CRU-TS) and analyzed to assess the correlation between precipitation patterns and fluoride concentration levels using GIS tools. Changes in rainfall can significantly influence the mobilization of fluoride in groundwater sources. Health Risk Analysis were conducted with the data obtained from PHED using standardized techniques employed by *USEPA*. Spatial analysis of health risks for the aforementioned period, were conducted by creating GIS maps. Primary data were used to validate the said findings and ensure the accuracy of the spatial patterns thus identified. This comprehensive approach allowed for a detailed examination of how seasonal variations impact fluoride levels, providing critical insights into potential health risks associated with water quality in the region.

5.2.2 Spatio-temporal analysis

In order to ascertain the spatio-temporal variations, groundwater quality data, particularly that of fluoride concentration, of Birbhum, were obtained from PHED, for the period of 2016 to 2019. These were further segregated into pre and post monsoon, depending on the date of collection. For each year and season more than 200 groundwater data were sorted and utilized. Geo-spatial maps of the same were constructed using Inverse Distance Weightage (IDW) method. Inverse Distance Weighting (IDW) method is a standard geospatial interpolation technique used to predict attributes at un-sampled locations. This method constructs geo-spatial maps by assigning weights to sampled data points based on their distance from the predicted location. Closer points have greater influence, as their weights are derived from the inverse of their distances. This method is particularly useful in spatial sampling contexts, allowing for the estimation of values at unmeasured locations while considering the geographical nature of the data (*Liu et al.,2020; Li 2021; Moussa and Aboud, 2024*). Using spatial analysis tools, the spatial extent or areas of the regions having excess fluoride in groundwater were approximated. This method was applied for both the pre and post-monsoon data for the aforesaid time period in order to understand the absolute extent of fluoride contamination and its temporal variations, if any.

In a similar manner, rainfall data obtained from Climate Research Unit-Time Series(CRS-TU), for the years 2016 to 2019, were analysed to create rainfall maps using GIS platforms. The CRU-TS data, once converted to ASCII format, become compatible with GIS platforms.



Inverse Distance Weightage (IDW) method is employed, to create rainfall maps for the said period (*Quaye-Ballard et al.,2013; Harris et al.,2020*).

The maps so constructed were segregated into five separate classes, as per their assigned values, in order to better demonstrate the variations inherent in them.

5.2.3 Health Risk Assessment

Health Risk Assessment (HRA) was conducted for the district of Birbhum based on the data obtained from PHED, WB for the years of 2016 to 2019. It was further segregated into pre and post monsoon to analyse the seasonal variations.

Non-carcinogenic Health Risk Assessment (HRA) was conducted using the standardized methodology mandated by USEPA, 2011. The assessment entails the calculation of Estimated Daily Intake (EDI) incurred due to consumption of groundwater with F⁻ levels above the permissible limit through oral (EDI_{oral}) and dermal (EDI_{dermal}) routes (USEPA 2011; Ali et al., 2019; Nazaroff and Alvarez-Cohen, 2001). Individual Hazard Quotients (HQ) for oral and dermal routes are calculated primarily. Finally the Total Hazard Quotient (THQ), which is the sum of the individual HQs, i.e. HQ_{ORAL} and HQ_{DERMAL}, is obtained. THQ values are reflective of the entailed risk. THQ values less than or equal to 1 indicate that the exposed population is not at health risk whereas THQ values greater than 1 indicate that the population is at adverse health risk. It is to be noted that THQ value varies with the age group as different standardized values are utilized for adult and children populations.

The process and parameters are detailed here-under:

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

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

Calculation of Hazard Quotient (HQ) was conducted through the following equations (*Nazaroff and Alvarez-Cohen 2001; EPA 2004*)

$$HQ_{ORAL} = EDI_{ORAL} / RfD_{ORAL}$$

$$HQ_{DERMAL} = EDI_{DERMAL} / RfD_{DERMAL}$$

$$THQ = HQ_{DERMAL} + HQ_{ORAL}$$



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)	l/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 (RfD _{ORAL})	mg/kg/day	0.06
Dermal reference dose (RfD _{DERMAL})	mg/kg/day	0.06

The THQ values thus obtained were used to generate geo-spatial maps. These maps were created using IDW method in GIS platforms. They were further segregated into five different classes, according to the THQ values, in order to understand the spatio-temporal dispositions of health risks and to identify potential hotspot areas. Separate set of maps were created for adult and children population. Using spatial analysis tools, approximation of the spatial extent of vulnerable areas were made to quantify the entailed risks.

Furthermore, the HRA maps were validated with primary data collected in more than fifty locations across four blocks of Birbhum district, in the year 2019, which were similarly segregated in pre and post monsoon. These locations were plotted on the HRA maps in an attempt to validate the process.

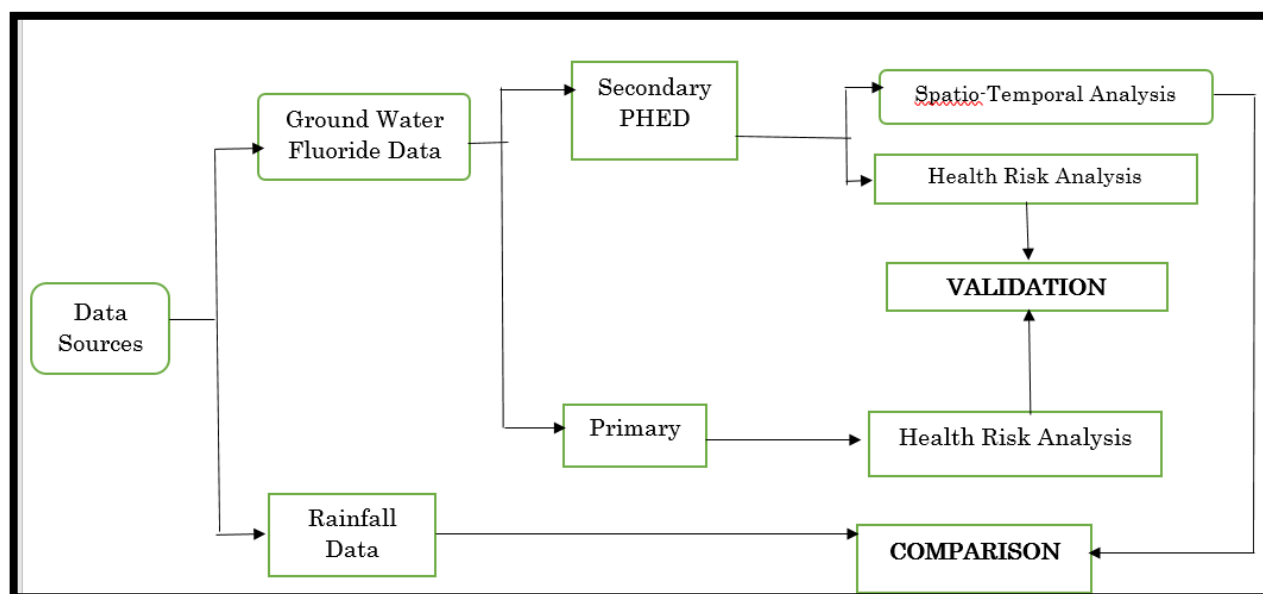


Fig 5.2: Methodology chart

5.3 Results

5.3.1 Spatio-temporal variations

From the comprehensive analysis of groundwater fluoride concentration maps, which were constructed over a period spanning from the year 2016 to the year 2019, it becomes abundantly clear that there has been a consistent documentation of elevated fluoride concentrations in the groundwater within the western and southwestern regions of the district under investigation. More precisely, the specific areas encompassed within the administrative blocks of Dubrajpur, Suri I, Suri II, Rajnagar, Khoyrasole, and Md Bazar reveal extensive geographical regions that are characterized by significantly high levels of fluoride present in the groundwater. Furthermore, it is important to highlight that certain specific regions located within the blocks of Nalhati I and Rampurhat I also exhibit extraordinarily high concentrations of fluoride that are noteworthy. In stark contrast, the blocks that are situated in the eastern and northeastern regions of the district, which include Bolpur, Labpur, Nanoor, Sainthia, and Mayureshwar I & II, demonstrate significantly lower



concentrations of fluoride, with average levels remaining below the World Health Organization's permissible threshold of 1 mg/L. Moreover, the geothermal spring waters found in the Bakreshwar – Tantoloi area, which is included in the Dubrajpur block and forms part of the Son-Narmada-Tapti (SONATA) geothermal province, show remarkably high fluoride concentrations that surpass the threshold of 14 mg/L. It is also of paramount significance to acknowledge that the spatial extent of areas having fluoride in groundwater

Table 5.2 : Spatial extent of areas with $F > 1.5 \text{ mg/L}$ (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

above statutory levels, that is $F > 1.5 \text{ mg/L}$, season vary notably with the monsoons. That is to say, higher spatial area is observed pre-monsoon and a notable reduction is noted post-monsoon. A mean decrease of 7.96 percentage points is observed.

Table 5.3: 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



Additionally, the rainfall maps that were developed for the same temporal framework exhibit a consistent trend of heightened precipitation predominantly in the southern regions, particularly within the southeastern zones of the district. Conversely, consistently lower levels of rainfall have been recorded from the northern and northwestern parts of the district. However, it is pertinent to note that the variations observed in absolute rainfall amounts between these two contrasting regions are not significantly pronounced, with a calculated mean difference of merely 6.87% in the respective values.

Table 5.4 Year-wise maximum and minimum rainfall

Year	Minimum Rainfall (mm)	Maximum Rainfall (mm)	Difference (%)
2016	1300.77	1367.42	5.12
2017	1442.37	1592.62	10.41
2018	995.35	1009.72	7.21
2019	1220.39	1278.66	4.77

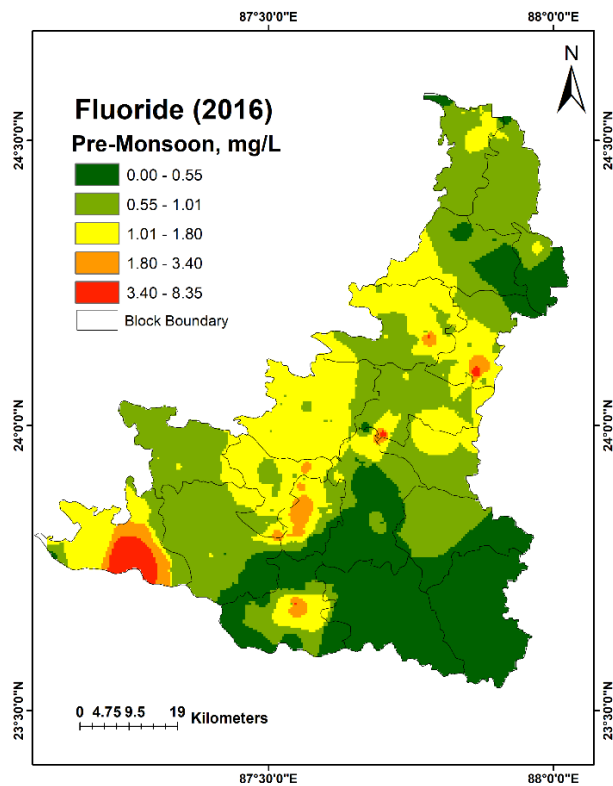


Fig 5.3: Spatial disposition of fluoride concentrations in groundwater, pre-monsoon 2016

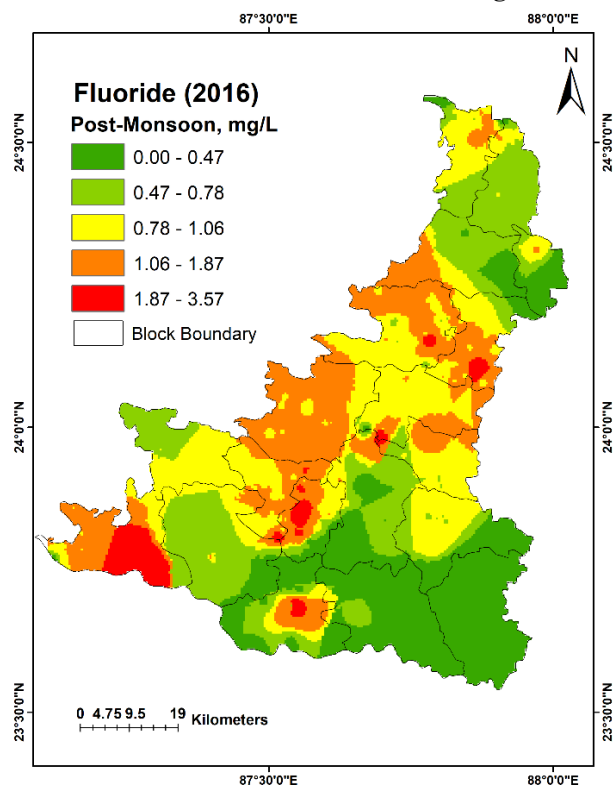


Fig 5.4: Spatial disposition of fluoride concentrations in groundwater, post-monsoon 2016

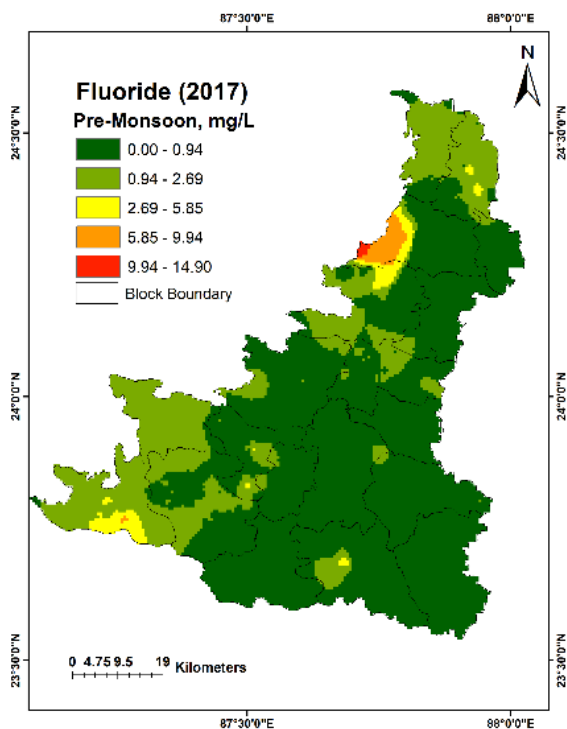


Fig 5.5: Spatial disposition of fluoride concentrations in groundwater, pre-monsoon 2017

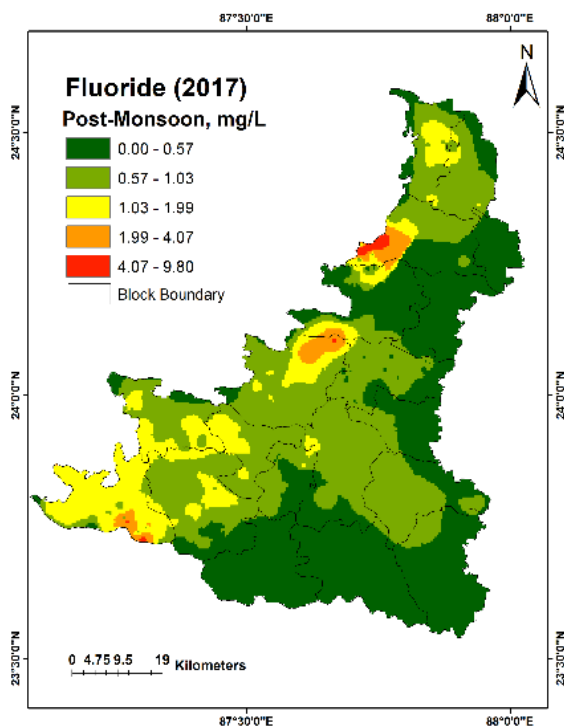


Fig 5.6: Spatial disposition of fluoride concentrations in groundwater, post-monsoon 2017

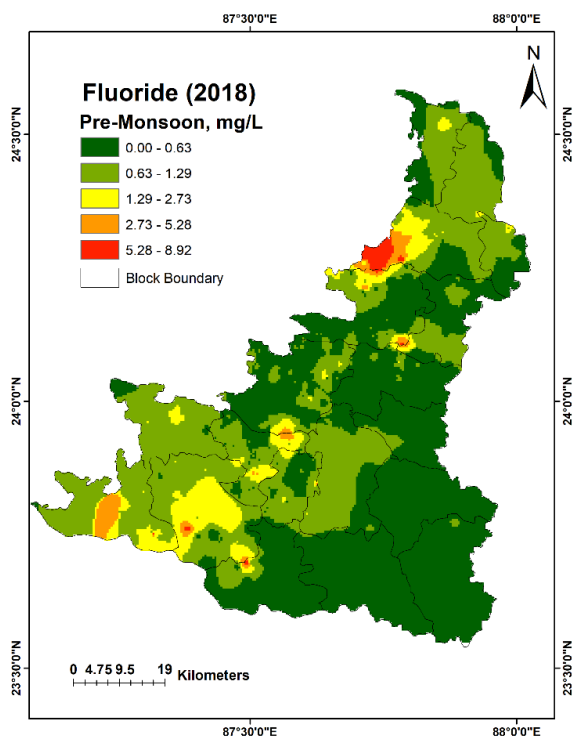


Fig 5.7: Spatial disposition of fluoride concentrations in groundwater, pre-monsoon 2018

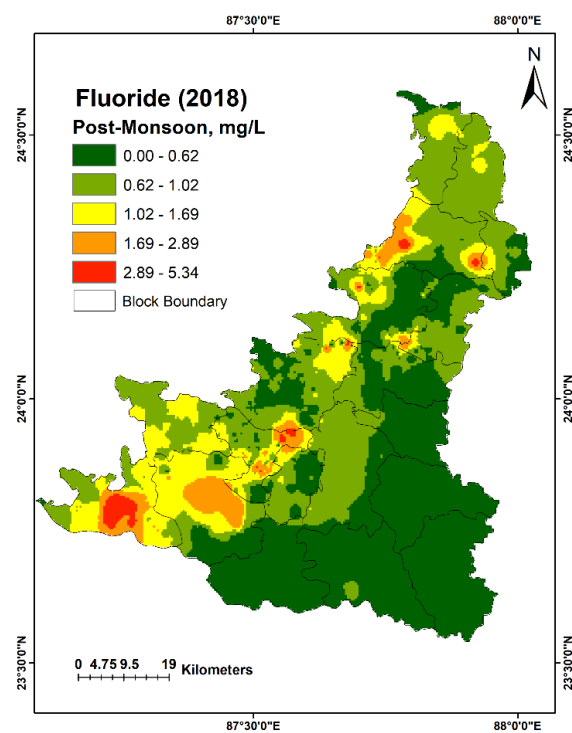


Fig 5.8: Spatial disposition of fluoride concentrations in groundwater, pre-monsoon 2018

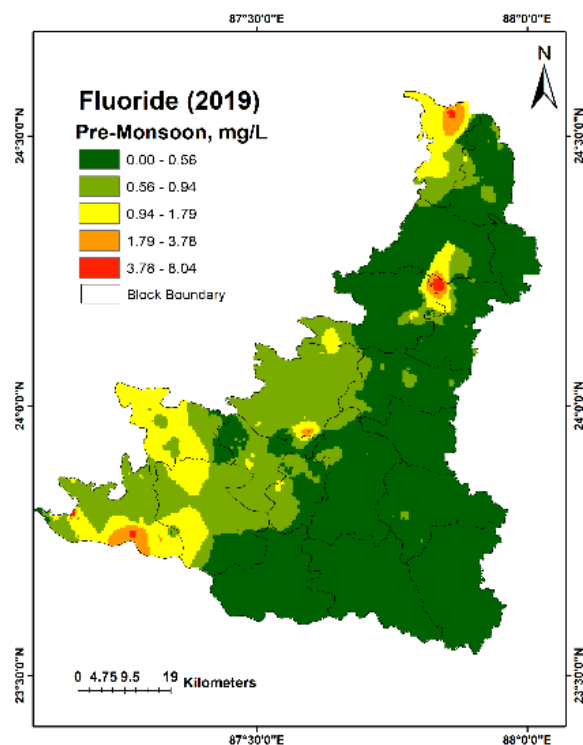


Fig 5.9: Spatial disposition of fluoride concentrations in groundwater, pre-monsoon 2018

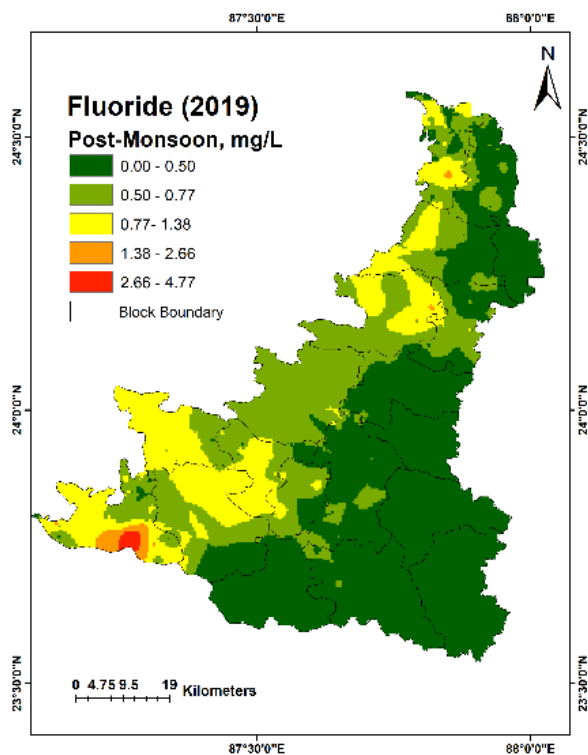


Fig 5.10: Spatial disposition of fluoride concentrations in groundwater, post-monsoon 2018

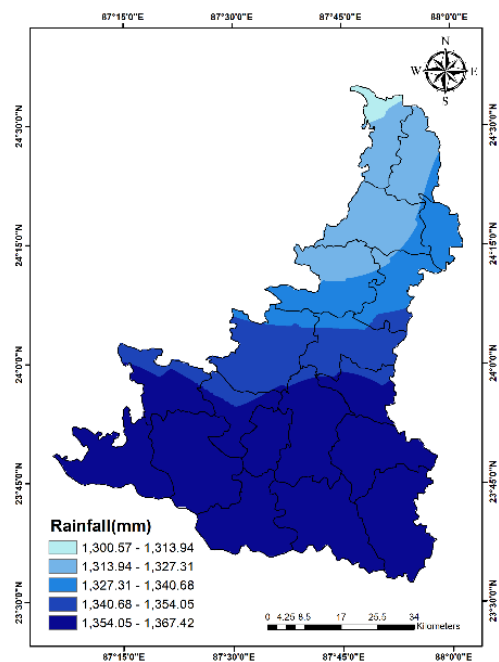


Fig. 5.11 Spatial distribution of rainfall, 2016

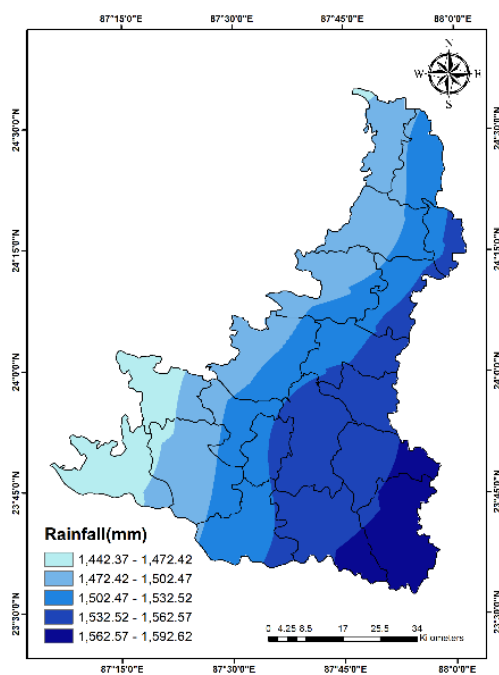


Fig. 5.12 Spatial distribution of rainfall, 2017

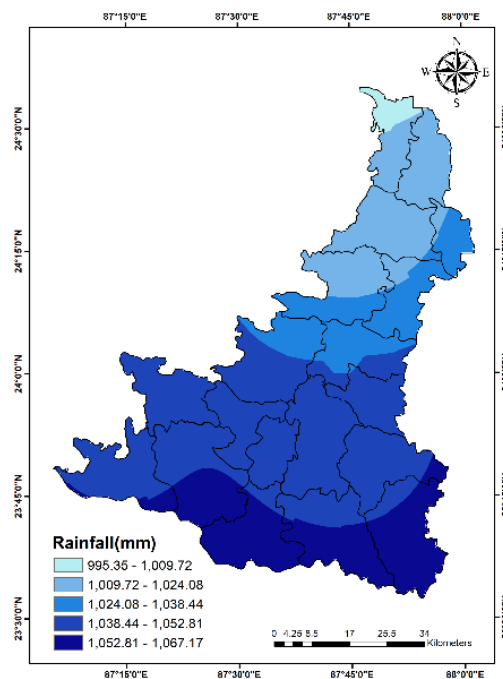


Fig. 5.13 Spatial distribution of rainfall, 2018

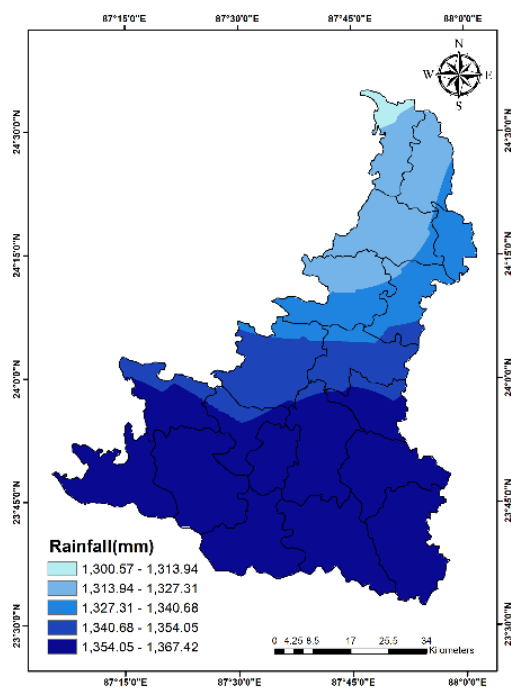


Fig. 5.14 Spatial distribution of rainfall, 2019



5.3.2 Health Risk Analysis

Health risk assessments conducted in accordance with USEPA, suggest that an extensive segment of the population residing in Birbhum is subjected to potential health hazards that are linked to elevated fluoride concentrations present in the groundwater resources. Notably, exceedingly high Total Hazard Quotients (THQ) have been documented across vast expanses of the district, encompassing both children and adult demographics. This highlights a significant public health concern, across the population. Specifically, within certain western and south-western administrative blocks of the district, including but not limited to Khoyrasole, Rajnagar, Dubrajpur, Suri I, and select regions of Rampurhat I, there have been alarming observations of THQ values reaching as high as 7.34 for adult individuals, alongside values exceeding 15 for children. It is imperative to underscore that a THQ value greater than 1 is regarded as indicative of a hazardous situation for both children and adult populations alike. It has been ascertained that in comparative analyses, the THQ values tend to be markedly elevated in the pediatric population relative to their adult counterparts. Furthermore, an examination of the geospatial risk assessment maps unequivocally illustrates that the spatial distribution of risk zones is significantly more pronounced for the child population, thereby indicating a higher susceptibility. A detailed comparison of the THQ values for children versus adults further elucidates the stark disparity in risk exposure. Furthermore, it has been distinctly noted that there exists a pronounced decline in the geographical extent of areas identified as high risk for both demographics as a function of seasonal variations. To elaborate, the geographical regions characterized by high health risks resulting from the consumption of groundwater containing fluoride levels that exceed established statutory limits, exhibit a pattern varying with the monsoons. That is to say, higher spatial extent is observed pre-monsoon while lesser is observed, post-monsoon. While the degree of variation in THQ values may differ, a consistent and observable decline has been documented across the board. A mean difference of 6.67 percentage points in pre and post-monsoonal spatial coverage has been observed for the adult population whereas the child population exhibits a mean difference of 4.91 percentage points.

Table 5.5: 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



Comprehensive field data pertaining to groundwater quality, which were collected from 51 discrete sampling points distributed across seven blocks of the district, namely Suri I and II, Dubrajpur, Md Bazar, Bolpur Sriniketan, and Rampurhat I and II, during both pre-monsoon and post-monsoon periods, has been utilized to substantiate the Health Risk Assessment maps that were developed through the interpolation of these sampling points along with their corresponding fluoride concentrations.

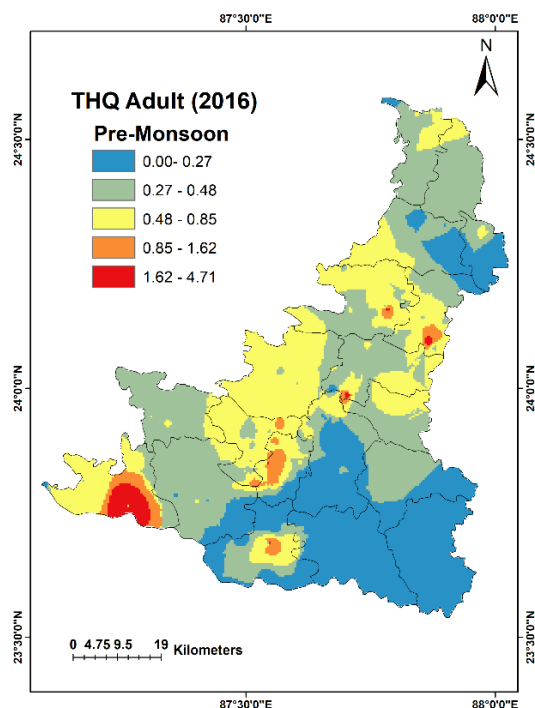


Fig 5.15: Spatial disposition of health risks in adults, pre-monsoon 2016

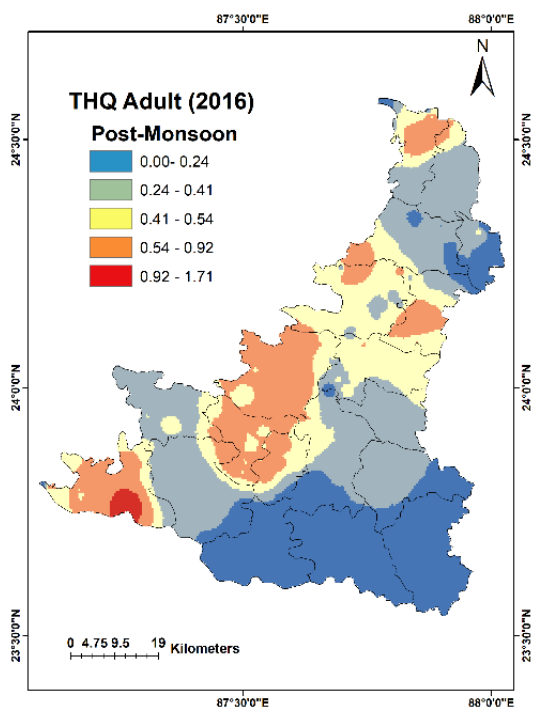


Fig 5.16: Spatial disposition of health risks in adults, post-monsoon 2016

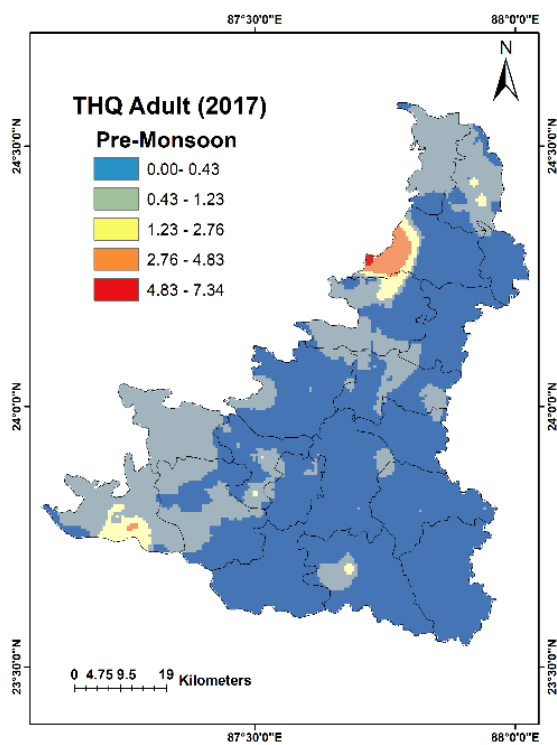


Fig 5.17: Spatial disposition of health risks in adults, pre-monsoon 2017

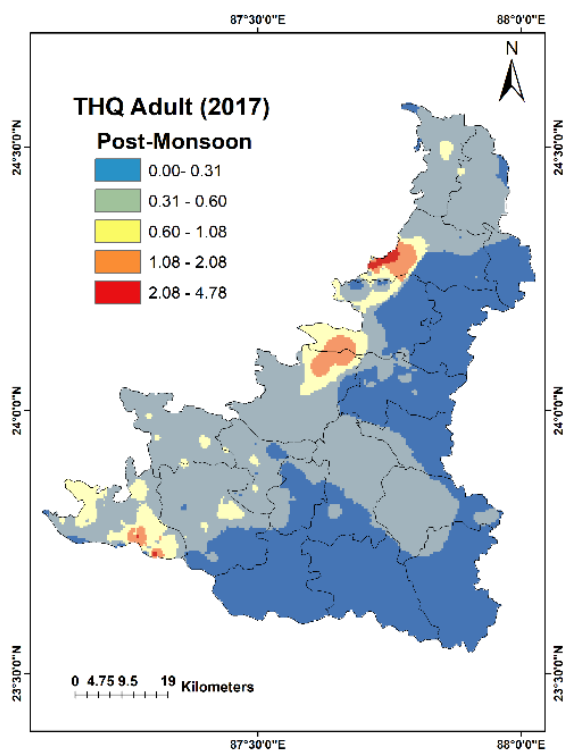


Fig 5.18: Spatial disposition of health risks in adults, post-monsoon 2017

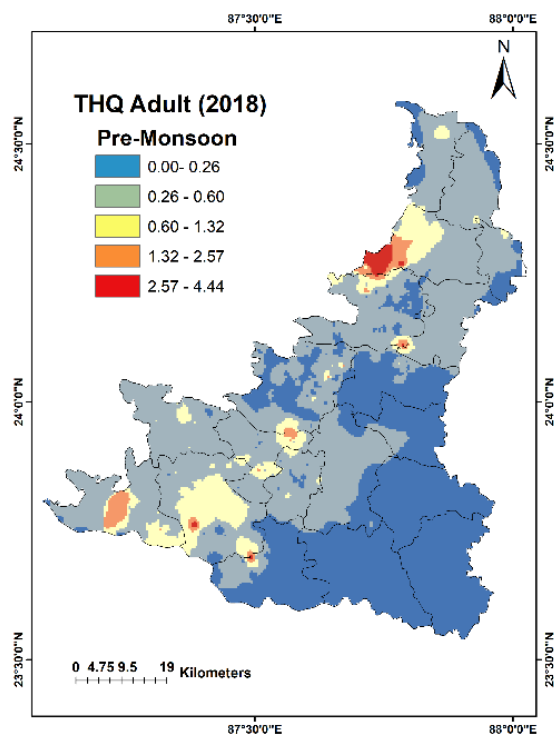


Fig 5.19: Spatial disposition of health risks in adults, pre-monsoon 2018

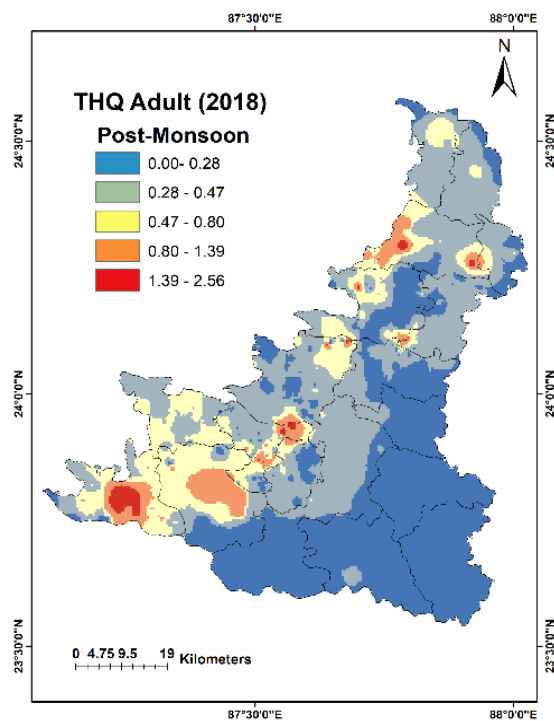


Fig 5.20: Spatial disposition of health risks in adults, post-monsoon 2018

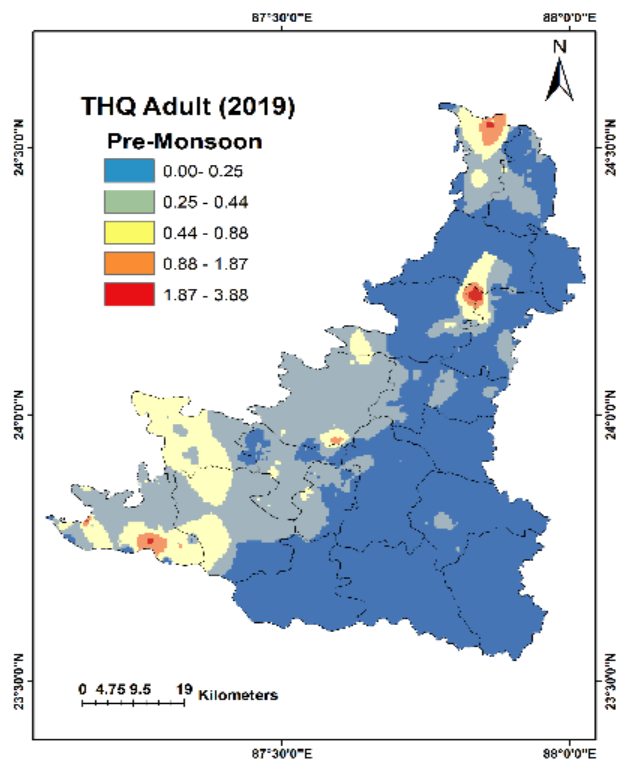


Fig 5.21: Spatial disposition of health risks in adults, pre-monsoon 2019

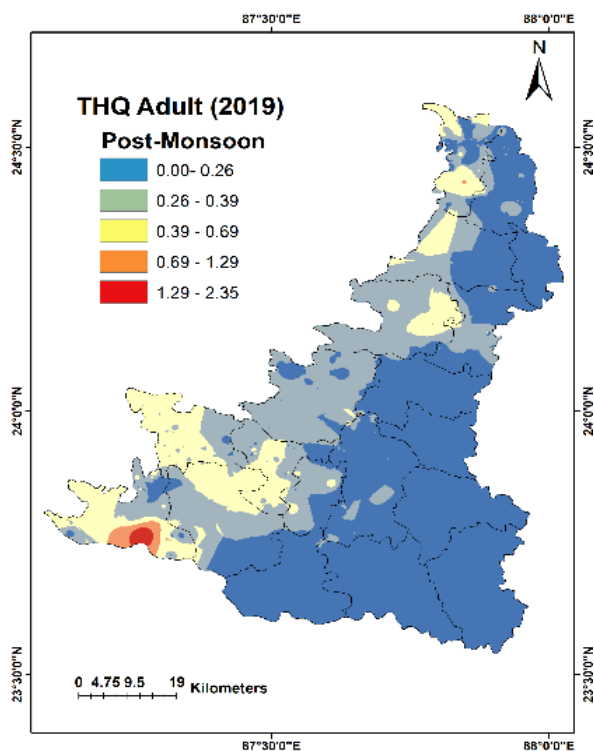


Fig 5.22: Spatial disposition of health risks in adults, post-monsoon 2019

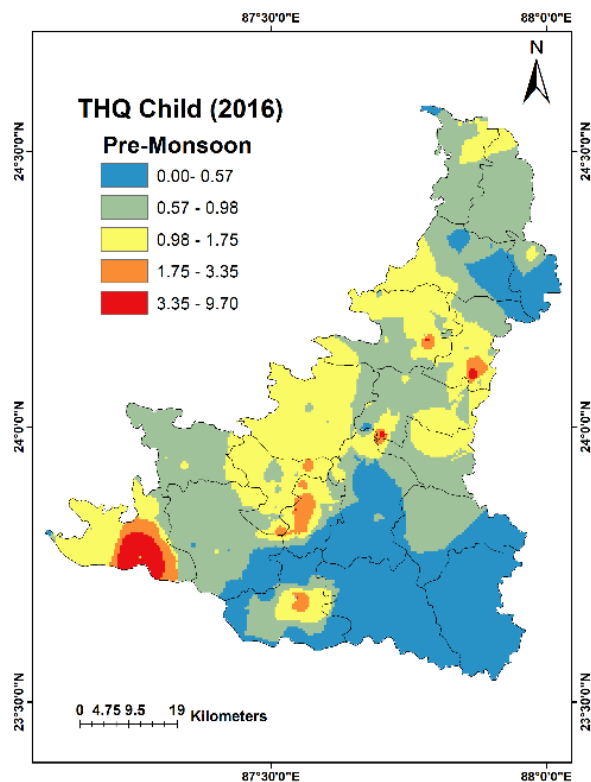


Fig 5.23: Spatial disposition of health risks in children, pre-monsoon 2016

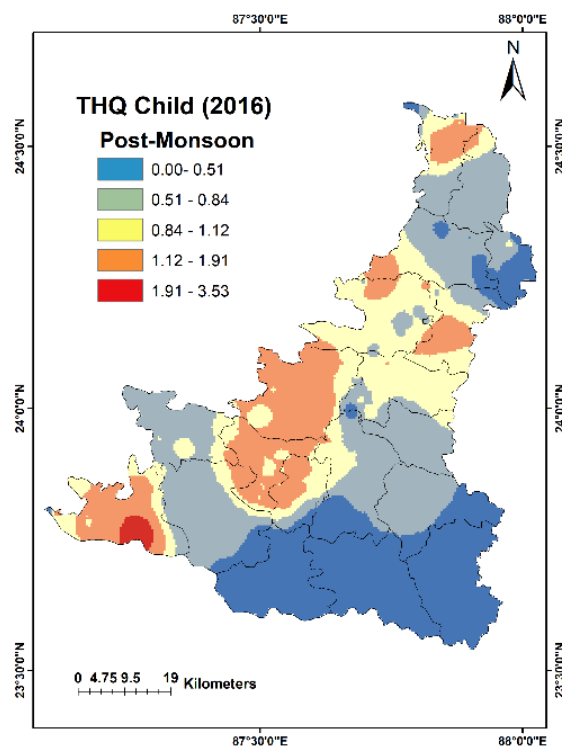


Fig 5.24: Spatial disposition of health risks in children, post-monsoon 2016

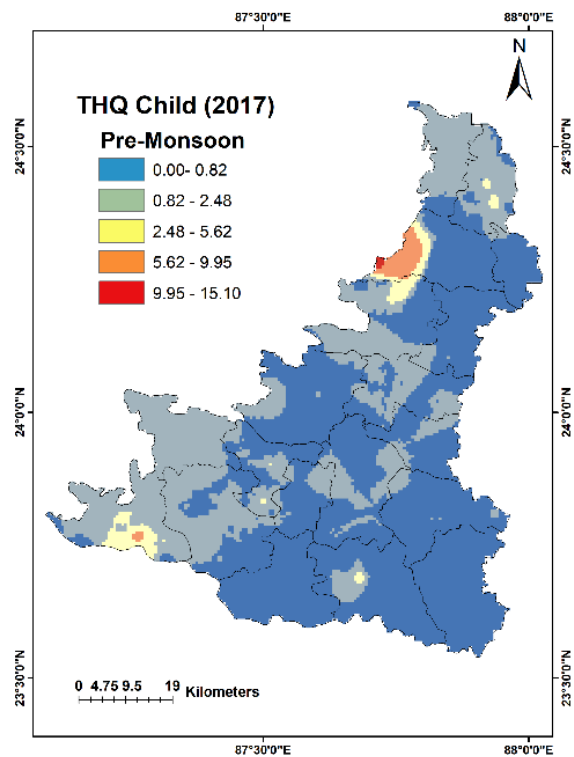


Fig 5.25: Spatial disposition of health risks in children, pre-monsoon 2017

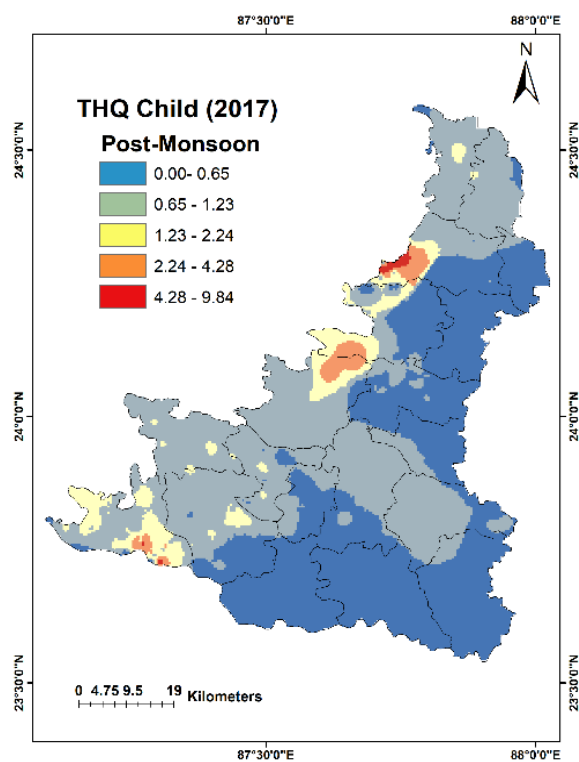


Fig 5.26: Spatial disposition of health risks in children, post-monsoon 2017

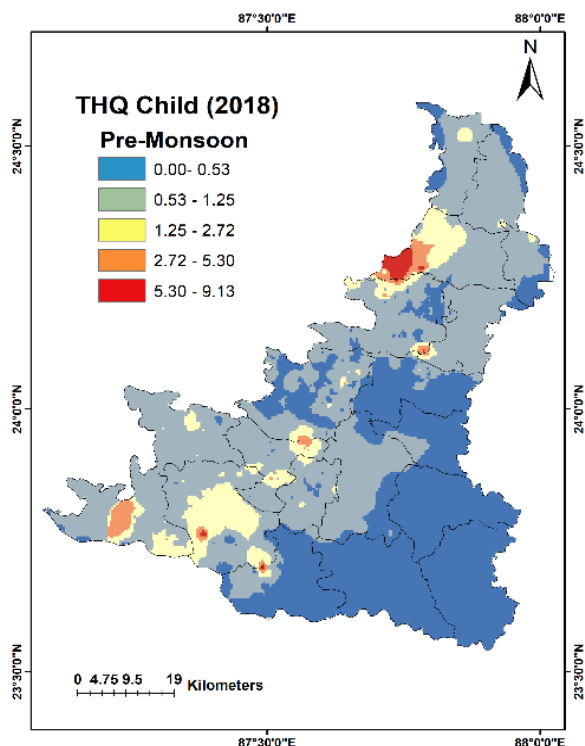


Fig 5.27: Spatial disposition of health risks in children, pre-monsoon 2018

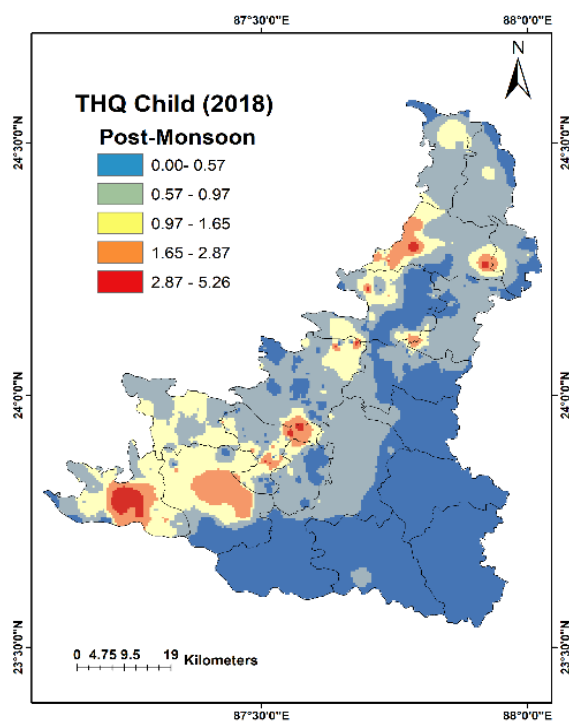


Fig 5.28: Spatial disposition of health risks in children, post-monsoon 2018

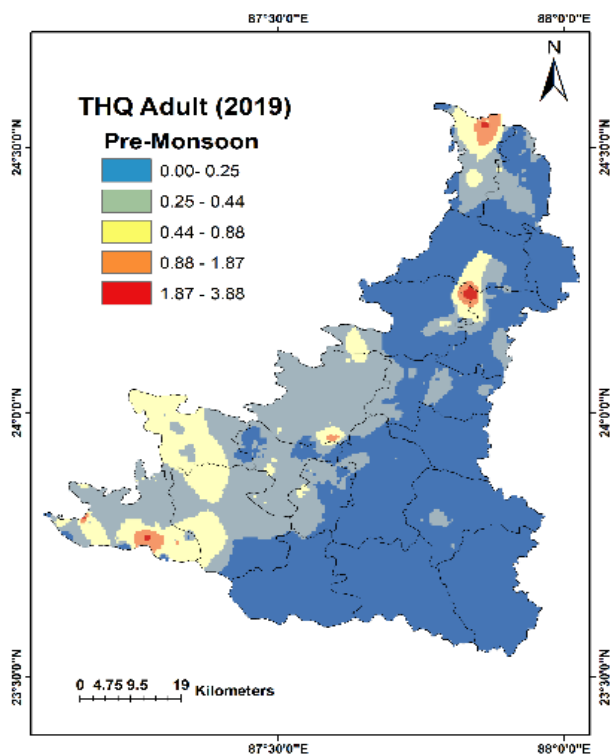


Fig 5.29: Spatial disposition of health risks in children, pre-monsoon 2019

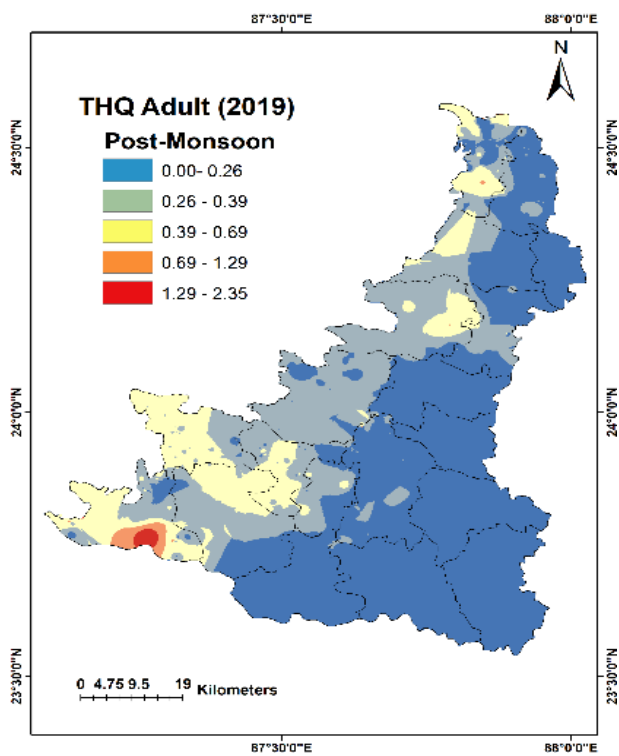


Fig 5.30: Spatial disposition of health risks in children, post-monsoon 2019

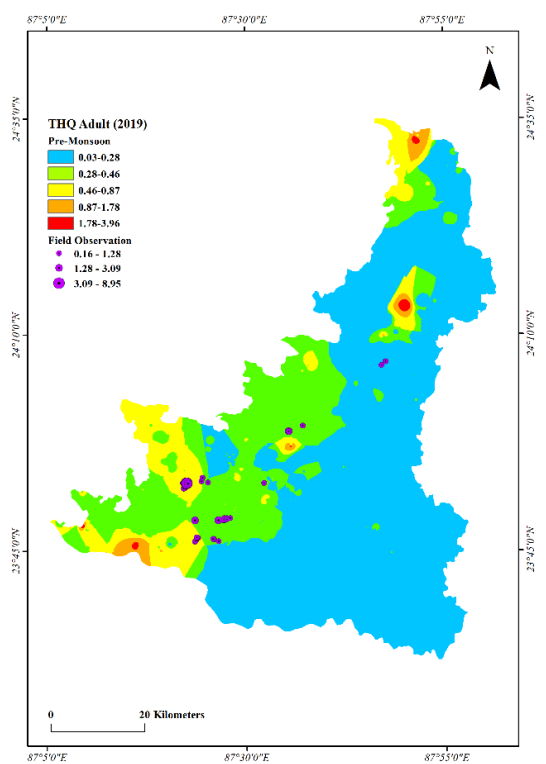


Fig 5.31: Validation of primary data points on HRA maps, adult population, pre-monsoon 2019

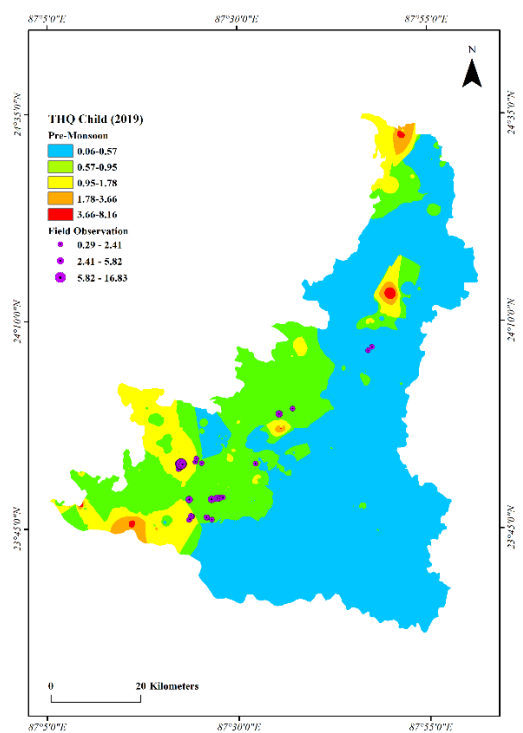


Fig 5.32: Validation of primary data points on HRA maps, child population, pre-monsoon 2019

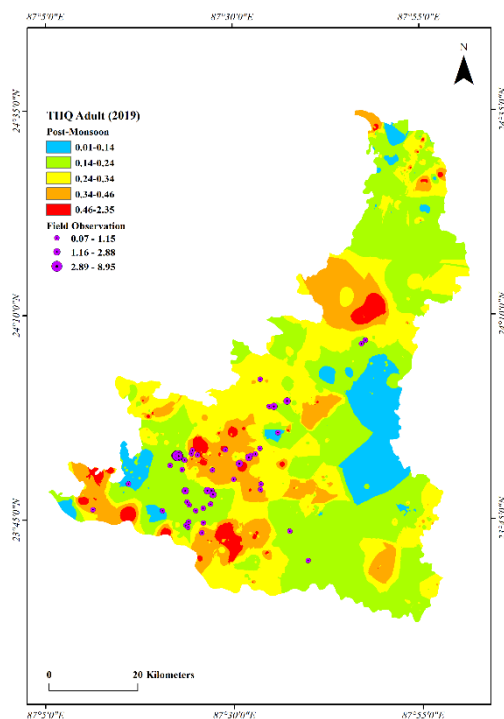


Fig 5.33: Validation of primary data points on HRA maps, adult population, post-monsoon 2019

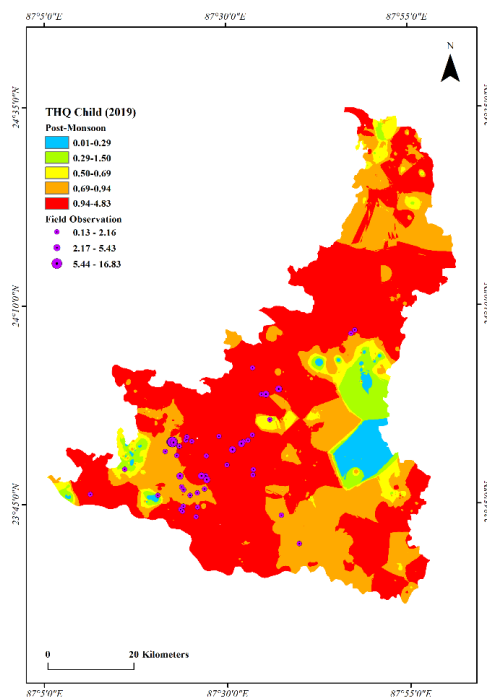


Fig 5.34: Validation of primary data points on HRA maps, child population, post-monsoon 2019



5.4 Discussions

5.4.1 Spatio-temporal Analysis

The phenomenon of fluoride contamination within groundwater sources exhibits a distinctly uniform spatial distribution, particularly characterized by the western and south-western administrative districts, which manifest substantially larger expanses of land exhibiting fluoride concentrations that exceed the legally established statutory limits. Specifically, the regions encompassed within the administrative divisions of Durbajpur, Suri I and II, Rajnagar, Khoyrasole, and Md. Bazar consistently demonstrate elevated levels of fluoride concentrations that are notably higher than those found in other areas. As previously delineated in the geological and geochemical analysis section of this comprehensive study, it is imperative to acknowledge that the geological composition of the western and south-western sectors of these districts predominantly consists of Archean Chotanagpur Granite-gneiss formations. In these granitic aquifers, the groundwater experiences significant enrichment in fluoride content due to the leaching of fluoride-bearing minerals, a process that is further exacerbated by extensive rock-water interactions over prolonged periods of time, as substantiated by the findings of *Das and Nag (2017)* and *Thapa et al. (2020)*. Conversely, in certain discrete locales within the Rampurhat I & II administrative blocks, which are characterized by older alluvial deposits, isolated areas exhibit sporadically higher levels of fluoride contamination. This particular increase can be attributed to the presence of intercalated clay layers within the affected aquifers, which serve to elevate fluoride concentrations through the mechanisms of ion-exchange and adsorption (*Thapa et al., 2020; Mukherjee and Singh, 2020*). In stark contrast, consistently lower fluoride concentrations are observed in the southern and south-eastern regions that border the districts of Burdwan and Murshidabad, which is attributable to the geological setup of these areas, as they are composed predominantly of newer alluvial deposits. The absence of fluoride-bearing minerals, such as apatite and fluorapatite, in these regions suggests that geological factors play a limited role in the enrichment of fluoride within the groundwater supplies.

The highest recorded concentrations of fluoride within groundwater sources have been documented in association with the Bakreshwar hot springs. This particular hot spring complex, which is strategically situated at the eastern extremity of the SONATA Geothermal province, has been noted for its disproportionately high fluoride content. The Bakreshwar hot spring complex is positioned at the eastern margins of two significant fault systems, namely the SONATA and ONGC faults, which, as a natural consequence, facilitate the existence of highly fractured basement rock formations that allow for groundwater to circulate through the deep granitic aquifer zones, as articulated in the studies conducted by *Majumdar et al. (2009)* and *Mukherjee et al. (2020)*. Furthermore, a remarkably high geothermal gradient, coupled with an elevated heat flow rate, has been documented, alongside a strikingly high temperature of approximately 200°C at a depth of 3 kilometers.



This elevated thermal condition is instrumental in promoting the dissolution of fluoride from the source minerals located within the confined aquifers at depth. Additionally, the prolonged residence time of the groundwater significantly contributes to and facilitates the dissolution process of fluoride-bearing minerals, a phenomenon that is driven by the intricate rock-water interactions occurring within the Granitic aquifers (*Hossain and Patra, 2020; Mukherjee et al., 2020*).

Spatial analysis conducted within the context of this study reveals that a remarkably significant expanse of the district exhibits elevated levels of fluoride within its groundwater resources, which has far-reaching implications for public health and environmental quality. The recorded fluoride concentrations display notable temporal fluctuations, with the pre-monsoon season manifesting higher fluoride levels, whereas a marked reduction in these values is evident during the post-monsoon period. Specifically, during the pre-monsoon season, approximately 29.89% of the district's geographical area is categorized as having fluoride concentrations in the groundwater that exceed the established statutory threshold of 1.5 mg/L, in stark contrast to the post-monsoon phase, where the mean spatial extent of fluoride contamination diminishes to around 21.90%. Moreover, there is an average decrease of 7.96 percentage points in the proportion of the area affected. This phenomenon suggests that the infiltration of rainwater into aquifers contaminated with fluoride plays a crucial role in the dilution process of fluoride concentrations found within the groundwater resources. Furthermore, this assertion is reinforced by the data collected from the Public Health Engineering Department (PHED), which corroborates the trend of reduction in mean fluoride concentration values observed in the groundwater following the monsoon season. Specifically, the mean fluoride concentration value, as calculated over the four-year period from 2016 to 2019, indicates a significant reduction of 20.4% in the post-monsoon phase. Additionally, primary data gathered during both the pre-monsoon and post-monsoon periods of 2019 further supports this trend, revealing a similar pattern of decline in mean fluoride concentration values. Notably, the mean fluoride concentration values exhibited a reduction of 16.11% during the observed timeframe across the 51 wells from which water samples were collected for analysis. From this, it can be inferred that there exists a negative correlation between both the absolute concentration values of fluoride and the spatial extent of fluoride contamination in relation to rainfall. Thus, it becomes evident that the fluoride levels recorded prior to the monsoon season experience a substantial decline in the subsequent post-monsoon period.

In an effort to further substantiate and validate these observations, rainfall data obtained from the Climate Research Unit-Time Series (CRU-TS) were examined and analyzed. Upon thorough investigation, it was observed that the highest average rainfall occurred in the year 2017, while the lowest average rainfall was recorded in 2018. These observed rainfall values appear to correspond with the noted decrease in average fluoride concentration values after the monsoon season, with the year 2017 demonstrating the most significant reduction and 2018 reflecting the least. However, it is critical to note that the maximum and minimum



reductions in the spatial extent of fluoride contamination do not align with the variations in maximum and minimum rainfall amounts. However, from the analyzed data, it may be deduced that rainfall reduces the spatial extent of fluoride concentrations. Therefore, inference maybe drawn that rainfall significantly influences the dilution of fluoride concentrations present in the groundwater, primarily through the process of water mixing (*Saxena and Ahmed, 2003*). Therefore, it could be unequivocally established that rainfall plays a significant role in offsetting fluoride concentrations and subsequently reduces the spatial extent of fluoride contamination in groundwater of Birbhum.

5.4.2 Health Risk Analysis

Health Risk Analysis (HRA), which has been computed utilizing the data procured from the Public Health Engineering Department (PHED) over an extensive temporal span extending from the year 2016 to the year 2019, illustrates the spatio-temporal variations pertaining to health risks that are intrinsically linked to the consumption of groundwater containing fluoride concentrations exceeding the permissible limits. In a comprehensive assessment, it has been discerned that a significantly elevated degree of risk is predominantly manifested within the pediatric demographic, particularly children, when contrasted with the adult demographic, who exhibit a comparatively lower level of risk exposure. Although the standardized risk assessment methodologies articulated by the United States Environmental Protection Agency (USEPA) in the years 2004 and 2011 inherently assign higher risk values to the calculations pertaining to the health repercussions of fluoride ingestion in children, it is nonetheless imperative to highlight that the spatial distribution patterns that have been observed throughout the aforementioned temporal span in the region of Birbhum underscore the alarming reality that children are subjected to a considerably heightened level of risk.

Through a detailed spatio-temporal analysis of the HRA maps, it can be inferred that, on average, approximately 31.17% of the geographical expanse of Birbhum is classified as exhibiting a high risk (Hazard Quotient greater than 1) for the pediatric population during the pre-monsoon period, whereas a smaller proportion, specifically 26.24% of the area, is categorized under the high-risk zone during the post-monsoon period. This salient observation elucidates the critical concern that children residing in Birbhum are exceedingly vulnerable to developing dental and skeletal deformities that are associated with the consumption of fluoride-laden water. In stark contrast, the spatial extent of health risks confronting the adult population is markedly diminished when juxtaposed with that of children. On average, it has been determined that around 11.66% of the spatial area within the district is deemed vulnerable to adults during the pre-monsoon season, a figure that witnesses a substantial decline to 4.86% in the subsequent post-monsoon period.

Likewise, alongside the geographical spread of groundwater contaminated with fluoride, the health hazards linked to the intake of this polluted water also show a significant decline after the monsoon rains. Statistically, the average spatial distributions reveal a decrease of 6.88



percentage points in the risks faced by the adult population, while the child population experiences a decline of 4.92 percentage points subsequent to the monsoon period.

From the primary field data obtained from the field, during the period of pre and post-monsoon, 2019, an attempt was made to validate the HRA maps, through the process of interpolation of the THQ values computed from the primary data into the HRA maps. It has been observed that the model demonstrates a commendable fit, with the majority of sampling points aligning with the designated risk zones as determined by their THQ values. Within the pediatric population, it has been identified that more than 75% of the sampling points display a strong alignment with the model, whereas for the adult population, a little more than half of the sampling points correspond to the predicted risk zones as delineated by the model (Fig. 5.31-5.34).

Consequently, it may be surmised that the pediatric population residing in Birbhum is subjected to a substantial health risk that arises from the consumption of water contaminated with fluoride, in stark contrast to the adult population, which demonstrates only mild to moderate risk levels. This concern is further exacerbated by the fact that children are likely to consume this contaminated water over a significantly extended temporal duration in comparison to adults, thereby amplifying their overall exposure and associated health risks., puts this already vulnerable population at more risk.

5.5 Summary

In the present chapter, an in-depth analysis was conducted regarding the spatio-temporal distributions of fluoride contamination in the groundwater sources located within the region of Birbhum, which was executed through the extensive application of various geo-spatial analytical tools and methodologies. This comprehensive analysis was systematically undertaken over a temporal span ranging from the year 2016 to the year 2019, during which the available data was diligently categorized into two distinct segments—namely, pre-monsoon and post-monsoon—based on the specific timing of data collection. The spatial and temporal variations of fluoride concentrations were scrutinized to elucidate the finer nuances and complexities of the underlying mechanisms that contribute to this contamination phenomenon. Furthermore, a concerted effort was made to ascertain the influence of rainfall patterns on the levels of fluoride contamination present in the groundwater sources. In addition to this, Health Risk Assessment (HRA) maps were constructed for the aforementioned temporal period, which were further delineated along the lines of the monsoons in order to provide a clearer picture of the variations in health risks associated with fluoride exposure. These HRA maps were specifically generated for both adult and child demographic groups to enhance the understanding of how fluoride contamination affects different segments of the population. The findings ultimately led to the conclusion that the health risks stemming from the consumption of excessive fluoride present in groundwater resources are significantly more pronounced among the pediatric population, a conclusion that was substantiated through the validation of primary data against the established HRA



maps. It was noted, however, that while rainfall does to perform a vital function in mitigating fluoride concentrations found in groundwater, thereby alleviating some of the associated health risks, it is insufficient to fully neutralize the detrimental health effects that arise from the consumption of fluoride-laden groundwater. Consequently, there is an imperative need to formulate and implement effective mitigation strategies aimed at the prevention of potential health hazards linked to fluoride pollution in our environment. In the subsequent chapter, a detailed discussion of potential amelioration strategies will be presented to address this critical issue.



Chapter 6: Remedial Measures

6.1 Preface

It is widely acknowledged within the scientific community that fluoride concentrations exceeding the established permissible threshold of more than 1.5 mg/L may induce severe and detrimental health conditions affecting both the dental structure and the skeletal system (*Podgorski and Berg, 2022*). This assertion is particularly relevant in the context of pediatric populations, who exhibit a heightened susceptibility to the various health hazards related to an excessive intake of fluoride (*Liu et al., 2023; Zhang et al., 2024*). As has been documented in the preceding chapter of this study, it has been determined that approximately 31% of the total geographical expanse of the Birbhum district is categorized as exhibiting high fluoride vulnerability specifically for children during the pre-monsoon season, a figure that subsequently diminishes to about 26% in the post-monsoon period. While these statistics indicate a significant reduction in risk for adult populations, it is important to note that roughly 11% and 5% of the district's area continues to be classified as high-risk zones for adults during the pre-monsoon and post-monsoon seasons, respectively. Extensive regions within the western and south-western blocks of the district are characterized by alarmingly high levels of fluoride contamination, thereby resulting in an increased potential for adverse health risks, which underscores the urgent need for the formulation and implementation of suitable and comprehensive remedial strategies aimed at mitigating the potential repercussions of consuming groundwater that is contaminated with fluoride. Plethora of solutions have been formulated to remove fluoride from water. These mainly center around two major techniques:

- a. De-fluoridation technologies
- b. Use of alternative water sources

The techniques employed for the purpose of de-fluoridation are fundamentally concerned with the systematic removal of fluoride ions from water sources, which subsequently results in a significant reduction of fluoride concentration to levels that fall below the established permissible limits set forth by health and safety regulations. Such processes typically necessitate the incorporation of various chemical agents that serve as coagulants, alongside adsorptive materials capable of binding fluoride to their surfaces, or the implementation of advanced methodologies such as electro-coagulation, electro-dialysis, and reverse osmosis, all of which are designed to effectively mitigate fluoride levels. A comprehensive table that summarizes the diverse range of methods available for fluoride removal is provided in the following section (**Table 6.1**).

In the context of India, coagulation-precipitation techniques are widely adopted due to their relative ease of implementation and cost-effectiveness, making them a practical choice for many communities. Notably, the Nalgonda method, which has been developed and refined by the National Environmental Engineering Research Institute (NEERI), stands out as a



particularly favored approach for the remediation of fluoride contamination at both the family and community levels, primarily owing to the low financial cost associated with its materials and their ready availability in local markets. Nevertheless, this method is not without its significant limitations; it requires the presence of a trained operator to conduct daily operations, as the procedure demands meticulous control over pH levels and the precise dosage of coagulants (*Kashyap et al., 2021; Karunanithi et al., 2023*). Such trained personnel may not be easily accessible in socio-economically disadvantaged districts, such as Birbhum, which exacerbates the challenges faced in implementing this solution effectively. Moreover, the routine application of aluminium sulphate in this method has the unfortunate consequence of elevating sulfate concentrations in the treated water, which, when used over prolonged periods, may induce detrimental cathartic effects on human health. Additionally, this process is prone to introducing neurotoxic Aluminium into the water supply, a factor that has been linked to the potential early onset of Alzheimer's disease (*Gupta et al., 2014*). Furthermore, the substantial volume of sludge produced as a byproduct of this de-fluoridation process contains excessive fluoride ions, and the effective disposal of this hazardous waste continues to represent a significant public health and environmental concern (*Yami et al., 2018*). In contrast, processes such as electro-coagulation and electro-dialysis necessitate a considerable degree of technical expertise to operate effectively, and they are characterized by their high energy demands, which require careful and regular maintenance (*Belkada et al., 2018*). Consequently, it becomes exceedingly challenging to regard these advanced methods as viable or effective solutions for the district of Birbhum, which is not only grappling with socio-economic adversities but also faces a substantial geographic area plagued by the adverse effects of fluoride contamination. Reverse osmosis (RO), on the other hand, has emerged as a commonly utilized technique for the de-fluoridation of drinking water, particularly in regions that are significantly affected by elevated fluoride concentrations. However, despite its proven efficacy in diminishing fluoride levels, reverse osmosis is associated with several inherent drawbacks that substantially limit its long-term sustainability and broader applicability in various contexts. Among these shortcomings is the considerable amount of water wastage that occurs during the reverse osmosis process, with approximately 30% of the incoming water being discarded as a reject stream, which is particularly problematic given that this reject stream often contains a higher concentration of fluoride, thus exacerbating environmental challenges (*Samrat et al., 2018; Khan et al., 2021*). Additionally, the elevated operational costs associated with reverse osmosis, particularly in terms of energy consumption, render it an impractical remedial method within the context of Birbhum. Moreover, the effectiveness of RO systems is often compromised in the presence of certain competing ions, which may necessitate the introduction of supplementary treatment processes to attain the desired fluoride reduction levels (*Sara et al., 2013*).



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/m³	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 Sara et al., (2013); Gupta et al., (2014); Yami et al., (2018); Belkada et al., (2018); Kashyap et al., (2021); Karunanithi et al., (2023)



The use of alternate water sources offers cheap, community based effective substitute to traditional de-fluoridation methods. Rainwater Harvesting(RWH) is a major endeavor in this regard. Rainwater harvesting (RWH) is a critical strategy for addressing water scarcity, particularly in arid and semi-arid regions. It involves the collection and storage of rainwater for various uses, contributing to water security, flood risk reduction, and climate change mitigation. The practice is gaining attention due to its potential to provide a sustainable water source and its role in environmental conservation (*Sakati et al.,2024; Qader et al., 2024*). RWH have been extensively and systematically installed across various rural regions in multiple countries, including but not limited to Brazil, China, New Zealand, Australia, Singapore, and Thailand, all of which have recognized the importance of these systems in managing their water resources effectively. Brazil, in particular, stands out as the foremost nation that has embraced and implemented these rainwater harvesting techniques on a significant scale, demonstrating a commitment to sustainable water management practices. Furthermore, even nations that are characterized by abundant water resources, such as Germany, have proactively initiated and established rainwater harvesting measures, reflecting a broader recognition of the utility and necessity of these systems in diverse geographical contexts. In India, the adoption of rainwater harvesting techniques is primarily aimed at mitigating the adverse effects of flooding while simultaneously enhancing the recharge of groundwater, thus addressing both immediate and long-term water management challenges. Notably, Tamil Nadu holds the distinction of being the pioneering state in India that has legislated the implementation of rooftop rainwater harvesting structures, making it a mandatory requirement for all residential buildings throughout the entirety of the state, thereby setting a precedent for water conservation efforts (*Vasudevan and Natarajan, 2021*). In addition to Tamil Nadu. Several other states in India, including Karnataka, Andhra Pradesh, Rajasthan, Gujarat, Himachal Pradesh, and others, have also engaged in the installation of rainwater harvesting systems, further contributing to the collective efforts aimed at improving water resource management across the nation.

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.

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)

The major factors influencing the viability of conducting RWH are listed here-under:

- **Rainfall:** Rainfall is a critical factor influencing the effectiveness and potential of rainwater harvesting (RWH) systems. The amount, intensity, and distribution of rainfall directly affect the volume of water that can be collected and stored, which in turn impacts the economic and practical viability of RWH systems. Understanding these dynamics is essential for optimizing RWH systems to meet water demands, especially in regions prone to water scarcity or erratic rainfall patterns. The extensive duration of thirty-two years, spanning from 1991 to 2023, during which a comprehensive collection of monthly station data was gathered for the purposes of this particular study, has been thoroughly obtained from the designated catchment area. The intricate network of monitoring stations is strategically situated within the geographical confines of the Birbhum districts, thereby encompassing the entirety of the specified catchment region.
- **Slope:** Slope, in geospatial analysis, is a critical parameter that influences various natural and anthropogenic processes, including hydrology, geomorphology, and hazard assessment. It is a measure of the steepness or incline of a surface and is essential for understanding terrain dynamics, water flow, sediment transport, and the potential for natural disasters such as landslides (*Cohen et al., 2018; Oyda et al., 2023*). Slope map for the area was prepared using GIS platforms with DEM data of 30m×30m resolution. This was further segregated into five classes.
- **Aspect:** The term 'aspect' pertains to the orientation or alignment of the land surface relative to cardinal directions, which holds significant importance in the accurate detection and understanding of the flow direction of various environmental and hydrological processes (*Faizan et al., 2023*). In order to develop a comprehensive aspect map, the data derived from the Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) was utilized and systematically processed using Geographic Information System (GIS) platform. This resulting map was subsequently



categorized into ten distinct classes, thereby facilitating a more thorough and nuanced representation of the distribution of slope direction throughout the designated area of interest, allowing for a more detailed analysis of the topographical features and their implications for environmental studies.

- **Drainage Density:** Drainage density in geospatial analysis refers to the total length of all drainage channels (streams, rivers) within a watershed divided by the area of that watershed. It is a crucial metric for understanding hydrological characteristics, as it reflects the network's efficiency in water conveyance and influences erosion, sediment transport, and ecological health (*Kim et al., 2023*). Using raster images from DEM, drainage networks were outlined. The map, thus constructed, is divided into five classes for better interpretation.
- **Distance from River:** The proximity to the river constitutes a critical variable in evaluating the viability of rainwater harvesting initiatives. The quantification of this distance is conventionally expressed in meters. To develop a cartographic representation delineating the distance from the river, a river network map was generated utilizing SRTM DEM data through advanced geo-spatial methodologies. The map, thus created, was segregated into five classes for nuanced spatial analysis.
- **Land Use Land Cover (LULC):** Land Use Land Cover (LULC) is an important tool in geo-spatial analysis that involves the monitoring and assessing changes in land use patterns over time using techniques such as using techniques such as Remote Sensing (RS) and GIS (*Cuyppers et al., 2023; Jasim et al., 2024*). LULC maps depicting changes in the patterns of land use, were constructed for the years 2000, 2010 and 2023, in order to comprehend the changes, over a period of more than two decades.
- **NDVI:** The Normalized Difference Vegetation Index (NDVI) is a widely used metric in geospatial analysis for monitoring vegetation health and land cover changes. It is calculated using satellite imagery by comparing the difference between near-infrared (NIR) and red light reflectance, which provides insights into the density and health of vegetation (*Cai et al., 2024; Serrano-Grijalva et al., 2024*). NDVI values range from -1 to 1, where higher values indicate healthier and denser vegetation. This index is crucial for various applications, including agriculture, environmental monitoring, and land management.
- **Soil Texture:** Soil texture represents a fundamental variable in the context of rainwater harvesting (RWH) as it governs the infiltration, retention, and runoff properties of the soil, which are imperative for the optimization of water resource management. The capacity of soil to either retain or facilitate the percolation of water significantly influences the design and operational efficacy of RWH systems. Varied soil textures, extending from sandy to clayey compositions, exert unique effects on the viability of rainwater harvesting practices, thus establishing it as a crucial factor in site assessment and system architecture (*Panigrahi et al., 2023; Chen et al., 2024*). In the present investigation, a soil texture map was developed utilizing data obtained



from the National Bureau of Soil Survey and Land Use Planning (NBSS-LUP), which was categorized into nine distinct classes to enhance understanding.

6.2.3 Analytical Hierarchy Process (AHP)

The Analytical Hierarchy Process, a sophisticated methodology for decision-making, was originally conceptualized and established by the esteemed scholar Thomas L. Saaty in the year 1980, and since that time, it has significantly evolved and garnered substantial recognition, thereby emerging as a widely utilized and critically important multi-criteria decision-making method that is frequently referenced in contemporary academic literature (*Faizan et al, 2023*). This esteemed process is particularly well-regarded for its remarkable effectiveness in addressing and resolving complex problems that often arise in various fields of study and practical applications. In contrast to traditional statistical methods, the Analytical Hierarchy Process stands out due to its distinctive ability to evaluate not only the individual impact of a single factor but also the collective influence of various classes of factors, which allows for a more nuanced and comprehensive analysis of decision-making scenarios (*Wubalem et al, 2021*). AHP is a structured technique for organizing and analyzing complex decisions based on mathematics and psychology. It involves pairwise comparisons of landscape-forming factors to determine their priorities relative to a main goal, such as achieving a zonal norm. AHP facilitates the assessment of various criteria across different hierarchical levels, allowing researchers to evaluate the influence of factors on geosystems and create maps that illustrate landscape variability based on these analyses (*Cherkashin & Frolov, 2023*). In geo-spatial analysis, AHP is a structured decision-making framework that helps prioritize and evaluate various criteria and sub-criteria for site selection. It involves assigning weights to parameters based on their importance, facilitating the comparison of alternatives (*Rimadeni et al., 2024*). The Analytical Hierarchy Process (AHP) framework encompasses four essential stages: initially, the issues must be meticulously dissected and organized into a hierarchical structure of sub-problems; subsequently, the data ought to be systematically arranged and computed through pair-wise comparisons of attributes; thereafter, the priority weights of the parameters at the individual level must be assessed; and finally, the consistency of the evaluations must be verified (*Chaulagain et al., 2023; Wubalem et al., 2021*). In this study, a comprehensive set of eight parameters were integrated to substantiate the areas designated for rainwater harvesting, namely rainfall, soil texture, LULC, NDVI, slope, aspect, drainage density and distance from river.

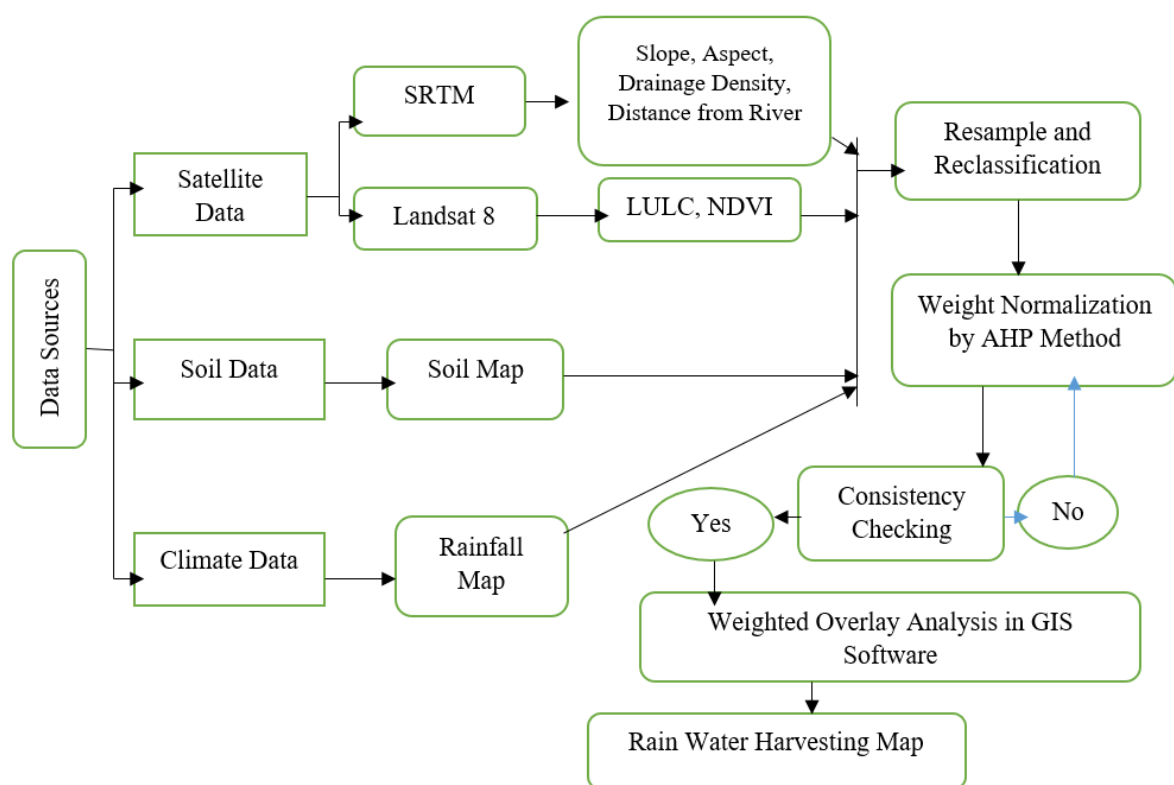


Fig 6.1 Methodology chart for creation of RHW maps using AHP

The Pairwise comparison matrix

The pairwise comparison matrix (Table 6.5) was assembled to approach the thematic layers and their parameters using the scale giving by Saaty (Table 6.3) (Faizan *et al*, 2023). The importance and prediction of every thematic layer in relation to the other layers for rain water harvested area were discovered by assigning weights, resulting in the formation of (8×8) matrix (Hagos *et al*, 2022). Rain water harvesting factors were assessed on a scale ranging from 1 to 8, where a rating of 1 marks equal importance of ratings whereas that of 8 denotes that one element is more remarkable than the other. The returned values of 1 to 8 (1/1 and 1/8) show relative importance (Penki *et al*, 2023). The weights allocated to the factors



were assessed to running a multi-criteria evaluation of their effect on rain water harvesting into the study area.

Into the pairwise comparison matrix (**Table 6.5**) S- Slope, R- Rainfall, DD- Drainage Density, SO- Soil, DR- Distance from River, LULC- Land Use and Land Cover, NDVI- Normalized Difference Vegetation Index, A- Aspect.

Table 6.3: Saaty's scale of relative importance

Intensity of Importance	Degree of Preference	Explanation
1	Equally	Two activity contribute equally to the objective
3	Moderately	Experience and judgment slightly favor one activity over another
5	Strongly	Experience and judgment strongly favor one activity over another
7	Very Strongly	An activity is strongly favored and its dominance demonstrated in practice
2,4,6,8	Intermediate	When composite is required

The matrix was normalized by summing the number in individual column and dividing every record in the column by the column sum to get its normalized score (**Table 6.6**). The total sum of every column is 1. The criteria weights were obtain utilizing the normalized matrix, with the arithmetic mean of particular row in the Table is being computed. Then, the percentage for every thematic layer was measured based on the got criteria weight (**Table 8**) (Faizan et al, 2023).

Table 6.4: Random Consistency Index

n	1	2	3	4	5	6	7	8
RCI	0	0	0.58	0.09	1.12	1.24	1.32	1.41



Consistency checks

The consistency ratio (CR) is utilized to decide the pair-wise comparison of factors and their sub-classification (Nguyen and Hoang, 2023). The CR is measured using the following equation:

$$CR = CI / RCI \text{ equation 2}$$

Where CR is the consistency ratio, CI is the Consistency Index and RCI is the random consistency index. The RCI values are constant as reported based on Saaty in Table 6.3. For separate n values and indexes, CI is calculated using the following equation

$$CI = (\lambda_{\max} - n) / (n-1) \text{ equation 3}$$

Where n is the number of the parameters and $\lambda_{\max}$ is the average value of the consistency vector. If the CR value is ≤ 0.1 then the AHP output can be regarded as acceptable. If the value of CR exceeds 0.1, then the acquired output does not orient with the objective of the assessment and needs a revision of the technique utilized (Penki et al, 2023).

The focal objective of this research endeavor is to identify and delineate the specific zones that are most suitable for the practice of rainwater harvesting. The study is explicitly centered on the intricate process of categorizing and mapping the zonation of rainwater harvesting by conducting a thorough investigation of eight distinct parameters that serve as key indicators for the effective mapping of these rainwater harvesting zones. Each individual factor that has been identified within this context has been systematically classified into various distinct classes that reflect their differing characteristics and implications. Subsequently, the weights that have been assigned to the several classes of each factor have been rigorously established and thoroughly evaluated, followed by the computation of their normalized weights to ensure consistency and comparability across the dataset. In order to derive the rainwater harvesting index, the comprehensive data that has been collected throughout this research has been analyzed utilizing advanced Geographic Information System (GIS) software, which allows for sophisticated spatial analysis and visualization. Moreover, specific weights have been judiciously assigned to the various classes of the parameters under consideration, facilitating a nuanced understanding of their relative importance in the context of rainwater harvesting.

In this analytical framework, RWH represents the mapping of rainwater harvesting, where W_i denotes the weight assigned to factor i, and X_i signifies the various classes associated with rainwater harvesting for each specific parameter i, thereby providing a structured approach to the evaluation of these critical factors.

The rigorous study culminated in the creation of a definitive and comprehensive rainwater harvesting map, which was generated through the application of the following mathematical



equation that incorporates various weighted parameters to accurately reflect the conditions conducive to successful rainwater harvesting:

$$\text{Rainwater Harvesting} = 30.62 \times (\text{Rainfall}) + 22.13 \times (\text{Slope}) + 15.38 \times (\text{Drainage Density}) + 12.13 \times (\text{Distance from River}) + 8 \times (\text{Aspect}) + 5.62 \times (\text{LULC}) + 3.62 \times (\text{Soil Texture}) + 2.5 \times (\text{NDVI}).$$

6.2.4 Surface Waterbodies mapping

Surface water bodies play a crucial role in rainwater harvesting by acting as natural or artificial reservoirs that collect and store rainwater for various uses. These water bodies, when integrated into rainwater harvesting systems, can significantly enhance water availability, especially in regions facing water scarcity. The utility of surface water bodies in rainwater harvesting is multifaceted, encompassing agricultural, domestic, and environmental benefits (*Walia et al., 2014; Thakur and Grendlar, 2022*). In order to attain a comprehensive understanding of the spatial distribution and overall availability of surface water resources within the geographical confines of the district of Birbhum, mapping of the various surface water bodies was conducted through the application of an unsupervised classification method, which was systematically implemented on Geographic Information System (GIS) platforms, employing high-resolution LANDSAT 8 satellite imagery as a primary data source (Fig. 6.11). Specifically, only those surface water bodies that possess an area exceeding 0.1 hectares were delineated and mapped, with the explicit intention of gaining insights into the presence and distribution of larger surface water bodies that could potentially serve as natural reservoirs, as well as sustainable sources of water supply that are particularly critical during the peak summer months or in regions experiencing elevated levels of water stress, thereby contributing to effective resource management strategies (Fig. 6.12).

6.2.5 Land Use Change mapping

Land use change mapping represents an immensely significant methodological instrument that is indispensable for comprehensively understanding and effectively managing the intricate and dynamic interactions that exist between anthropogenic activities and the various components of natural environments. This sophisticated analytical approach provides crucial insights into the ways in which land is utilized, modified, and transformed throughout the passage of time, which is of paramount importance for the processes of urban planning, the management of natural resources, and the overarching goals of environmental conservation. The significance of land use change mapping is further accentuated by its multifaceted applications across a diverse array of disciplines, which include, but are not limited to, urban development, agricultural practices, forestry management, and the study of hydrological phenomena. The efficacy of this mapping technique is greatly enhanced through the utilization of advanced technological tools such as remote sensing and Geographic Information Systems (GIS), which collectively enable the accurate, systematic,



and efficient monitoring of changes in land use patterns over time (*Ezeomodo et al., 2024; Phuong & Thien, 2024; Teja et al., 2024*). In order to comprehend the changes in land use pattern over the last two decades, Land Use Land Cover (LULC) maps were created for the years 2000, 2010 and 2023. From these maps

6.3 Results

6.3.1 Rainwater Harvesting factors

The cartographic representation of rainwater harvesting for the Birbhum district was developed by considering eight parameters that contribute to the efficacy of rainwater harvesting. These parameters encompass precipitation, topographical slope, drainage density, proximity to river systems, aspect, Land Use and Land Cover (LULC), soil characteristics, and the Normalized Difference Vegetation Index (NDVI). The classes and the weights assigned have been enlisted in table 6.11.

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.

6.3.1.1 Slope

The range of slope values in the current study exhibited a remarkable variation from a minimum measurement of less than 1.36 degrees to a maximum exceeding 36.70 degrees, a phenomenon that can be thoroughly examined in the illustrative representation provided in **Figure 6.2**. Slope values that are categorized as low, specifically those falling below the threshold of 1.36 degrees, are indicative of a correspondingly low harvesting area, which predominantly encompasses the northern segment of the study area; conversely, slope values that exceed 36.79 degrees serve to denote regions characterized by high harvesting potential, a characteristic that has been observed in certain distinct western portions of this particular district.

6.3.1.2 Aspect

Aspect in geospatial analysis refers to the direction that a slope faces, which is crucial for understanding land exposure. It plays a significant role in various applications, such as determining sunlight exposure, moisture retention, and vegetation patterns. These



parameters impact the infiltration to run-off ratio and management of the slope segment. The aspect map was generated with 10 classes (**Fig 6.3**). These divisions include:

Flat, North (0-22.5 degree), Northeast (22.5-67.5 degree), East (67.5-112.5 degree), Southeast (112.5-157.5 degree), South (157.5-202.5 degree), Southwest (202.5-247.5 degree), West (247.5- 292.5 degree), Northwest (292.5- 337.5 degree) and North (337.5- 360 degree).

6.3.1.3 Rainfall

The rainfall map, as illustrated in **Figure 6.4**, delineates the classification of the study area into five distinct annual rainfall categories, which exhibit a range of values spanning from a minimum of 1246.47 millimeters to a maximum of 1330.62 millimeters. Within this context, the regions characterized by elevated rainfall measurements, specifically those falling within the range of 1310.82 to 1330.62 millimeters, are identified as being situated in the southeastern section of the district, and are consequently deemed to have a reduced level of suitability for the implementation of Rainwater Harvesting (RWH) strategies. Conversely, the geographical areas that exhibit lower rainfall measurements, which range from 1246.47 to 1267.26 millimeters, have been recognized as being more favorable for RWH practices, and these areas are predominantly located in the northern and southwestern sectors of the district.

6.3.1.4 Drainage Density

The drainage density within the geographic confines of the Birbhum district exhibits considerable variability, ranging from a minimum threshold of 0 to a maximum of 44 kilometers per square kilometer, a range that is clearly illustrated in **Figure 6.5**. In order to facilitate a comprehensive understanding of this spatial variation in drainage density, the corresponding drainage density map has been systematically categorized into a total of five distinct divisions or classifications. Notably, regions characterized by low drainage density, which is defined as being within the range of 0 to 6.1 kilometers per square kilometer, have been identified as particularly suitable for the implementation of rainwater harvesting (RWH) strategies, and these areas are predominantly located in the northern and western parts of the district, along with certain isolated sections scattered throughout the area. Conversely, areas that exhibit a high drainage density, specifically within the range of 29 to 44 kilometers per square kilometer, are indicative of a diminished feasibility for effective rainwater harvesting initiatives, and such regions have been predominantly observed in the eastern segment of the study area under consideration.



6.3.1.5 Distance from River

The values representing distances from river exhibit a comprehensive spectrum that ranges from a minimum of 0 meters to a maximum of 12,350.51 meters, thereby indicating a significant variation in proximity to this vital water source. The distance from river is visually represented in the accompanying map (**Fig 6.6**), which has been systematically categorized into five distinct classes based on the varying degrees of distance from the river. Specifically, regions characterized by considerable distances from the river, measured between 0 and 2470.11 meters, demonstrate a high degree of suitability for the implementation of rainwater harvesting practices, thereby facilitating optimal utilization of this natural resource. Conversely, regions that are situated at closer proximities to the river exhibit a reduced level of suitability for rainwater harvesting initiatives.

6.3.1.6 Soil

Clay, silty clay, clayey loam, silty clayey loam, sandy clayey loam, loam, silty loam, sandy loam are among the soil types shown in the map (**Fig. 6.7**). Loam soil was found most suitable for rain water harvesting, as these soils are characterized by a balanced mixture of sand, silt, and clay which offer a combination of permeability and water-holding capacity that is ideal for capturing and storing rainwater (Dlapa et al., 2020). This makes them particularly suitable for agricultural and environmental applications where water conservation is critical. These types of soils are particularly observed in the western areas of the district of Birbhum.

6.3.1.7 Land Use Land Cover (LULC)

The cartographic representation of land use and land cover, commonly referred to as LULC, as illustrated in **Fig 6.8** pertaining to the district of Birbhum, has been systematically classified into a total of six distinct categories, which encompass agriculture, built-up environments, fallow land, various types of vegetation, as well as water bodies and wetlands. In this context, it is noteworthy to mention that water bodies, wetlands, and built-up regions exhibit a significantly higher degree of suitability for the implementation of rainwater harvesting techniques; conversely, areas dominated by vegetation tend to demonstrate a comparatively lower level of appropriateness for such rainwater harvesting practices.

6.3.1.8 NDVI

The construction of a Normalized Difference Vegetation Index (NDVI) map was undertaken for the geographical of Birbhum. The range of NDVI values identified in this analysis spans from a minimum of -0.26 to a maximum of 0.10, as illustrated in **Figure 6.9**, thereby providing a comprehensive visualization of the variability in vegetation



across the region. It is important to note that lower NDVI values are indicative of an increased potential for the implementation and efficiency of rainwater harvesting systems, while conversely, higher NDVI values suggest a decreased feasibility for such practices. In the context of this research endeavor, the NDVI values were systematically categorized into five distinct classes, which vary significantly from -0.26 to 0.58, thereby facilitating a more intricate and nuanced spatial understanding.

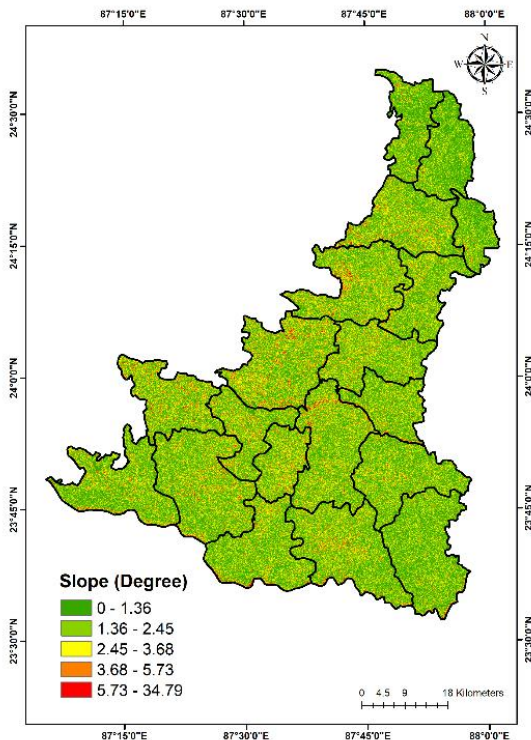


Fig. 6.2 Slope of the Study Area

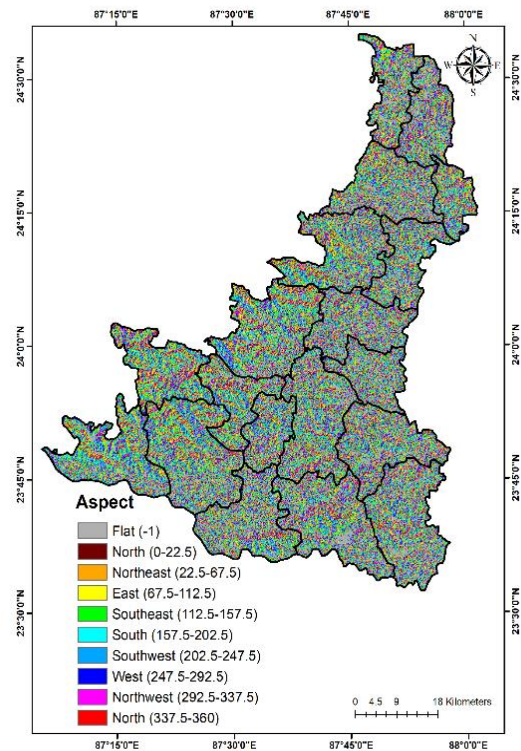


Fig. 6.3 Aspect of the Study Area

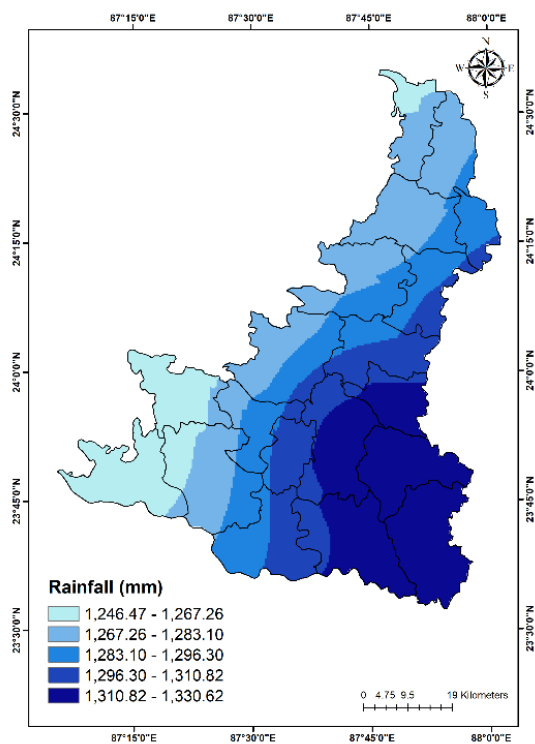


Fig. 6.4 Average rainfall in the study area

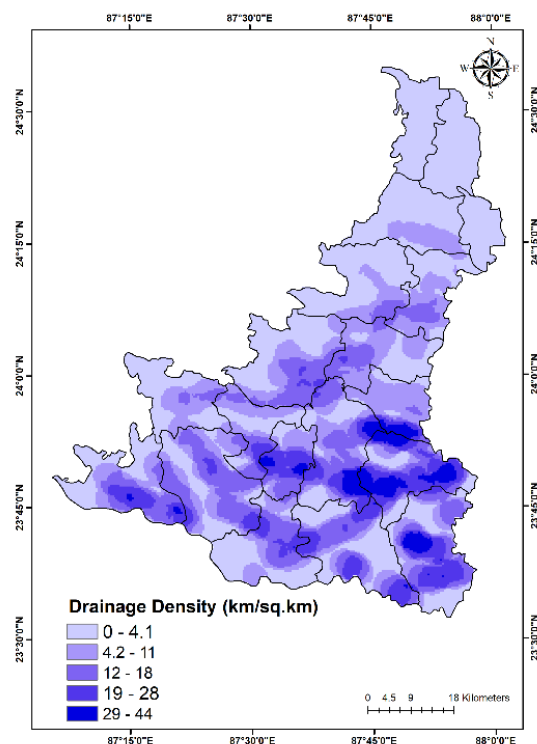


Fig. 6.5 Drainage Density of the study area

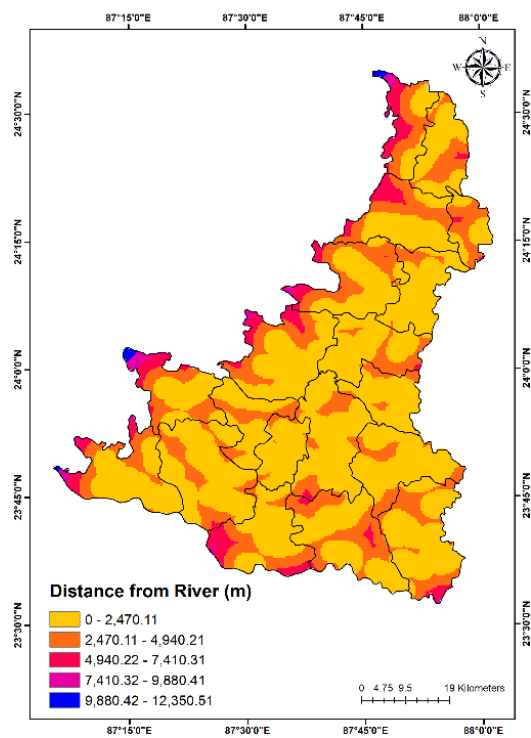


Fig. 6.6 Distance from River in the Study Area

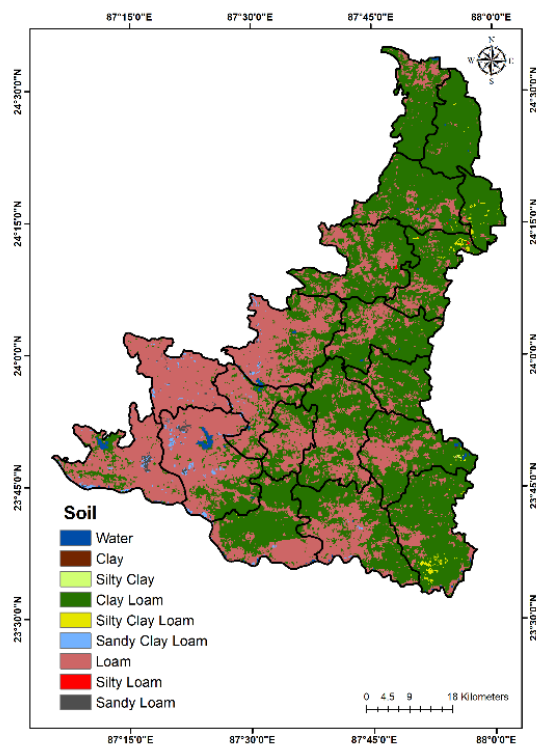


Fig. 6.7 Soil of the Study Area

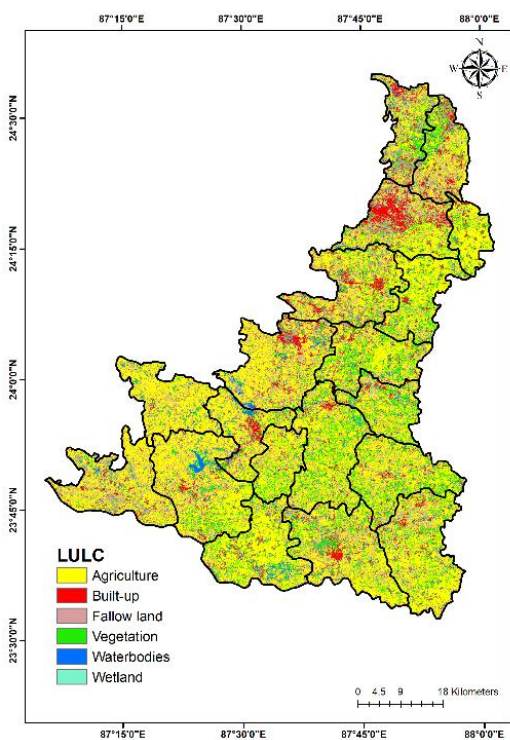


Fig. 6.8 LULC of the Study Area

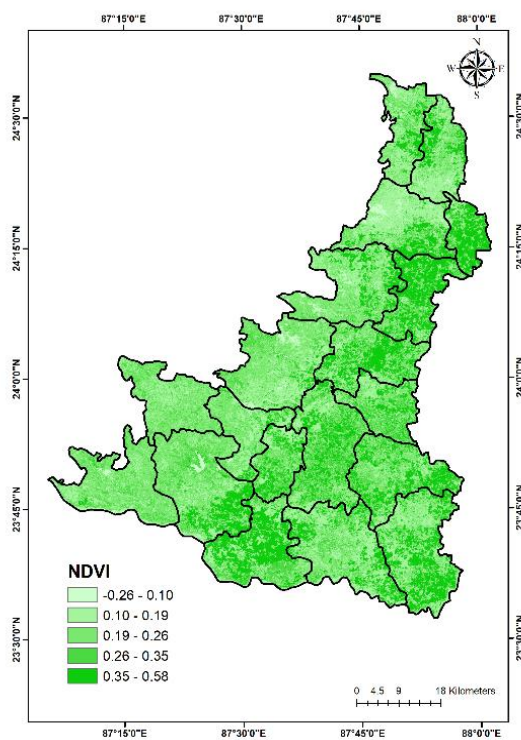


Fig. 6.9 NDVI of Study Area



Table 6.5 Pairwise comparison matrix

	R	S	DD	DR	A	LULC	SO	NDVI
R	1.00	2.00	2.00	3.00	6.00	5.00	6.00	6.00
S	0.50	1.00	2.00	2.00	3.00	6.00	5.00	5.00
DD	0.33	0.50	1.00	2.00	2.00	3.00	6.00	6.00
DR	0.25	0.33	0.50	1.00	2.00	3.00	6.00	6.00
A	0.20	0.25	0.33	0.50	1.00	2.00	3.00	3.00
LULC	0.17	0.20	0.25	0.33	0.50	1.00	2.00	2.00
SO	0.17	0.17	0.20	0.25	0.33	0.50	1.00	2.00
NDVI	0.14	0.14	0.17	0.20	0.25	0.33	0.50	1.00
sum	2.76	6.59	6.45	9.28	13.08	18.33	25.5	27

Table 6.6 Normalized Pairwise Matrix

	R	S	DD	DR	A	LULC	SO	NDVI
R	0.36	0.44	0.31	0.32	0.30	0.27	0.23	0.22
S	0.18	0.22	0.31	0.22	0.23	0.22	0.20	0.19
DD	0.12	0.11	0.16	0.22	0.15	0.16	0.16	0.15
DR	0.09	0.07	0.08	0.11	0.15	0.16	0.16	0.15
A	0.07	0.05	0.05	0.05	0.08	0.11	0.12	0.11
LULC	0.07	0.04	0.04	0.04	0.04	0.06	0.08	0.08
SO	0.06	0.04	0.03	0.02	0.02	0.02	0.03	0.07
NDVI	0.05	0.03	0.02	0.02	0.01	0.01	0.01	0.03



Table 6.7 Determined relative criteria weights

	R	S	DD	DR	A	LULC	SO	NDVI	Criteria weights
R	0.36	0.44	0.31	0.32	0.30	0.27	0.23	0.22	0.3062
S	0.18	0.22	0.31	0.22	0.23	0.22	0.20	0.19	0.2213
DD	0.12	0.11	0.16	0.22	0.15	0.16	0.16	0.15	0.1538
DR	0.09	0.07	0.08	0.11	0.15	0.16	0.16	0.15	0.1213
A	0.07	0.05	0.05	0.05	0.08	0.11	0.12	0.11	0.0800
LULC	0.07	0.04	0.04	0.04	0.04	0.06	0.08	0.08	0.0562
SO	0.06	0.04	0.03	0.02	0.02	0.02	0.03	0.07	0.0362
NDVI	0.05	0.03	0.02	0.02	0.01	0.01	0.01	0.03	0.0250



Table 6.8 Influence percentage for the factors

Factors	Criteria weights	(Influence)%
R	0.3062	30.62
S	0.2213	22.13
DD	0.1538	15.38
DR	0.1213	12.13
A	0.0800	8.00
LULC	0.0562	5.62
SO	0.0362	3.62
NDVI	0.0250	2.50

Table 6.9 Consistency check of the AHP model

λ_{max}	n	RCI	CI	CR	Consistency Check	Remark
8.53	8	1.41	0.075	0.053	CR<0.1 (Yes)	Consistency is Acceptable



Table 6.10 Ranks and weights assigned for the factors of Rainwater Harvesting Mapping using AHP

SL No	Parameters	Rank	Normalized weight	Sub -Parameters	Area Cover (%)	Rank	Normalized weight	Harvesting Classes
1	Rainfall	7	30.62	1246.47-1267.26	12.87	5	6.29	Very High
				1267.27-1283.10	26.75	4	9.95	High
				1283.10-1296.30	19.93	3	16.16	Moderate
				1296.30-1310.82	16.85	2	25.80	Low
				1310.82-1330.62	25.59	1	41.80	Very Low
2	Slope	8	22.13	>1.36	37.23	1	5.27	Very Low
				1.37 – 2.46	35.52	2	8.11	Low
				2.47 – 3.68	19.59	3	16.80	Moderate
				3.69 – 5.73	6.73	4	28.53	High
				5.74- 36.8	0.93	5	43.29	Very high
3	Drainage Density	5	15.38	> 6.1	46.33	5	41.09	Very high
				6.2 – 11	23.82	4	26.85	High
				12 -18	19.08	3	16.31	Moderate
				19 -28	9.40	2	10.96	Low
				29 - 44	3.37	1	6.79	Very low
4	Distance from River	4	12.13	> 2470.11	35.39	1	42.77	Very low
				2470.11 – 4940.21	31.35	2	26.75	Low
				4940.22 – 7410.31	21.60	3	15.66	Moderate
				7410.32 – 9880.41	9.08	4	9.21	High
				9880.42 – 12350.51	2.59	5	5.62	Very high
5	Aspect	6	8.00	Flat (-1)	11.06	5	26.72	Moderate
				North > 22.5	11.01	10	18.69	Very High
				Northeast (22.5-67.5)	10.56	4	16.59	Low
				East (67.5-112.5)	10.41	3	11.15	Low
				Southeast (112.5-157.5)	10.34	2	8.57	Very low
				South (157.5-202.5)	9.72	1	6.50	Very low
				Southwest (202.5-247.5)	9.72	7	5.10	High
				West (247.5-292.5)	9.71	8	3.75	High
					8.76	6	2.81	Moderate



				Northwest (292.5-337.5)	8.70	9	2.11	Very high
				North (337.5-360)				
6	Land Use and Land Cover	2	5.62	Agriculture	51.81	2	6.37	Low
				Built-up	7.46	4	17.03	Moderate
				Fallow land	19.21	3	9.76	Low
				Vegetation	15.74	1	3.80	Very Low
				Water bodies	3.15	6	37.74	Very High
				Wetlands	2.63	5	25.30	High
7	Soil Texture	3	3.62	Water	0.50	9	29.64	Very high
				Clay	0.01	2	21.02	Very low
				Silty Clay	0.01	5	15.16	Moderate
				Clay Loam	56.79	1	10.52	Very low
				Silty Clay Loam	0.32	3	8.37	Low
				Sandy Clay Loam	0.67	7	5.87	High
				Loam	41.41	8	6.12	High
				Silty Loam	0.02	4	3.12	Low
				Sandy Loam	0.26	6	2.18	Moderate
8	Normalized Difference Vegetation Index	1	2.50	-0.27 – 0.11	2.24	5	41.65	Very High
				0.11 – 0.21	26.27	4	26.20	High
				0.21 – 0.26	36.83	3	16.08	Moderate
				0.27 – 0.36	18.94	2	9.84	Low
				0.37 – 0.59	19.72	1	6.23	Very low

6.3.2 Rainwater Harvesting map

Prior to the comprehensive creation of the ultimate rainwater harvesting map, it was imperative to measure the consistency ratio (CR) for each parameter layer, along with their respective sub-layers, to ensure the reliability of the data. It was duly noted that the judgment matrices attained a commendably satisfactory level of consistency, as indicated by a value of less than 0.10, thereby validating the robustness of the assessments conducted. Consequently, the eight reclassified layers that represent various rainwater harvesting parameters were systematically amalgamated into a Geographic Information System (GIS) platform, employing their designated weights to facilitate a precise integration process. Thus, the final rainwater harvesting map was generated by synthesizing the factor weight and class weight values which were obtained through the rigorous application of the Analytic Hierarchy Process (AHP), utilizing raster calculations enabled by advanced GIS software. In the context of this research endeavor, the allocation



of weights for the purpose of formulating the rainwater harvesting map specific to the Birbhum district was delineated as follows: rainfall was assigned a weight of 30.62%, slope received a weight of 22.13%, drainage density was allocated a weight of 15.38%, distance from the river was given a weight of 12.13%, aspect was designated a weight of 8%, land use and land cover (LULC) was assigned a weight of 5.63%, soil characteristics received a weight of 3.61%, and the normalized difference vegetation index (NDVI) was assigned the lowest weight of 2.5%. Furthermore, the consistency ratio was determined to be acceptable, falling below the threshold value of 0.1, specifically yielding a CR of 0.053, as presented in Table 6.8, which signifies a consistent judgment process and the establishment of tolerable weights.

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, as illustrated in **Table 6.10**. 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.

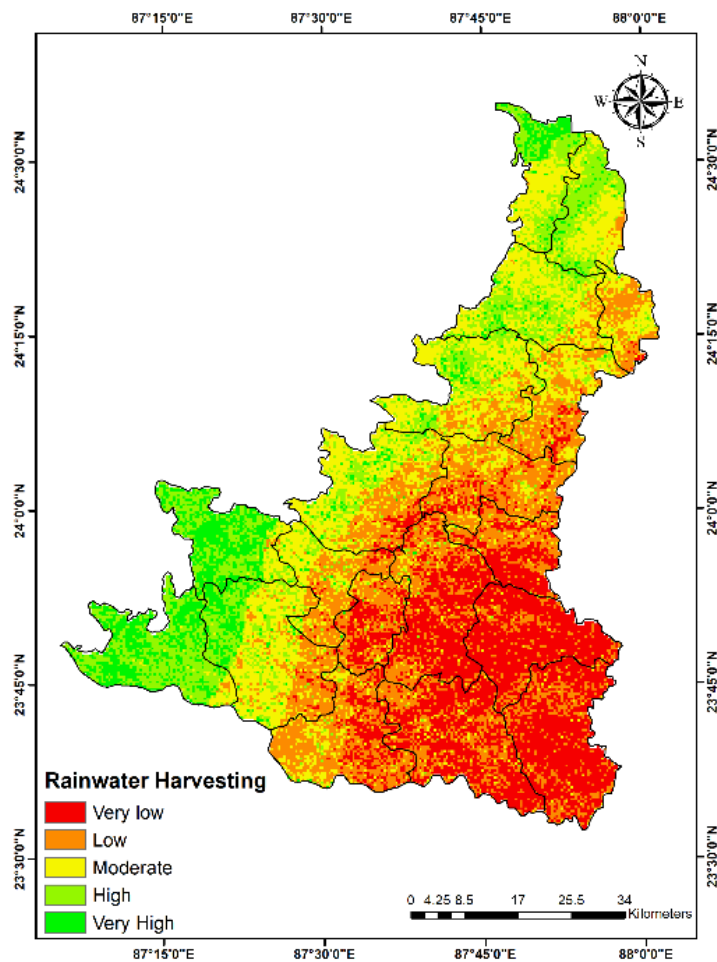


Fig. 6.10 Rainwater Harvesting (RWH) map



Table 6.11 Class-wise area cover for the RWH

SL NO	CLASS	Area in sq.km	Area in %
1	VERY LOW	647.64	23.27
2	LOW	750.69	26.97
3	MODERATE	676.44	26.30
4	HIGH	463.5	16.65
5	VERY HIGH	246.98	8.80

6.3.3 Surface water mapping

In the district of Birbhum, comprehensive surface water maps were developed in a systematic two-phase approach, with the initial phase encompassing the entire geographic area of the district, followed by a more focused second phase that specifically targeted regions characterized by the presence of waterbodies that exceed a minimum size threshold of 0.1 hectares. Upon careful examination and analysis of these maps, it becomes evident that there exists a substantial concentration of waterbodies distributed throughout the entirety of the district, indicating a rich hydrological landscape. The geo-spatial analysis derived from the mapped data reveals that the total cumulative area occupied by these various waterbodies extends impressively over a grand total of 9000 hectares, with the precise figure amounting to 9107 hectares, thus underscoring the significant aquatic resources within the district. Furthermore, it has been noted that water bodies exhibiting dimensions greater than 30 meters by 30 meters in surface area are notably prevalent in specific administrative blocks such as Khoirasole, Rampurhat I, and Suri II, thereby highlighting the uneven distribution of these hydrological features within the district's varied topography.

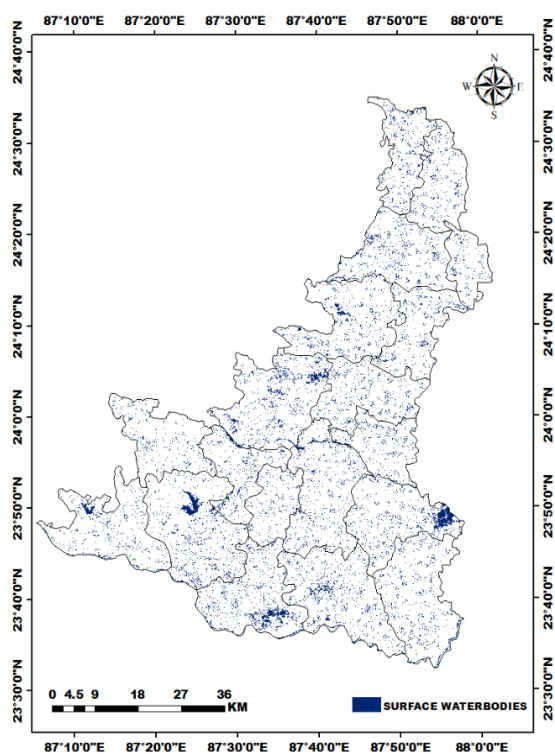


Fig. 6.11 Surface waterbodies of Birbhum

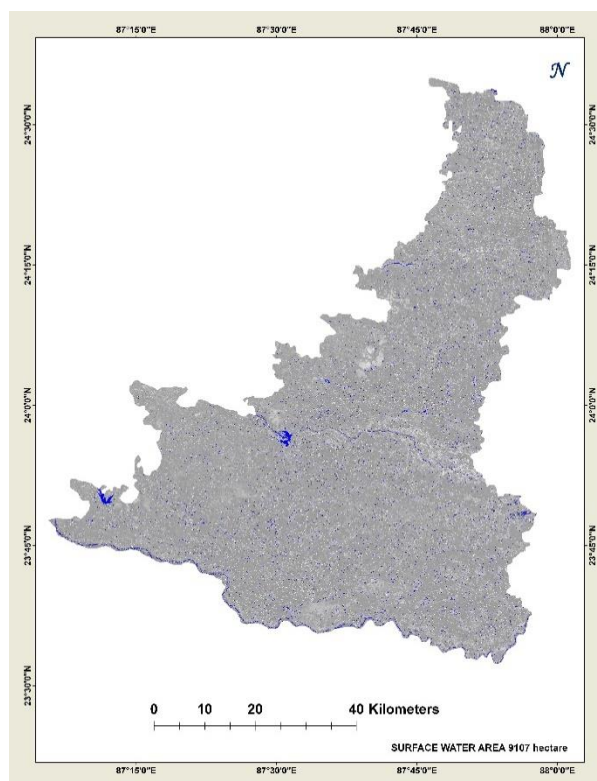


Fig. 6.12 Surface water bodies >0.1 hectares



6.3.4 Land Use change maps

Land use change patterns, which are critical for understanding the dynamics of environmental and socio-economic interactions, have been illustrated in the accompanying maps (Fig. 6.13-6.15), while the specific variations and transformations associated with these land use changes have been thoroughly cataloged and presented in Table 6.11 for comprehensive analysis. It is imperative to highlight that the Land Use Land Cover (LULC) maps have been systematically categorized into five predominant classes, which include agricultural land, built-up areas, fallow land, vegetation, as well as water bodies and wetlands, thereby facilitating a nuanced examination of land use trends. Between the years spanning from 2000 to 2010, there has been a marginal yet notable increase in built-up areas, quantified to be less than 2 percentage points, which indicates a gradual urbanization process. In a similar vein, comparable trends have been documented concerning agricultural land, which has exhibited a slight decline, approximating nearly 2 percentage points, thus reflecting shifts in land utilization priorities. Conversely, the remaining land use classes have only demonstrated minimal fluctuations, which may suggest relative stability in those categories. Nevertheless, a significant transformation in land use patterns can be distinctly observed within the temporal framework of 2010 to 2023, marking a period of pronounced change. During the previous decade, there has been a substantial reduction in agricultural land, which has decreased by approximately 5 percentage points, while water bodies have similarly diminished by 6 percentage points, indicating a concerning trend of resource depletion. However, the most drastic alterations have been recorded in vegetation cover, which has experienced a staggering decline of nearly 16 percentage points, underscoring the detrimental impacts of anthropogenic activities on natural ecosystems. In stark contrast, the built-up area has witnessed a remarkable expansion, with a documented increase amounting to 17 percentage points, suggesting a vigorous construction boom within the district that has had far-reaching consequences for the existing vegetation cover. The data implies that this unprecedented surge in built-up areas has predominantly occurred at the expense of vegetation, which has suffered significantly due to adverse human interventions and development practices. From an analytical perspective, the maps indicate an overarching increase in built-up areas throughout the district; however, traditional zones characterized by high human habitation, such as Suri and Rampurhat, exhibit a notably higher rate of urban expansion. The increased built-up areas within blocks such as Md. Bazar, Khoyrasole, and certain parts of Dubrajpur and Suri can be directly attributed to the region's coal mining activities. Similarly, the presence of stone quarries in blocks such as Rampurhat I, Nalhati I, and portions of Mayureshwar I has contributed to the concentration of built-up areas in these particular regions, illustrating the complex interplay between resource extraction and land use development.

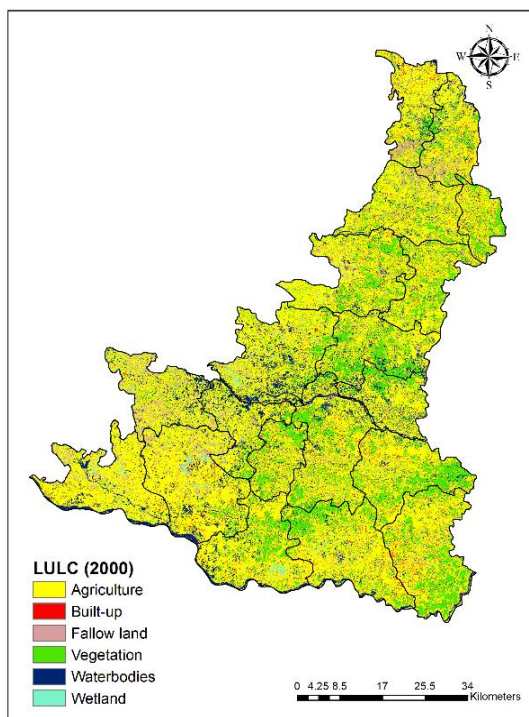


Fig. 6.13 LULC map, 2000

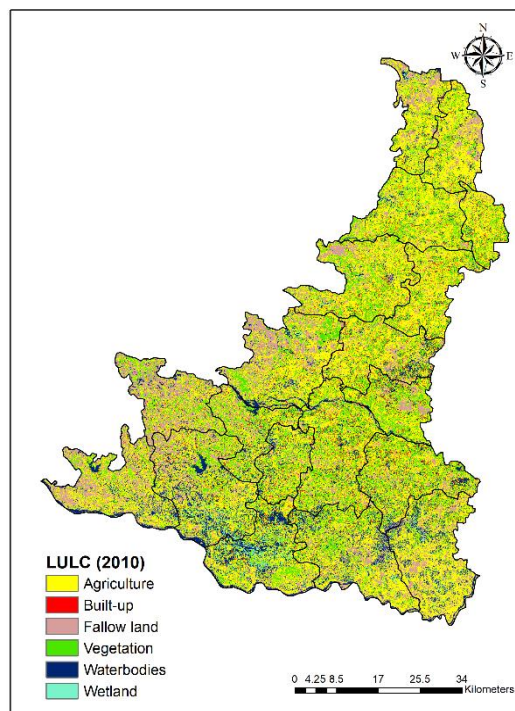


Fig. 6.14 LULC map, 2010

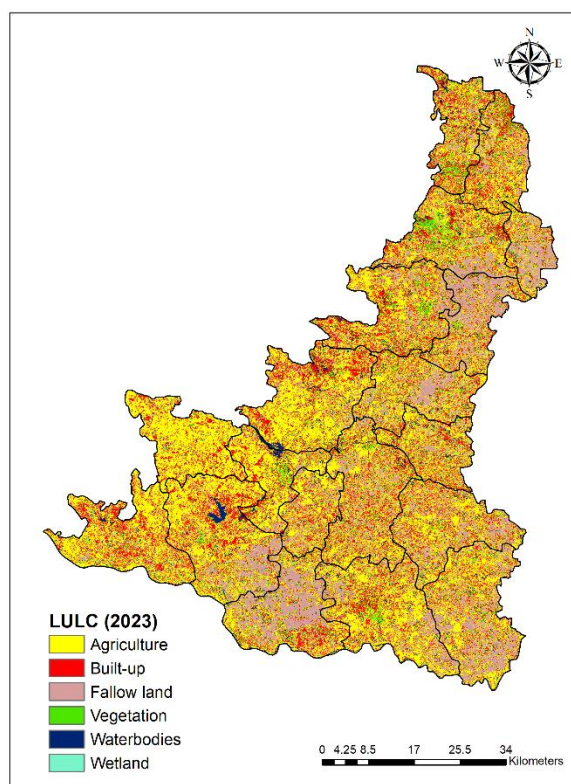


Fig. 6.15 LULC Map, 2023



Table 6.12 Land Use patterns segregated across classes for the years 2000, 2010 and 2023

Year	Class_Name	Area (sq.km)	Percentage (%)
2000	Agriculture	240566.02	49.53
	Built-up	12908.34	2.66
	Fallow land	78697.48	16.20
	Vegetation	93992.29	19.35
	Waterbodies	46745.1	9.62
	Wetland	12773.67	2.63
2010	Agriculture	215544	47.59
	Built-up	18590.7	6.10
	Fallow land	77047.1	17.01
	Vegetation	87420.9	19.30
	Waterbodies	42545.8	9.39
	Wetland	11761.5	2.60
2023	Agriculture	195073.74	42.98
	Built-up	97009.63	21.37
	Fallow land	106919.01	23.56
	Vegetation	30866.31	6.80
	Waterbodies	13768.11	3.03
	Wetland	10272.07	2.26

6.4 Discussions

The presence of fluoride concentrations that exceed the legally mandated limits within groundwater sources has emerged as a significant public health concern, particularly within the context of the Global South, where a considerable proportion of the population inhabiting these socio-economically disadvantaged regions relies heavily on groundwater



resources to satisfy their essential water requirements for daily living. Comprehensive research has established that a substantial segment of the population residing in the Birbhum district is subjected to heightened health risks associated with the consumption of groundwater that is contaminated with fluoride, which poses serious threats to their overall well-being. This issue is particularly alarming when considering that children, who are still in their developmental stages, are especially vulnerable to the dental and skeletal deformities that can result from exposure to fluorosis, a condition directly linked to elevated fluoride levels.

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, as illustrated in Table 6.10. Consequently, it can be inferred that nearly half of the total area encompassed within the district possesses the inherent potential to develop and implement effective and sustainable RWH systems. Moreover, as depicted in figure 6.10, it becomes evident that nearly the entirety of the area classified within the aforementioned categories occurs predominantly within the western, south-western, and north-western blocks of the district, specifically in regions such as Khoyrasole, Mohammad Bazar, Rajnagar, Dubrajpur, Nalhati I, Rampurhat I, Murarai I, as well as discrete northeastern blocks including Murarai II. Additionally, certain portions of Suri I are also identified as being conducive to the implementation of RWH systems. These specific blocks collectively constitute nearly the entire spatial extent of the areas that are adversely affected by fluoride contamination within the Birbhum district. Furthermore, it is noteworthy that a significant portion of these blocks experiences water stress as a direct result of the prevailing semi-arid climatic conditions. As a direct consequence of this water scarcity, the local populace is compelled to consume and utilize water that is contaminated with fluoride for their daily activities, thereby leading to both oral and dermal ingestion of excessive fluoride levels. The intersection of fluoride contamination and water stress is particularly pronounced in northern Birbhum, specifically within the blocks of Murarai, Rampurhat, and Nalhati, where the dependency on groundwater resources is at its highest. The phenomenon of over-extraction of groundwater has resulted in a lowered water table, consequently increasing the concentration of fluoride as the water remains in contact with fluoride-rich minerals for extended periods (*Mukherjee et al., 2020*). To provide a concrete example, groundwater levels in Murarai have experienced a significant decline of 4.0 m over the temporal span from 2010 to 2015, which correlates with a notable 30% increase in fluoride levels (*CGWB, 2020*). In a similar vein, Rampurhat I has recorded a decline in groundwater levels of 2.8 m, alongside an increase in mean fluoride content from 1.9 mg/L to 2.4 mg/L (*PHED, 2018*). Naturally, these regions have been identified in the current research as being at high health risks due to the consumption of water that contains fluoride concentrations exceeding statutory safety levels. Therefore, it is posited that the implementation of Rain Water Harvesting practices should be aggressively pursued in these critical regions to provide safe and potable water to the affected population. Furthermore, the Central Ground Water Board (*CGWB, 2020*) has classified the Khoyrasole and Dubrajpur blocks as being in a semi-critical condition in terms of groundwater depletion, a situation that has arisen primarily due to excessive extraction linked to intensive mono-cropping practices of paddy, thereby



further emphasizing the importance of RWH as a viable remedial solution to this multifaceted problem.

A diverse array of Rainwater Harvesting techniques has been implemented globally, functioning as an ameliorative strategy particularly in regions where the concentrations of fluoride present in groundwater exceed the permissible limits set by health and environmental standards. These systems can range from relatively simple configurations, such as rooftop rainwater harvesting systems designed for individual family units, to more intricate networks that encompass multiple large-scale collection units, which are integrated with advanced filtration and distribution systems to ensure water quality and accessibility (*Wuta et al., 2018; Qi et al., 2019; Mouhoumed et al., 2024*). The innovative "Kilimanjaro Concept," as proposed by *Qi et al. (2018)*, envisions a comprehensive network of interconnected systems capable of efficiently collecting not only rainwater but also surface runoff, thereby maximizing water resource utilization. This particular system, which has been conceptualized specifically for the East African Rift regions characterized by alarmingly high concentrations of fluoride in groundwater, could potentially serve as a model for replication in Birbhum, a region that is currently grappling with similar socio-economic challenges and constraints related to water quality. Within the district of Birbhum, there exist extensive water bodies distributed throughout the area, particularly in the fluoride-affected blocks of Khoyrasole, Suri I, and Dubrajpur, which could be strategically utilized as repositories for the collection and storage of rainwater. Given that these surface water bodies collectively cover an expansive area exceeding 9000 hectares, as illustrated in Fig. 6.12, they are ideally situated to function as natural reservoirs that can store significant volumes of water. A well-designed system may be conceptualized, as depicted in Fig. 6.15, wherein excess water from one reservoir could be directed to flow naturally into another, thereby optimizing water management and resource efficiency. Furthermore, it is imperative that each of these reservoirs is equipped with a low-cost treatment system to ensure that the water stored is of sufficient quality for direct consumption by the local population. In contexts where there exists a risk of rainwater contamination by pathogenic microorganisms, it is highly advisable to routinely heat the stored water—ideally on a weekly basis—to a temperature of approximately 80°C, maintaining this temperature for a duration of around 10 minutes, thereby effectively conducting pasteurization of the water to eliminate harmful pathogens. In such scenarios, the implementation of advanced heating systems may be considered for this purpose, leveraging renewable energy sources such as solar energy or biomass derived from rapidly growing plant species that possess favorable calorific characteristics conducive to efficient heating. To alleviate excessive costs associated with this process, the pasteurization should be strategically confined to local treatment facilities that process only a designated portion of the stored rainwater intended for distribution. With enhanced strategic efforts from government agencies, it would be feasible to lay down pipelines to facilitate the supply of this treated water to the nearest



habitations, including urban areas where the demand for clean drinking water is significantly greater than in rural regions.

On a smaller scale, the implementation of rooftop tanks can be an effective strategy for the collection and accumulation of rainwater, thereby enhancing water resource management at the individual building level. In a comprehensive study conducted by **Mukherjee and Roy (2023)** in the region known as Dakshin Gobindapur, situated in South 24 Parganas, West Bengal, it was discovered that with a cumulative rooftop area totaling an impressive 5180 sq.m, it becomes feasible to harvest nearly 4.0 million liters of water on an annual basis. Consequently, the robust and intensive development of rooftop rainwater harvesting (RWH) systems throughout the district has the potential to significantly mitigate a substantial proportion of the issues that arise from the consumption of groundwater that is contaminated with fluoride.

Managed Aquifer Recharge (MAR) represents a highly effective and scientifically validated methodology for the enhancement of groundwater levels, which is accomplished through the percolation of water that has been collected via rainwater harvesting systems, utilizing a variety of processes, including the installation of percolation tanks. Percolation tanks are engineered structures designed to capture and store rainwater efficiently, thus facilitating its gradual seepage into the subsurface soil layers. This process is critically important for the recharging of groundwater levels, a factor that is essential for ensuring a reliable water supply in arid and semi-arid regions, as emphasized by the research conducted by **Shinde et al. (2010)**. Nevertheless, the effectiveness of this method is contingent upon the specific lithological characteristics of the aquifer in question. In terrains characterized by granitic and granite-gneissic rock formations, the leaching of fluoride into the groundwater may continue unabated, even after the recharge process has been implemented, as highlighted by the findings of **Brindha and Elango (2021)**. Therefore, in the context of fluoride-affected regions within Birbhum, it is plausible that Managed Aquifer Recharge may not serve as a viable or effective policy for mitigation.

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.

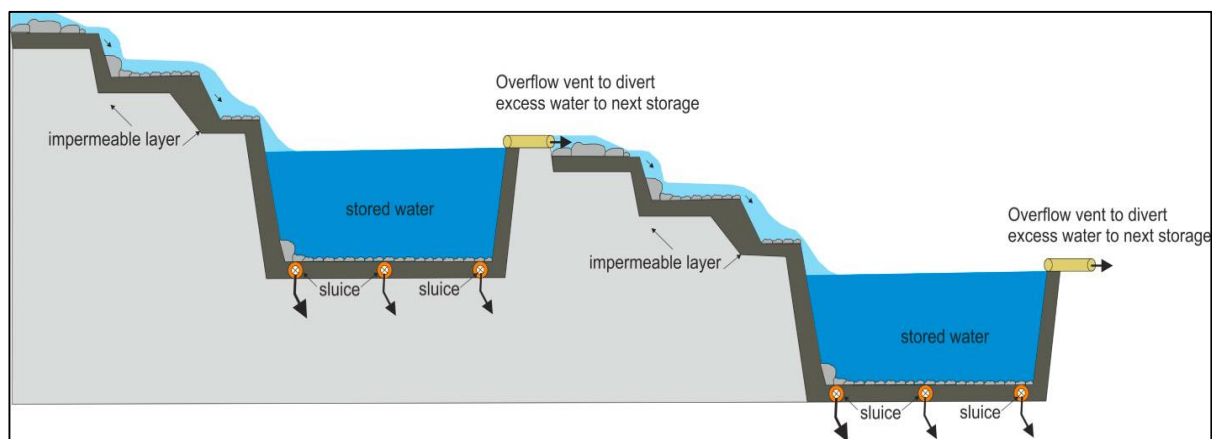


Fig. 6.16 Conceptual depiction of a system for storing rainwater/storm water
(after Qi et al.,2019)

6.5 Summary

In this particular chapter, a multitude of remedial methodologies has been comprehensively deliberated upon with the objective of formulating a suitable ameliorative strategy that aims to effectively address the pressing issue of groundwater fluoride contamination, alongside the subsequent health hazards that have been observed in the district of Birbhum. The consideration of defluoridation technologies was ultimately dismissed, primarily due to the myriad of inherent challenges associated with their implementation, particularly at the grassroots level where practical execution is crucial. Furthermore, it was observed that, given the extensive geographical expanse of the area in question, these particular technologies would not only be largely ineffective but would also incur exorbitant costs that are not justifiable. As a result of this critical analysis, rainwater harvesting emerged as the preeminent ameliorative strategy deemed most appropriate for the context. The effectiveness of rainwater harvesting within the district was examined through geospatial methodologies, utilizing the sophisticated Analytical Hierarchy Process (AHP) methodology as a guiding framework for the investigation. The findings revealed that nearly fifty percent of the spatial area within the district possesses characteristics that are conducive to the successful implementation of rainwater harvesting initiatives. Intriguingly, it was noted that the regions exhibiting fluoride contamination within the groundwater supply coincidentally align with those areas identified as being particularly effective for the application of rainwater harvesting techniques. Moreover, the existence of substantial water bodies within these specific regions presents a significant opportunity for utilizing these natural reservoirs for the purpose of storing rainwater or stormwater, which would otherwise have been lost to runoff and evaporation. In the subsequent chapter, an extensive and comprehensive conclusion summarizing the entirety of the study will be presented.



Chapter 7: Conclusions and Future Scope of Work

7.1 Preface

The present investigation was executed across three principal phases, with the overarching objective of gaining a profound understanding of the geological and geochemical factors that dictate the levels of fluoride contamination present within the groundwater of the Birbhum region, while simultaneously evaluating the potential health risks that may affect various demographic groups within the population, coupled with an analysis of the spatial and temporal fluctuations of fluoride concentration in these water sources, and ultimately, to propose relevant and actionable strategies for amelioration that could be effectively implemented at the grassroots level, thereby offering viable solutions and remedies to the communities that have been adversely impacted by this environmental issue.

7.2 Conclusions of Phase I: Geogenic controls on fluoride contamination in the groundwater

The comprehensive investigations that were carried out during the initial phase of the research endeavor have conclusively demonstrated that the granitic rocks of the Archaean Chotanagpur Granite-Gneiss formation serve as the predominant source of fluoride contamination present within the groundwater resources of the Birbhum district. An in-depth analysis of the mineralogical composition of these granitic rocks distinctly indicates the existence of a variety of minerals that are notably rich in fluoride, including, but not limited to, fluorite, apatite, and several members of the feldspar group of minerals. The predominantly alkaline character exhibited by the groundwater significantly facilitates and accelerates the leaching and subsequent dissolution of fluoride ions from these fluoride-rich minerals into the aqueous environment. Furthermore, the ionic composition of the groundwater samples unequivocally suggests that there is a dynamic interaction taking place which involves the mixing of hot, ascending waters that are enriched in fluoride with the cooler, descending meteoric waters. Additionally, the presence of deep-seated geothermal waters located in the Bakreshwar-Tantoloi hot springs not only contributes to but significantly enhances the leaching processes of fluoride from the surrounding granitic rock formations. The elevated thermal conditions characteristic of the geothermal province in question exacerbate the situation regarding fluoride contamination, as can be inferred from the exceedingly high concentrations of fluoride that have been documented in the analyses conducted on the water sourced from these hot springs. A thorough analysis of the lineament structures in the region has revealed the existence of several deep-seated fault and fracture zones that are integral to the geological framework. These geological features function as conduits, facilitating the movement and dispersion of fluoride-contaminated water throughout the various districts, with a particular emphasis on the western blocks where the density of lineaments is markedly higher. In summary, it can be conclusively inferred that the high-temperature, highly alkaline waters emanating from the Bakreshwar-Tantoloi hot springs represent the primary source of fluoride, with the fluoride-laden water being effectively circulated through the intricate pathways established by the deep-seated faults and fractures within the geological substrate. The geochemical characteristics of the water,



coupled with the geology of the region, play a pivotal role in influencing the overall dynamics and mechanisms underlying the phenomenon of fluoride contamination in this area.

7.3 Conclusions of Phase II: Spatio-Temporal Variations of Fluoride Contamination and estimation of potential Health Hazards

Detailed geo-spatial analyses, which incorporate a variety of intricate methodologies and data interpretations, reveal that the presence of fluoride contamination within the groundwater systems displays a remarkably consistent and predictable spatial distribution pattern throughout the entirety of the district of Birbhum. It has been observed that the western regions of this district demonstrate markedly elevated levels of fluoride when contrasted with their eastern counterparts, thereby signifying a distinct regional inequality. Specifically, various administrative blocks, including but not limited to Dubrajpur, Suri I and II, Khoyrasole, Rajnagar, Md Bazar, Nalhati I, and certain portions of Rampurhat I, demonstrate fluoride levels that surpass the legally established statutory limits, thereby raising concerns regarding public health and environmental quality. Through comprehensive geo-spatial analysis, it has been conclusively determined that approximately 29.89% of the total area of the district displays groundwater fluoride contamination during the pre-monsoon season, a figure that undergoes a considerable reduction, amounting to an 8 percentage point decrease, to 21.96% during the subsequent post-monsoon season. Furthermore, the mean fluoride concentration value, calculated over an extensive period stretching from 2016 to 2019, also experiences a substantial decline of 20.6 percentage points in the post-monsoon timeframe, thereby indicating a significant correlation between seasonal changes and fluoride concentration levels. This phenomenon suggests that the occurrence of rainfall plays a crucial role in the reduction of fluoride concentrations within the groundwater systems of the region, a conclusion that is further substantiated by the accompanying rainfall data which illustrates that increased rainfall correlates with a more pronounced reduction in fluoride levels in the groundwater. Consequently, it can be inferred that rainwater effectively infiltrates into the contaminated aquifers, thereby facilitating a natural process of water mixing that results in the dilution and subsequent reduction of fluoride concentration levels within these vital water resources.

Health Risk Analysis (HRA), executed in accordance with the guidelines established by the United States Environmental Protection Agency in the year 2011, elucidates the significant observation that the pediatric demographic is subject to a considerably elevated level of potential health risks that are intrinsically linked to the consumption of groundwater contaminated with fluoride, particularly when compared to the adult demographic which exhibits a comparatively lower level of risk exposure. Through the application of geo-spatial analytical techniques, it was ascertained that within the temporal framework spanning from the year 2016 to the year 2019, approximately 31.17% and 26.24% of the total geographical expanse of the district of Birbhum could, on average, be classified as high-risk zones for the child population during the pre-monsoon and post-monsoon seasons, respectively, thereby indicating a significant public health concern. In stark contrast, the data indicates that only about 6.88% and 4.92% of the geographical area may, on average, be classified as high-risk



zones for the adult population during the pre-monsoon and post-monsoon seasons, respectively, thus highlighting a pronounced disparity in risk levels between these two demographic groups. Furthermore, the aforementioned findings have been rigorously corroborated through the collection of field data that was gathered throughout the designated periods of pre-monsoon and post-monsoon in the year 2019, thereby reinforcing the validity of the initial assessments made regarding health risks associated with fluoride contamination.

7.4 Conclusions of Phase III: Remedial measures

In the aforementioned chapter, several remedial methods were investigated that could possibly alleviate the health risks arising out of the consumption of fluoride contaminated groundwater in the district of Birbhum.

De-fluoridation technologies, which encompass a variety of methods including but not limited to coagulation–precipitation, adsorption, and reverse osmosis, are frequently implemented in efforts to mitigate fluoride contamination in water sources. Among these techniques, the Nalgonda method, an indigenous and traditional coagulation–precipitation approach, is particularly prevalent and widely adopted throughout various regions of the nation. Nevertheless, it is imperative to note that the successful application of these methodologies necessitates not only precise technical expertise but also entails significant operational and maintenance costs that can be burdensome. Furthermore, one must consider the environmental implications of these techniques, as they often generate waste products, which may manifest as sludge or wastewater, leading to challenges related to disposal and the potential for soil and groundwater contamination. Consequently, when evaluated in the specific context of Birbhum, it was determined that de-fluoridation, as a remedial strategy, is ultimately unsustainable.

Rainwater harvesting (RWH), defined as the systematic collection, storage, and utilization of rainwater for various purposes including drinking and irrigation, represents a potentially effective and sustainable strategy for amelioration, particularly due to its low financial cost and the absence of additional waste generation associated with its implementation. This innovative technique has been effectively employed in several regions characterized by elevated levels of fluoride contamination, such as the East African Ridge (EAR) regions, as well as in various states across India, including Andhra Pradesh, Jharkhand, and Rajasthan, where it serves as an integrated solution to the complex challenges of water management.

A comprehensive study was conducted utilizing the Analytical Hierarchy Process (AHP) methodology, aimed at assessing the suitability of rainwater harvesting practices within the district of Birbhum. For this purpose, eight specific criteria were selected and assigned weights, leading to the construction of a suitability map for RWH based on the aforementioned analytical framework. The resulting map indicates that nearly half of the district exhibits a moderate to very high suitability for the implementation of rainwater harvesting techniques. It was particularly noted that the western blocks of Birbhum are optimally positioned for such practices. This revelation underscores the effectiveness of



RWH, as a substantial proportion of the regions adversely affected by fluoride contamination resides within the areas that are most conducive to the application of rainwater harvesting strategies. In specific locales that suffer from fluoride contamination, such as Khoyrasole, Suri I, and Suri II, large water bodies exceeding one hectare in size are already established, rendering these sites ideal for the collection and storage of rainwater. In densely populated areas like Rampurhat and Suri town, where the built environment is notably extensive, the practice of rooftop rainwater harvesting is both feasible and beneficial. Overall, it can be concluded that rainwater harvesting has emerged as the most sustainable, economically viable, and community-oriented remedial measure to effectively address the potential health risks associated with the consumption of fluoride-contaminated groundwater.

7.5 Overall conclusions

This extensive research endeavour has observed and concluded that the predominant processes of geo-genic origin are primarily accountable for the significant fluoride contamination that is manifest in the groundwater resources of the Birbhum district. The geological sources that are implicated in this phenomenon include not only the mineralogical characteristics of the host rocks but also encompass the geo-chemical properties of the water, along with the structural geological features of the underlying lithological strata, notably the deep-seated fault lines and fracture channels, which collectively exert a controlling influence over both the concentration and the mobilization dynamics of fluoride ions within the groundwater system. Furthermore, it has been identified through rigorous analysis that the Archean Chotanagpur Granite-Gneiss formation serves as the predominant source of fluoride-bearing minerals that contribute to this contamination. In the specific context of the Bakreshwar hot spring, the interaction of thermal waters, characterized by elevated temperatures, with the granite-gneissic host rock is responsible for the anomalously high concentrations of fluoride observed, a phenomenon primarily attributable to the leaching processes that occur in this geological setting. This deep-seated water or aquifer system traverses through the extensive fault and fracture zones, which can be delineated through studies of lineaments, subsequently reaching various locations across the district. Moreover, the elevated pH levels and the high sodium content present in this groundwater exacerbate the situation by facilitating the mobilization and removal of fluoride from the host rock through both weathering processes and ionic exchange mechanisms. Conversely, it has been observed that regions characterized by higher calcium concentrations and lower pH levels exhibit diminished fluoride concentrations, a pattern that is predominantly noted in the eastern and southeastern areas of the district, which are fundamentally composed of alluvial deposits from a geological perspective.

Through a comprehensive spatio-temporal analysis, it has been conclusively determined that a substantial expanse of the Birbhum district manifests fluoride concentrations in its groundwater that exceed the statutory permissible limits, indicating a significant public health concern. In particular, the western and southwestern sectors of the district are markedly affected by this pervasive issue of fluoride contamination in the groundwater resources. Additionally, it has been consistently documented that the levels of fluoride



contamination, both in terms of absolute values and in terms of the spatial extent of its distribution, tend to decrease in the post-monsoon period. Health Risk Analysis (HRA) findings elucidate that children are particularly vulnerable and at a much higher risk of experiencing potential health hazards stemming from the consumption of fluoride-contaminated groundwater, with approximately 30% of the spatial area being classified as high-risk zones. Adults, while also facing potential risks across substantial areas, experience a considerably lesser degree of contamination both in terms of absolute values and spatial extent compared to that which affects children. Overall, the highest recorded concentrations of fluoride are consistently observed in proximity to the Bakreshwar hot springs, which also serve as a compelling indicator that these springs may represent a principal source of fluoride contamination in the groundwater resources of the Birbhum district.

The method of Rainwater Harvesting (RWH) has been identified as the most effective and sustainable strategy for mitigating the health risks that are associated with the consumption of groundwater contaminated by fluoride. Through the application of the Analytic Hierarchy Process (AHP), it has been determined that the western segments of the district, which incidentally exhibit notably high levels of fluoride contamination, are optimally suited for the implementation of Rainwater Harvesting systems. The large water bodies that are present in these geographical areas may be utilized as effective repositories for the collection of rainwater, which can subsequently be used directly or blended with fluoride-contaminated water for the purposes of human consumption and hence, to ensure public health safety. Moreover, areas characterized by a greater extent of built-up are also deemed suitable for the implementation of rooftop rainwater harvesting initiatives. The establishment of rainwater repositories may not only provide a solution to the problem of fluoride contamination but may also alleviate the challenges of water scarcity during the dry seasons, particularly given that Birbhum is classified as a semi-arid region that suffers from a significant lack of adequate drinking water resources. Furthermore, the relatively low technical and capital investment required for the establishment of Rainwater Harvesting units enhances the appeal of this approach as a viable, community-driven solution to address the pressing water quality and quantity issues faced by the local population.

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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ANNEXURE A : PHED DATA

Village	Latitude	Longitude	pH	Ca	Mg	SO4	NO3	Na	K	EC	HCO3	Cl	F ⁻ (mg/l)	THQ Adult	THQ Child
JALALPUR	23.76089	87.382278	6.53	13	4.9	7	8.08	23.6	2.1	187	74.7	7.2	6.76	3.252847619	6.6924
ELEMA	23.81084	87.43969	6.53	13	4.9	15	8.08	23.6	2.1	187	74.7	7.2	3.57	1.71785	3.5343
TAPASPUR	23.81131	87.451705	6.53	13	4.9	6	8.08	23.6	2.1	187	74.7	7.2	2.25	1.082678571	2.2275
ELEMA	23.81065	87.441277	7.4	49.1	6.1	5	7.37	5.8	3.3	290	117.9	19	2.11	1.015311905	2.0889
TAPASPUR	23.81117	87.45273	6.84	10	9.1	5	5.82	8.7	8.6	163	37	28	2.06	0.991252381	2.0394
ELEMA	23.80954	87.441757	7.97	18.7	1	8	0.69	7.8	0.8	119	55.5		2	0.962380952	1.98
ELEMA	23.81097	87.43956	5.68	111.7	27.5	12	11.1	56	3.4	1120	222.2	290	1.98	0.952757143	1.9602
TAPASPUR	23.81128	87.451688	6.5	20	2.4	13.5	58.8	14.2	6.6	202	23.1	26	1.95	0.938321429	1.9305
TAPASPUR	23.81118	87.452827	6.81	42.9	16.7	7.5	0.2	33.8	1.6	496	157.6	50	1.9	0.914261905	1.881
CHHOTA SALUNCHI	23.78176	87.438042	7.8	47.1	16.4	12	13.7	28.5	23	461	143.4	47	1.83	0.880578571	1.8117
TAPASPUR	23.81116	87.452803	7.68	37.1	15.2	5	0.5	22.5	1.5	317	157.3	9.4	1.77	0.851707143	1.7523
TAPASPUR	23.81097	87.445342	5.74	4	1.7	1	8.91	1	3.1	58	12	8.2	1.74	0.837271429	1.7226
ELEMA	23.81188	87.442633	6.51	61.5	22.6	3	0.2	41.6		626	195.9	65	1.71	0.822835714	1.6929
KENDULA	23.77386	87.39909	6.51	61.5	22.6	4.8	0.2	41.6		626	195.9	65	1.64	0.789152381	1.6236
BODAKURI	23.7883	87.448161	7.46	50.1	18.2	16.5	66.5	26	3.2	433	10.8	52	1.64	0.789152381	1.6236
TAPASPUR	23.81129	87.451705	8.05	11	7.9	10	0.62	12.4	2.1	140	55.5	9.4	1.62	0.779528571	1.6038
TAPASPUR	23.81185	87.45189	7.61	20	7.3	5	0.5	10.5	0.8	178	87.9	12	1.6	0.769904762	1.584
TAPASPUR	23.81122	87.452848	8.45	51.1	17.6	14	0.5	25.5	2.9	506	196.6	33	1.58	0.760280952	1.5642
SATKENDURI (P)	23.80006	87.402124	7.64	80.2	19.4	5	1.03	30	2.9	672	85.6	125	1.4	0.673666667	1.386
ELEMA	23.81318	87.443845	6.44	58.3	32.4	21	4.25	32.6	1.7	648	198	85	1.4	0.673666667	1.386
RUPSIMULI	23.8254	87.36	7.73	21	6.5	7.5	0.5	17	1.3	262	122.6	14	1.37	0.659230952	1.3563
ASHATGANJA	23.77167	87.399812	7.53	23	27.3	5	0.5	20	1.2	440	228.9	9.4	1.35	0.649607143	1.3365
GADADHARPUR	23.88595	87.358812	7.48	100.2	59.5	36	103.1	45.5	2.8	1196	171.1	236	1.32	0.635171429	1.3068
JATRA	23.87267	87.416236	6.58	31.6	13.3	5	4.34	91.7		286	103	24	1.32	0.635171429	1.3068
GHATGOPALPUR	23.86213	87.345393	7.19	30.1	4.9	29	16.3	46.5	2.4	418	48.6	68	1.29	0.620735714	1.2771
CHANDIPUR	23.79394	87.343669	7.83	79.2	20.7	90	101.5	88.9	5.5	1395	219.7	257	1.29	0.620735714	1.2771
BUREMA	23.87802	87.346629	7.51	7	4.3	5.5	2.13	6.6	2.2	101	41.6	4.7	1.27	0.611111905	1.2573
GOURGANJA	23.87686	87.342856	7.8	59.1	12.8	15.8	10.8	23.2	3.2	535	161.9	64	1.27	0.611111905	1.2573
METEGAON	23.89082	87.403605	7.48	48.1	32.8	69	0.18	53.9	1.6	721	180.4	94	1.25	0.601488095	1.2375
GOPALNAGAR	23.84812	87.347395	7.38	158.3	45	88	147.2	47	3.6	1319	224.3	222	1.25	0.601488095	1.2375
GOURGANJA	23.87787	87.340823	7.13	27.1	8.5	11.5	80.1	40	1.3	390	64.8	50	1.24	0.59667619	1.2276
HETAMPUR	23.78235	87.398403	6.53	13	4.9	16	8.08	23.6	2.1	187	74.7	7.2	1.24	0.59667619	1.2276
GADADHARPUR	23.88515	87.358213	6.53	13	4.9	5	8.08	23.6	2.1	187	74.7	7.2	1.22	0.587052381	1.2078
ADAMPUR	23.83085	87.342582	6.53	13	4.9	14	8.08	23.6	2.1	187	74.7	7.2	1.21	0.582240476	1.1979
HARIDASPUR	23.87912	87.368565	7.4	49.1	6.1	5	7.37	5.8	3.3	290	117.9	19	1.2	0.577428571	1.188
DURLLABHPUR	23.87303	87.461801	6.84	10	9.1	5	5.82	8.7	8.6	163	37	28	1.2	0.577428571	1.188
BAKRESWAR	23.88273	87.370878	7.97	18.7	1		0.69	7.8	0.8	119	55.5		1.2	0.577428571	1.188
DHULIARA	23.86704	87.418071	5.68	111.7	27.5		11.1	56	3.4	1120	222.2	290	1.2	0.577428571	1.188
RAMPUR	23.8615	87.332049	6.5	20	2.4	13.5	58.8	14.2	6.6	202	23.1	26	0.7	0.336833333	0.693



'Integrated approach on discerning fluoride contamination mechanisms in the groundwater and formulating remedial strategies for potential health hazards in Birbhum District, West Bengal'.

SHIMULDIHI	23.74533	87.400545	6.81	42.9	16.7		0.2	33.8	1.6	496	157.6	50	0.52	0.250219048	0.5148
SHIMULDIHI	23.74529	87.401263	7.8	47.1	16.4	12	13.7	28.5	23	461	143.4	47	0.5	0.240595238	0.495
Village	Latitude	Longitude	pH	Ca	Mg	SO4	NO3	Na	K	EC	HCO3	Cl	F⁻ (mg/l)	THQ Adult	THQ Child
RAMPUR	23.85992	87.331369	5.74	4	1.7	1	8.91	1	3.1	58	12	8.2	0.29	0.139545238	0.2871
KHOJ MAHAMMADPUR	23.75078	87.42839	6.51	61.5	22.6		0.2	41.6		626	195.9	65	0.25	0.120297619	0.2475
BODHGRAM	23.69719	87.420045	6.51	61.5	22.6		0.2	41.6		626	195.9	65	0.24	0.115485714	0.2376
RAKONA	23.69678	87.490648	7.46	50.1	18.2	16.5	66.5	26	3.2	433	10.8	52	7.39	3.555997619	7.3161
GALTIA	23.70983	87.539358	8.05	11	7.9	10	0.62	12.4	2.1	140	55.5	9.4	0.49	0.235783333	0.4851
BALTA	23.77686	87.526762	7.61	20	7.3	5	0.5	10.5	0.8	178	87.9	12	0.49	0.235783333	0.4851
DAKSHIN SULTANPUR	23.70166	87.584854	8.45	51.1	17.6	14	0.5	25.5	2.9	506	196.6	33	0.44	0.21172381	0.4356
KAYERA	23.68984	87.544427	7.64	80.2	19.4	5	1.03	30	2.9	672	85.6	125	0.44	0.21172381	0.4356
TULAMARA	23.70001	87.521341	6.44	58.3	32.4		4.25	32.6	1.7	648	198	85	0.44	0.21172381	0.4356
TULAMARA	23.70054	87.521408	7.73	21	6.5	7.5	0.5	17	1.3	262	122.6	14	0.44	0.21172381	0.4356
AMLADIHI	23.721	87.575222	7.53	23	27.3	5	0.5	20	1.2	440	228.9	9.4	0.43	0.206911905	0.4257
KURMITHA	23.73676	87.519785	7.48	100.2	59.5	36	103.1	45.5	2.8	1196	171.1	236	0.43	0.206911905	0.4257
DUMRUI	23.63884	87.481642	6.58	31.6	13.3		4.34	91.7		286	103	24	0.43	0.206911905	0.4257
BALTA	23.7752	87.528765	7.19	30.1	4.9	29	16.3	46.5	2.4	418	48.6	68	0.43	0.206911905	0.4257
HALSIDANGA	23.61761	87.615631	7.83	79.2	20.7	90	101.5	88.9	5.5	1395	219.7	257	0.43	0.206911905	0.4257
CHELLA	23.62633	87.619755	7.51	7	4.3	5.5	2.13	6.6	2.2	101	41.6	4.7	0.43	0.206911905	0.4257
CHHATAR BANDI	23.71818	87.564822	7.8	59.1	12.8	15.8	10.8	23.2	3.2	535	161.9	64	0.42	0.2021	0.4158
JALALNAGAR	23.67158	87.538115	7.48	48.1	32.8	69	0.18	53.9	1.6	721	180.4	94	0.42	0.2021	0.4158
GOPINATHPUR	23.69786	87.501883	7.38	158.3	45	88	147.2	47	3.6	1319	224.3	222	0.42	0.2021	0.4158
TINOR	23.66209	87.496118	7.13	27.1	8.5	11.5	80.1	40	1.3	390	64.8	50	0.42	0.2021	0.4158
MAKRA	23.72251	87.53651	7.87	83.2	19.4	5	0.83	35	3.2	656	268.3	59	0.42	0.2021	0.4158
AMLADIHI	23.72142	87.577978	7.41	150.3	26.7	60	145.5	89.9	5	1359	134.1	290	0.42	0.2021	0.4158
BARUIPUR	23.63966	87.528832	7.69	32.1	18.2	15.5	10.2	29.5	1.5	735	185	127	0.42	0.2021	0.4158
PAYER	23.63587	87.53002	7.84	29.1	23.7	5	1.04	32	0.9	411	212.8	35	0.42	0.2021	0.4158
SUNUT	23.69196	87.475075	7.3	86.2	35.2		1.57	43	1.4	610	78.6	99	0.42	0.2021	0.4158
IKSHUSARA	23.7549	87.523605	7.66	61.1	28.6	18.5	1.51	29	6.6	600	203.5	71	0.42	0.2021	0.4158
MAHESWARPUR	23.70478	87.573495	7.43	31.1	7.3	5	2.59	20.7	0.8	268	131.8	9.4	0.42	0.2021	0.4158
DUMRUI	23.63814	87.481787	7.71	132.3	14.6	85	12.4	53.9	6.9	1487	372.3	236	0.42	0.2021	0.4158
BAGHAIPUR	23.73967	87.55846	7.95	87.2	48	38	90.9	33	2.6	897	198.9	139	0.42	0.2021	0.4158
NACHANSAHA	23.68666	87.59458	6.83	111.7	13.7		8.13	40.8	1.7	860	166.7	154	0.42	0.2021	0.4158
CHAUMANDALPUR	23.72787	87.560854	7.46	16	4.9	5	0.5	13.4	1	144	67.1	12	0.42	0.2021	0.4158
KATNA	23.69357	87.553501	7.66	24	9.1	6.3	0.5	20.5	1.5	373	189.6	12	0.42	0.2021	0.4158
KATNA	23.69324	87.55502	7.37	356.7	66.8	185	256.5	234.8	5.1	3808	344.6	790	0.42	0.2021	0.4158
HALSIDANGA	23.61455	87.610545	6.5	80.2	26.7		64.99	103.9	52.3	1085	158.1	202	0.42	0.2021	0.4158
HALSIDANGA	23.61675	87.615063	8.49	36.1	10.9	5	5.67	27	1.1	343	127.2	26	0.42	0.2021	0.4158
BILLWAMANGAL	23.66315	87.421823	7.47	157.3	9.1	82	5.28	54.9	5.7	1315	284.4	219	0.42	0.2021	0.4158
BELURI	23.66731	87.537583	7.83	28.1	8.5	7.5	7.12	25.6	1.3	379	143.4	35	0.41	0.197288095	0.4059
JALALNAGAR	23.66731	87.537583	7.83	28.1	8.5	7.5	7.12	25.6	1.3	379	143.4	35	0.41	0.197288095	0.4059
CHHATAR BANDI	23.71705	87.565635	6.94	48.6	8.3		1.3	17.3	1.3	350	176.8	7.2	0.41	0.197288095	0.4059
JALALNAGAR	23.6699	87.537632	6.94	48.6	8.3		1.3	17.3	1.3	350	176.8	7.2	0.41	0.197288095	0.4059
CHAUPAHARI JANGAL	23.61449	87.573652	7.77	19	11.5	10.8	0.87	19	1.3	334	175.8	17	0.41	0.197288095	0.4059



TINOR	23.66537	87.491793	7.68	108.2	28.6	78	96.5	110	24	1224	231.3	184	0.41	0.197288095	0.4059
BARUIPUR	23.63944	87.529957	6.92	11.33	2.9		0.33	5.6	6.2	104	40.4	7.2	0.41	0.197288095	0.4059
Village	Latitude	Longitude	pH	Ca	Mg	SO4	NO3	Na	K	EC	HCO3	Cl	F- (mg/l)	THQ Adult	THQ Child
SUNUT	23.6887	87.475347	7.87	27.1	1.8	5	0.62	15.4	0.9	206	97.1	17	0.41	0.197288095	0.4059
IKSHUSARA	23.75326	87.52383	8	35.1	11.5	5	1.06	10.2	2.7	273	131.8	19	0.41	0.197288095	0.4059
IKSHUSARA	23.75116	87.525212	7.15	44.1	6.1	23.5	6.08	58.9	2.5	501	115.6	83	0.41	0.197288095	0.4059
SALDANGA	23.65371	87.592203	8.06	22	7.3	5	8.58	9.7	1.8	202	67.1	21	0.41	0.197288095	0.4059
CHUNPALASHI	23.67268	87.543463	8.15	38.1	15.8	34.3	0.8	60.9	141	919	270.6	99	0.41	0.197288095	0.4059
PANCHRA	23.75172	87.317021	7.67	67.1	14.6	26.8	0.98	53.9	8	1059	365.4	130	7.54	3.62817619	7.4646
LAUBERE	23.7908	87.241388	8.01	43.1	41.3	5.8	8.84	27	1.5	589	254.4	57	6.64	3.195104762	6.5736
LAUBERE	23.79089	87.241492	7.77	30.1	4.3	5	5.31	10.1	2	232	94.8	14	6.09	2.93045	6.0291
LAUBERE	23.79086	87.241553	7.87	83.2	19.4	5	0.83	35	3.2	656	268.3	59	5.72	2.752409524	5.6628
LAUBERE	23.79095	87.24261	7.41	150.3	26.7	60	145.5	89.9	5	1359	134.1	290	5.59	2.689854762	5.5341
LAUBERE	23.79165	87.240858	7.69	32.1	18.2	15.5	10.2	29.5	1.5	735	185	127	4.77	2.295278571	4.7223
LAUBERE	23.79102	87.242798	7.84	29.1	23.7	5	1.04	32	0.9	411	212.8	35	4.65	2.237535714	4.6035
BARRAH	23.7918	87.168823	7.3	86.2	35.2		1.57	43	1.4	610	78.6	99	1.73	0.832459524	1.7127
PANCHRA	23.75798	87.312987	7.66	61.1	28.6	18.5	1.51	29	6.6	600	203.5	71	1.65	0.793964286	1.6335
PANCHRA	23.75134	87.317652	7.43	31.1	7.3	5	2.59	20.7	0.8	268	131.8	9.4	1.61	0.774716667	1.5939
KHAYRASOLE	23.78842	87.260849	7.71	132.3	14.6	85	12.4	53.9	6.9	1487	372.3	236	1.55	0.745845238	1.5345
KAYTHI	23.79211	87.175667	7.95	87.2	48	38	90.9	33	2.6	897	198.9	139	1.48	0.712161905	1.4652
KESE	23.84065	87.196695	6.83	111.7	13.7		8.13	40.8	1.7	860	166.7	154	1.45	0.69772619	1.4355
NINGA	23.83042	87.297897	7.46	16	4.9	5	0.5	13.4	1	144	67.1	12	1.45	0.69772619	1.4355
PURBA BORKOLA	23.7716	87.25551	7.66	24	9.1	6.3	0.5	20.5	1.5	373	189.6	12	1.44	0.692914286	1.4256
BARRAH	23.79354	87.164782	7.37	356.7	66.8	185	256.5	234.8	5.1	3808	344.6	790	1.28	0.61592381	1.2672
BATASPUR	23.83963	87.198103	6.5	80.2	26.7		64.99	103.9	52.3	1085	158.1	202	1.27	0.611111905	1.2573
LOKPUR	23.86038	87.279666	8.49	36.1	10.9	5	5.67	27	1.1	343	127.2	26	1.27	0.611111905	1.2573
BARRAH	23.7926	87.164763	7.47	157.3	9.1	82	5.28	54.9	5.7	1315	284.4	219	1.26	0.6063	1.2474
BARRAH	23.78996	87.16955	7.83	28.1	8.5	7.5	7.12	25.6	1.3	379	143.4	35	1.25	0.601488095	1.2375
BARRAH	23.79216	87.168599	6.94	48.6	8.3		1.3	17.3	1.3	350	176.8	7.2	1.25	0.601488095	1.2375
PARSUNDI	23.789	87.138532	6.94	48.6	8.3		1.3	17.3	1.3	350	176.8	7.2	1.24	0.59667619	1.2276
KAMALPUR	23.85203	87.289713	7.77	19	11.5	10.8	0.87	19	1.3	334	175.8	17	1.24	0.59667619	1.2276
PURBA BORKOLA	23.77102	87.256818	7.68	108.2	28.6	78	96.5	110	24	1224	231.3	184	1.22	0.587052381	1.2078
JAHDIPUR	23.85337	87.260274	6.92	11.33	2.9		0.33	5.6	6.2	104	40.4	7.2	1.21	0.582240476	1.1979
ALIAT	23.8763	87.2805	8.8	12	7.3		0.29	46.9	16.4	317	91.8	52	1.2	0.577428571	1.188
PURBA BORKOLA	23.76922	87.261898	7.87	27.1	1.8	5	0.62	15.4	0.9	206	97.1	17	1.2	0.577428571	1.188
PURBA BORKOLA	23.76935	87.260763	8	35.1	11.5	5	1.06	10.2	2.7	273	131.8	19	1.2	0.577428571	1.188
KENDGORE	23.76904	87.264463	7.15	44.1	6.1	23.5	6.08	58.9	2.5	501	115.6	83	1.2	0.577428571	1.188
BARRAH	23.79317	87.167084	8.06	22	7.3	5	8.58	9.7	1.8	202	67.1	21	1.2	0.577428571	1.188
BARRAH	23.80028	87.165945	8.15	38.1	15.8	34.3	0.8	60.9	141	919	270.6	99	1.2	0.577428571	1.188
KARIDHA	23.84442	87.294052	7.67	67.1	14.6	26.8	0.98	53.9	8	1059	365.4	130	1.2	0.577428571	1.188
TILSHUR	23.85173	87.208722	8.01	43.1	41.3	5.8	8.84	27	1.5	589	254.4	57	1.2	0.577428571	1.188
LOKPUR	23.85931	87.284738	7.77	30.1	4.3	5	5.31	10.1	2	232	94.8	14	1.18	0.567804762	1.1682
HARIPUR	23.87648	87.29798	6.92	17.8	3.9		10.47	56	1.1	367		33	1.18	0.567804762	1.1682



'Integrated approach on discerning fluoride contamination mechanisms in the groundwater and formulating remedial strategies for potential health hazards in Birbhum District, West Bengal'.

BARRAH	23.79119	87.163475	7.35	16	5.5	5	0.44	24.7	1.8	226	71.7	24	1.1	0.529309524	1.089
PURBA BORKOLA	23.77204	87.256312	8.42	34.1	13.4	5	3.26	13.6	3.6	269	111	14	1.1	0.529309524	1.089
Village	Latitude	Longitude	pH	Ca	Mg	SO4	NO3	Na	K	EC	HCO3	Cl	F⁻ (mg/l)	THQ Adult	THQ Child
BARRAH	23.7938	87.170651	7.29	42.1	15.7		0.23	86.6	1.2	475	228.3	9.6	1.1	0.529309524	1.089
PUTKA	23.88124	87.24615	7.29	42.1	15.7		0.23	86.6	1.2	475	228.3	9.6	1.1	0.529309524	1.089
HARIEKTALA	23.81656	87.182073	7.72	45.1	7.9	8.3	0.89	29	2.4	407	159.6	33	1.1	0.529309524	1.089
KAMALPUR	23.86274	87.283766	7.9	46.1	13.4	5	0.5	24.7	1.6	426	92.5	80	1.1	0.529309524	1.089
BATASPUR	23.83756	87.199113	7.8	17	6.1	17.5	5.41	78.9	2.6	426	185	19	1.08	0.519685714	1.0692
PARSUNDI	23.79181	87.13668	8.23	59.1	8.5	18.3	3.36	50	16.5	565	256.7	26	1.08	0.519685714	1.0692
BARRAH	23.79202	87.16303	7.48	30.1	8.5	11	77.4	22.5	2.5	312	55.5	42	1.08	0.519685714	1.0692
HARIEKTALA	23.81506	87.182945	7.13	35.6	6.9		0.2	17.5	1.3	296	131.3	9.6	1.08	0.519685714	1.0692
LAUBERE	23.79192	87.242208	6.9	44.1	8.5		0.42	43.8	10.4	455	142.8	62	1.07	0.51487381	1.0593
HARIEKTALA	23.81251	87.170175	6.5	12	14.6		4.48	14	5.8	188	61.2	26	1.07	0.51487381	1.0593
AMLAKURI	23.88351	87.286343	7.43	52.1	7.9	5	1.67	22.5	0.5	384	187.3	17	1.05	0.50525	1.0395
BUDHPUR	23.87801	87.299988	7.8	82.2	23.1	20	129.5	42	1.6	607	226.6	68	1.05	0.50525	1.0395
PURBA BORKOLA	23.77215	87.259137	7.78	50.1	10.9	16.5	3.31	28	1.8	399	203.5	21	1.05	0.50525	1.0395
PARSUNDI	23.79132	87.13659	7.23	21	3.6	7.5	13	9.7	2.2	179	60.1	17	1.04	0.500438095	1.0296
BATASPUR	23.84362	87.20178	7.62	102.2	7.3	14.3	0.81	52.9	3.7	901	300.6	106	1.04	0.500438095	1.0296
AMLAKURI	23.87931	87.285977	8.1	2	1.2		0.5	9.5	3.1	63	20.4	14	1.04	0.500438095	1.0296
PARSUNDI	23.79341	87.130277	7.07	58.3	14.7		2.08	38.7	1.2	529	270.7	9.6	1.04	0.500438095	1.0296
BARRAH	23.79398	87.164695	7.07	58.3	14.7		2.08	38.7	1.2	529	270.7	9.6	1.04	0.500438095	1.0296
PANCHRA	23.75592	87.313782	7.29	80.2	18.8	19	107.5	35	5.7	735	113.3	123	1.04	0.500438095	1.0296
KAMALPUR	23.85531	87.288012	7.19	38.9	9.8		0.2	44.8	2.2	419	200	14	1.04	0.500438095	1.0296
ALIAT	23.87624	87.280517	7.19	38.9	9.8		0.2	44.8	2.2	419	200	14	1.04	0.500438095	1.0296
KHAYRASOLE	23.78891	87.260417	6.5	112.2	34		85.8	64.2	3.3	1080	91.8	240	1.02	0.490814286	1.0098
BABULJORE	23.83562	87.183647	7.5	154.3	35.2	77	102.5	101.9	3.8	1477	201.2	278	1.02	0.490814286	1.0098
BARRAH	23.79598	87.166021	7.89	88.2	17	30.8	15.3	42	1.2	682	198.9	92	1.02	0.490814286	1.0098
PARSUNDI	23.79001	87.136803	7.1	88.2	36.5		33.25	31.6	7.6	771	219.3	102	1.01	0.486002381	0.9999
PARSUNDI	23.79109	87.136673	7.62	38.1	4.3	14.8	24.2	49	0.7	423	111	47	1.01	0.486002381	0.9999
DEMURTITA	23.85112	87.295503	7.52	12	2.4	5	5.02	14.2	2	127	60.1	9.4	1.01	0.486002381	0.9999
BARRAH	23.79202	87.16453	7.81	64.1	21.9	5	2.22	31	3.1	521	231.3	38	1.01	0.486002381	0.9999
BARRAH	23.79453	87.171203	8.08	60.1	14	17.3	12.7	27.5	3.2	484	175.8	40	1.01	0.486002381	0.9999
BARRAH	23.79337	87.171811	7.79	48.1	27.9	17.8	108.4	59.9	1.9	647	189.6	61	1.01	0.486002381	0.9999
PANCHRA	23.7514	87.319676	7.3	32.1	9.7	6.5	15.9	29	1.5	292	74	47	1	0.481190476	0.99
BARRAH	23.78955	87.16656	7.78	60.1	14.6	8.8	105.3	13.8	2.4	437	106.4	47	0.99	0.476378571	0.9801
BARRAH	23.79095	87.166392	7.87	40.1	8.5	14.3	1.09	76.9	3.4	782	383.9	42	0.99	0.476378571	0.9801
ALIAT	23.8732	87.284596	7.71	124.2	42.5	87	93.3	94.9	12	1476	289.1	248	0.98	0.471566667	0.9702
PARATIA	23.8374	87.29502	8.44	50.1	16.4	14.5	94.2	31.5	1.7	487	101.8	57	0.98	0.471566667	0.9702
HARIEKTALA	23.81302	87.1706	8.58	48.1	24.3	5	2.35	44	0.7	471	235.9	17	0.98	0.471566667	0.9702
PARSUNDI	23.79305	87.131547	6.3	156.3	43.7		5.08	62.2	8.4	1253	255	240	0.97	0.466754762	0.9603
KESE	23.84048	87.197772	7.57	26.1	12.2	5	4.22	13.8	1.4	254	115.6	14	0.97	0.466754762	0.9603
NINGA	23.82889	87.295657	7.62	118.2	17	44	7.51	52.9	8.1	1051	245.1	165	0.97	0.466754762	0.9603
ALIAT	23.87372	87.284231	8.05	28.1	4.9	5	10.3	28	3.8	268	129.5	12	0.97	0.466754762	0.9603



'Integrated approach on discerning fluoride contamination mechanisms in the groundwater and formulating remedial strategies for potential health hazards in Birbhum District, West Bengal'.

BARRAH	23.79339	87.16533	6.9	144.3	43.7		25.09	142.6	8.9	1603	402.9	238	0.96	0.461942857	0.9504
PARSUNDI	23.79613	87.132558	6.6	68.1	26.7		0.95	61	3.4	738	163.2	114	0.95	0.457130952	0.9405
AMLAKURI	23.88307	87.285407	7.88	18	3.6	5	2.91	21.7	0.9	203	83.3	14	0.95	0.457130952	0.9405
BAGASHOLA	23.79573	87.28607	7.33	16	12.2	6.3	5.57	21.9	1.8	230	230	13	0.95	0.457130952	0.9405
KHAYRASOLE	23.78968	87.265477	7.5	74.1	20.7		0.72	50.9	8.2	701	173.4	112	0.95	0.457130952	0.9405
BARRAH	23.78948	87.169277	7.99	40.1	20.7	6	1.36	32.5	0.9	456	231.3	19	0.94	0.452319048	0.9306
PARSUNDI	23.78702	87.13977	7.77	40.1	15.2	5	1.03	24	1.2	332	166.5	12	0.94	0.452319048	0.9306
PARSUNDI	23.7916	87.135623	6.8	20	4.9		17.27	44.8	1	312	81.6	38	0.94	0.452319048	0.9306
PARSUNDI	23.79617	87.13243	7.72	110.2	22.5	17.8	5.81	58.9	4.4	1037	245.1	156	0.94	0.452319048	0.9306
BARRAH	23.79538	87.160097	6.8	60.1	19.4		10.36	32.6	3.2	566	153	76	0.94	0.452319048	0.9306
BARRAH	23.79504	87.169298	8.2	36.1	18.2	5	0.62	50	6.2	441	238.2	12	0.94	0.452319048	0.9306
BARRAH	23.79572	87.170129	6.61	34.5	9.2	21	0.94	9.8	2.9	295	112	26	0.94	0.452319048	0.9306
BARRAH	23.78987	87.165767	6.82	56.1	9.2	42	1.08	43.8	19	558	252	25	0.94	0.452319048	0.9306
BARRAH	23.79165	87.166602	7.64	32.1	1.8		0.5	20	1.3	262	129.5		0.94	0.452319048	0.9306
BARRAH	23.78745	87.148446	7.66	45.1	8.5	5	128.3	26.5	1.2	366	157.3	26	0.94	0.452319048	0.9306
PARATIA	23.83734	87.294983	7.5	60.1	26.7		1.25	50.9	2.6	554	316.2	19	0.94	0.452319048	0.9306
PARATIA	23.83664	87.294667	6.8	60.1	17		5.02	32.6	1.5	528	158.1	74	0.94	0.452319048	0.9306
ISLAMKURI	23.81744	87.195395	6.8	8	6.1		5.37	5.37	1	105	51	7.1	0.87	0.418635714	0.8613
JAHDIPUR	23.83837	87.25693	7.55	40.1	17	5	0.5	4.7	1.7	355	189.6	12	0.86	0.41382381	0.8514
BABULJORE	23.8361	87.180633	7.65	106.2	16.4	11.5	0.62	60.9	4.5	938	349.2	99	0.86	0.41382381	0.8514
PARSUNDI	23.79206	87.133092	6.92	17.8	3.9		10.47	56	1.1	367		33	0.86	0.41382381	0.8514
KESE	23.84065	87.196775	7.35	16	5.5	5	0.44	24.7	1.8	226	71.7	24	0.86	0.41382381	0.8514
BARRAH	23.79366	87.168962	8.42	34.1	13.4	5	3.26	13.6	3.6	269	111	14	0.85	0.409011905	0.8415
HARIEKTALA	23.80657	87.186895	6.87	84.2	13.4	66	132.2	87.6	8.5	1025	200	101	0.85	0.409011905	0.8415
AMLAKURI	23.87973	87.285315	7.29	42.1	15.7		0.23	86.6	1.2	475	228.3	9.6	0.84	0.4042	0.8316
PARSUNDI	23.7943	87.131422	7.29	42.1	15.7		0.23	86.6	1.2	475	228.3	9.6	0.84	0.4042	0.8316
BABULJORE	23.8367	87.175383	7.72	45.1	7.9	8.3	0.89	29	2.4	407	159.6	33	0.84	0.4042	0.8316
HARIEKTALA	23.81493	87.175495	7.9	46.1	13.4	5	0.5	24.7	1.6	426	92.5	80	0.84	0.4042	0.8316
GOPALPUR	23.87838	87.272551	7.8	17	6.1	17.5	5.41	78.9	2.6	426	185	19	0.84	0.4042	0.8316
KESE	23.84446	87.20302	8.23	59.1	8.5	18.3	3.36	50	16.5	565	256.7	26	0.84	0.4042	0.8316
LOKPUR	23.86616	87.284867	7.48	30.1	8.5	11	77.4	22.5	2.5	312	55.5	42	0.84	0.4042	0.8316
BAGASHOLA	23.76911	87.298438	7.13	35.6	6.9		0.2	17.5	1.3	296	131.3	9.6	0.82	0.39457619	0.8118
PARSUNDI	23.79154	87.136262	6.9	44.1	8.5		0.42	43.8	10.4	455	142.8	62	0.82	0.39457619	0.8118
PARSUNDI	23.79053	87.134728	6.5	12	14.6		4.48	14	5.8	188	61.2	26	0.82	0.39457619	0.8118
PARSUNDI	23.79048	87.13855	7.43	52.1	7.9	5	1.67	22.5	0.5	384	187.3	17	0.82	0.39457619	0.8118
BARKURI	23.76369	87.320722	7.8	82.2	23.1	20	129.5	42	1.6	607	226.6	68	0.82	0.39457619	0.8118
BARRAH	23.79554	87.170642	7.78	50.1	10.9	16.5	3.31	28	1.8	399	203.5	21	0.82	0.39457619	0.8118
PANCHRA	23.75688	87.314526	7.23	21	3.6	7.5	13	9.7	2.2	179	60.1	17	0.82	0.39457619	0.8118
HARIEKTALA	23.81706	87.170845	7.62	102.2	7.3	14.3	0.81	52.9	3.7	901	300.6	106	0.82	0.39457619	0.8118
ALIAT	23.87529	87.283795	8.1	2	1.2		0.5	9.5	3.1	63	20.4	14	0.82	0.39457619	0.8118
AMLAKURI	23.879	87.286855	7.07	58.3	14.7		2.08	38.7	1.2	529	270.7	9.6	0.81	0.389764286	0.8019
PARSUNDI	23.7874	87.137213	7.07	58.3	14.7		2.08	38.7	1.2	529	270.7	9.6	0.81	0.389764286	0.8019
PARSUNDI	23.79229	87.133827	7.29	80.2	18.8	19	107.5	35	5.7	735	113.3	123	0.81	0.389764286	0.8019



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BARRAH	23.79453	87.169079	7.19	38.9	9.8		0.2	44.8	2.2	419	200	14	0.81	0.389764286	0.8019
KESE	23.84412	87.203837	7.19	38.9	9.8		0.2	44.8	2.2	419	200	14	0.81	0.389764286	0.8019
BARRAH	23.79194	87.16314	6.5	112.2	34		85.8	64.2	3.3	1080	91.8	240	0.8	0.384952381	0.792
PURSUNDA	23.75956	87.339867	7.5	154.3	35.2	77	102.5	101.9	3.8	1477	201.2	278	0.8	0.384952381	0.792
BARRAH	23.79358	87.166667	7.89	88.2	17	30.8	15.3	42	1.2	682	198.9	92	0.8	0.384952381	0.792
BIBHARPUR	23.7573	87.317359	7.1	88.2	36.5		33.25	31.6	7.6	771	219.3	102	0.8	0.384952381	0.792
BARKURI	23.76306	87.31973	7.62	38.1	4.3	14.8	24.2	49	0.7	423	111	47	0.8	0.384952381	0.792
ALIAT	23.87171	87.284146	7.52	12	2.4	5	5.02	14.2	2	127	60.1	9.4	0.8	0.384952381	0.792
BARRAH	23.79102	87.164142	7.81	64.1	21.9	5	2.22	31	3.1	521	231.3	38	0.79	0.380140476	0.7821
KHAYRASOLE	23.79034	87.269781	8.08	60.1	14	17.3	12.7	27.5	3.2	484	175.8	40	0.79	0.380140476	0.7821
DHASUNIA	23.88746	87.246484	7.79	48.1	27.9	17.8	108.4	59.9	1.9	647	189.6	61	0.79	0.380140476	0.7821
KAYTHI	23.79198	87.178745	7.3	32.1	9.7	6.5	15.9	29	1.5	292	74	47	0.79	0.380140476	0.7821
DHASUNIA	23.88917	87.249675	7.78	60.1	14.6	8.8	105.3	13.8	2.4	437	106.4	47	0.78	0.375328571	0.7722
PARSUNDI	23.79448	87.13209	7.87	40.1	8.5	14.3	1.09	76.9	3.4	782	383.9	42	0.78	0.375328571	0.7722
PARSUNDI	23.79299	87.131653	7.71	124.2	42.5	87	93.3	94.9	12	1476	289.1	248	0.78	0.375328571	0.7722
KAYTHI	23.79112	87.174225	8.44	50.1	16.4	14.5	94.2	31.5	1.7	487	101.8	57	0.78	0.375328571	0.7722
PUTKA	23.87972	87.247373	8.58	48.1	24.3	5	2.35	44	0.7	471	235.9	17	0.77	0.370516667	0.7623
PARSUNDI	23.79347	87.133755	6.3	156.3	43.7		5.08	62.2	8.4	1253	255	240	0.76	0.365704762	0.7524
BARRAH	23.79828	87.158518	7.57	26.1	12.2	5	4.22	13.8	1.4	254	115.6	14	0.76	0.365704762	0.7524
HARIEKTALA	23.81878	87.171426	7.62	118.2	17	44	7.51	52.9	8.1	1051	245.1	165	0.76	0.365704762	0.7524
PURSUNDA	23.75436	87.34823	8.05	28.1	4.9	5	10.3	28	3.8	268	129.5	12	0.75	0.360892857	0.7425
PARSUNDI	23.79103	87.136547	6.9	144.3	43.7		25.09	142.6	8.9	1603	402.9	238	0.75	0.360892857	0.7425
PARATIA	23.83736	87.296168	6.6	68.1	26.7		0.95	61	3.4	738	163.2	114	0.75	0.360892857	0.7425
ANANDANAGAR	23.85644	87.308248	7.88	18	3.6	5	2.91	21.7	0.9	203	83.3	14	0.72	0.346457143	0.7128
BUDHPUR	23.87608	87.302036	7.33	16	12.2	6.3	5.57	21.9	1.8	230	230	13	0.72	0.346457143	0.7128
KHAYRASOLE	23.79372	87.255312	7.5	74.1	20.7		0.72	50.9	8.2	701	173.4	112	0.72	0.346457143	0.7128
PANCHRA	23.75646	87.315758	7.99	40.1	20.7	6	1.36	32.5	0.9	456	231.3	19	0.72	0.346457143	0.7128
BATASPUR	23.83748	87.19907	7.77	40.1	15.2	5	1.03	24	1.2	332	166.5	12	0.72	0.346457143	0.7128
BABUJORE	23.83307	87.212552	6.8	20	4.9		17.27	44.8	1	312	81.6	38	0.72	0.346457143	0.7128
HARIEKTALA	23.81511	87.179813	7.72	110.2	22.5	17.8	5.81	58.9	4.4	1037	245.1	156	0.71	0.341645238	0.7029
BHIMGARH	23.74249	87.2801	6.8	60.1	19.4		10.36	32.6	3.2	566	153	76	0.71	0.341645238	0.7029
MAJURA	23.74475	87.32843	8.2	36.1	18.2	5	0.62	50	6.2	441	238.2	12	0.71	0.341645238	0.7029
KANKARTALA	23.7922	87.197942	6.61	34.5	9.2	21	0.94	9.8	2.9	295	112	26	0.7	0.336833333	0.693
LOKPUR	23.8597	87.284238	6.82	56.1	9.2	42	1.08	43.8	19	558	252	25	0.7	0.336833333	0.693
PARSUNDI	23.78916	87.134393	7.64	32.1	1.8		0.5	20	1.3	262	129.5		0.7	0.336833333	0.693
BARKURI	23.77196	87.331018	7.66	45.1	8.5	5	128.3	26.5	1.2	366	157.3	26	0.7	0.336833333	0.693
KHAYRASOLE	23.79164	87.256782	7.5	60.1	26.7		1.25	50.9	2.6	554	316.2	19	0.7	0.336833333	0.693
PASCHIM GOBINDAPUR	23.80517	87.764918	6.8	60.1	17		5.02	32.6	1.5	528	158.1	74	0.51	0.245407143	0.5049
PASCHIM GOBINDAPUR	23.81135	87.766948	6.8	8	6.1		5.37	5.37	1	105	51	7.1	0.5	0.240595238	0.495
GOPALPUR	23.80364	87.775989	7.55	40.1	17	5	0.5	4.7	1.7	355	189.6	12	0.5	0.240595238	0.495
KURUMBA	23.74343	87.794308	7.65	106.2	16.4	11.5	0.62	60.9	4.5	938	349.2	99	0.48	0.230971429	0.4752
KURUMBA	23.7317	87.775311	7.77	78.2	37.7	51	20.3	49	4	815	245.1	90	0.48	0.230971429	0.4752
KURUMBA	23.72914	87.776312	7.21	53.1	16.4	16.5	10.6	34	4.8	508	131.8	71	0.46	0.221347619	0.4554



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KURUMBA	23.7259	87.778864	8.1	51.1	29.2	6.3	0.8	46	6	695	314.5	47	0.46	0.221347619	0.4554
KURUMBA	23.7266	87.780023	8.41	62.1	34	7.5	1.06	80.9	3.2	488	235.9	12	0.46	0.221347619	0.4554
KUNIARA	23.83111	87.841943	7.04	48.6	13.7		0.2	46.9	2.1	475	222.2	15	0.46	0.221347619	0.4554
KURUMBA	23.72517	87.779077	6.8	32.1	12.2		16.65	50.9	1.5	446	255	50	0.45	0.216535714	0.4455
KURUMBA	23.72644	87.781473	8.26	26.1	17.6	12.5	0.5	59.9	7.3	626	321.4	21	0.45	0.216535714	0.4455
KUNIARA	23.83258	87.838781	6.46	76.2	24.3		1.22	25.9	2.3	581	209.1	78	0.45	0.216535714	0.4455
KUNIARA	23.83153	87.840838	6.94	92.2	34	56	2.33	51	4.5	942	300	104	0.45	0.216535714	0.4455
DHRUBABATI	23.78909	87.917735	7.78	158.3	15.8	65	3.05	111.9	7	1967	351.5	401	0.43	0.206911905	0.4257
GHATTOR	23.83974	87.791398	6.9	220.4	58.3		38.1	78.5	6.1	1597	413.1	261	0.42	0.2021	0.4158
KURUMBA	23.72627	87.77657	7.7	54.1	60.8	35	1.21	69.9	6.4	1029	261.3	156	0.42	0.2021	0.4158
KURUMBA	23.72571	87.776713	7.75	28.1	5.5	5	14.8	16.2	0.8	250	87.9	24	0.42	0.2021	0.4158
JAMNA	23.79563	87.918253	7.73	54.1	18.2	20.5	0.5	43	3.6	520	203.5	33	0.42	0.2021	0.4158
KURUMBA	23.72993	87.775614	8.11	150.3	45	57	64.8	143.9	2.6	1808	300.6	354	0.41	0.197288095	0.4059
KURUMBA	23.72607	87.777272	7.45	48.1	12.2	40	25.5	66.9	1.1	600	101.8	94	0.41	0.197288095	0.4059
KURUMBA	23.72583	87.778281	8.4	24	12.2		0.6	49.9	2.3	403	127.5	62	0.41	0.197288095	0.4059
PHALGRAM	23.84165	87.807933	8.08	124.2	7.3	24	0.5	50	2.2	1280	305.3	208	0.41	0.197288095	0.4059
DHRUBABATI	23.79511	87.919775	7.71	70.1	25.5	47.5	25	69.9	1.9	820	154.9	130	0.41	0.197288095	0.4059
BABNA	23.80652	87.732203	7.72	30.1	32.2	6.8	0.5	32	2	464	233.6	17	0.4	0.19247619	0.396
KURUMBA	23.72817	87.774844	7.1	132.3	51		22.62	80.5	2.2	1278	336.6	195	0.4	0.19247619	0.396
KUNIARA	23.83235	87.840615	7.1	84.2	31.6		6.6	49.9	3.7	777	234.6	109	0.4	0.19247619	0.396
PHALGRAM	23.84239	87.807585	6.69	57.7	8.7	25	0.43	24.7	3.9	528	176	55	0.4	0.19247619	0.396
DHRUBABATI	23.7904	87.924957	7.6	32.1	6.1	5	2.59	22	2.5	281	129.5	19	0.4	0.19247619	0.396
NAUTARA	23.79211	87.768966	6.25	20.8	10	45	6.08	7.3	7.6	248	49	14	0.39	0.187664286	0.3861
BABNA	23.80543	87.735653	7.55	44.1	10.9	22.5	67.9	64.9	1	572	134.1	85	0.39	0.187664286	0.3861
KURUMBA	23.72345	87.776614	7.79	48.1	27.9	17.8	108.4	59.9	1.9	647	189.6	61	0.39	0.187664286	0.3861
KURUMBA	23.7317	87.775311	7.79	48.1	27.9	17.8	108.4	59.9	1.9	647	189.6	61	0.39	0.187664286	0.3861
KUNIARA	23.83292	87.839172	6.55	9.6	4.4	4.3	5.17	18.1	0.5	164	58	14	0.39	0.187664286	0.3861
DHRUBABATI	23.79415	87.919605	7.7	44.1	18.2	18.3	6.71	35	5.8	438	175.8	26	0.39	0.187664286	0.3861
BHALAS	23.84108	87.785378	7.4	30.1	13.4		0.35	17.8	1	260	122.4	21	0.38	0.182852381	0.3762
EKUT	23.79689	87.747752	6.96	19	8.5	7.5	15.2	56.9	28	460	85.6	75	0.38	0.182852381	0.3762
KAMARMATH	23.84392	87.808022	7.78	40.1	10.9	5	0.5	20.5	1.1	338	157.3	24	0.38	0.182852381	0.3762
KURUMBA	23.72417	87.775328	7.35	53.4	11.3		0.2	110.1	2.2	813	250.5	104	0.38	0.182852381	0.3762
KURUMBA	23.72657	87.78123	8.11	25.1	11.5	6.8	0.5	51.9	4.4	405	191.9	19	0.38	0.182852381	0.3762
KUNIARA	23.83308	87.838881	7.55	98.2	7.3	37	7.13	119.9	6.6	1144	296	182	0.38	0.182852381	0.3762
DHRUBABATI	23.79645	87.918645	7.2	40.1	12.2		2.71	40.3	1.7	405	102	26	0.38	0.182852381	0.3762
BAGTOR	23.78671	87.93117	7.45	8	4.9	9.3	4.89	30	17	240	55.5	33	0.38	0.182852381	0.3762
AMNAHAR	23.75558	87.767501	7.07	40.5	33.4		0.2	60.1	2.7	728	329.3	25	0.38	0.182852381	0.3762
KURUMBA	23.72588	87.779722	7	4	4.9		0.63	20.4	9.4	146	40.8	19	0.37	0.178040476	0.3663
KUNIARA	23.82654	87.838918	7.26	32.4	14.7		0.2	96.8	2.1	588	220.2	48	0.3	0.144357143	0.297
KUNIARA	23.83128	87.840182	7.74	23.2	10.4	23	2.85	26.5	1.1	311	114	17	0.3	0.144357143	0.297
GOPALPUR	23.80285	87.775774	7.77	15	10.3	30.5	1.49	90.9	13	503	208.1	21	0.3	0.144357143	0.297
PUNNA	23.85308	87.775183	6.96	44.9	17.5	34	0.92	48.9	3.4	559	260	21	0.29	0.139545238	0.2871
GANUTIA	23.86962	87.833455	7.44	47.1	41.3	225	0.5	81.9	3.2	862	238.2	14	0.29	0.139545238	0.2871



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GANUTIA	23.86669	87.832475	7.83	37.1	9.1	93	0.5	85.9	13.6	586	201.2	17	0.29	0.139545238	0.2871
UTTAR ISHAKPUR	23.84902	87.769047	7.3	128.3	20.7		0.68	187.5	2.2	1482	438.6	221	0.29	0.139545238	0.2871
UTTAR ISHAKPUR	23.84999	87.768832	8.23	34.1	19.4	11	0.5	48	4.8	395	180.4	19	0.29	0.139545238	0.2871
TATINAPARA	23.77804	87.757422	7.39	6.5	2.9		0.2	134.5	1	402	163.6	19	0.29	0.139545238	0.2871
DANRKA	23.87206	87.813727	8.73	18	7.3	22	3.13	96.9	5.1	556	152.6	59	0.29	0.139545238	0.2871
CHHOTA GOGA	23.81501	87.79062	8.18	20	3	36.5	1.25	131.9	3.8	708	157.3	87	0.29	0.139545238	0.2871
CHHOTA GOGA	23.81675	87.793264	7.39	30.8	12.3		10.36	150.8	2.9	912	250.5	113	0.29	0.139545238	0.2871
CHAUHATA	23.85743	87.744102	7.95	19.4	6.9		0.2	218.1	6.7	1106	254.5	183	0.29	0.139545238	0.2871
CHAUHATA	23.85435	87.743341	9.62	1	2.9								0.29	0.139545238	0.2871
CHAUHATA	23.85326	87.74252	7.77	78.2	37.7	51	20.3	49	4	815	245.1	90	0.29	0.139545238	0.2871
CHAUHATA	23.85256	87.742082	7.21	53.1	16.4	16.5	10.6	34	4.8	508	131.8	71	0.29	0.139545238	0.2871
MAHODARI	23.77471	87.743176	8.1	51.1	29.2	6.3	0.8	46	6	695	314.5	47	0.29	0.139545238	0.2871
PASCHIM GAMINI	24.07454	87.7782	8.41	62.1	34	7.5	1.06	80.9	3.2	488	235.9	12	2.08	1.00087619	2.0592
GOURBAZAR	24.04555	87.774905	7.04	48.6	13.7		0.2	46.9	2.1	475	222.2	15	1.48	0.712161905	1.4652
NAMAKANDA	24.08371	87.779237	6.8	32.1	12.2		16.65	50.9	1.5	446	255	50	1.44	0.692914286	1.4256
PASCHIM GAMINI	24.07666	87.775183	8.26	26.1	17.6	12.5	0.5	59.9	7.3	626	321.4	21	1.34	0.644795238	1.3266
DABUK	24.06455	87.813349	6.46	76.2	24.3		1.22	25.9	2.3	581	209.1	78	1.28	0.61592381	1.2672
BIRAJPUR	24.09851	87.685998	6.94	92.2	34	56	2.33	51	4.5	942	300	104	0.99	0.476378571	0.9801
TALOAN	24.06847	87.780068	7.78	158.3	15.8	65	3.05	111.9	7	1967	351.5	401	0.97	0.466754762	0.9603
FATEHPUR	24.08125	87.728868	6.9	220.4	58.3		38.1	78.5	6.1	1597	413.1	261	0.94	0.452319048	0.9306
NAMAKANDA	24.08612	87.780595	7.7	54.1	60.8	35	1.21	69.9	6.4	1029	261.3	156	0.92	0.442695238	0.9108
MAJHARIPARA	24.07896	87.791357	7.75	28.1	5.5	5	14.8	16.2	0.8	250	87.9	24	0.84	0.4042	0.8316
NAMAKANDA	24.08623	87.77937	7.73	54.1	18.2	20.5	0.5	43	3.6	520	203.5	33	0.83	0.399388095	0.8217
MAJHARIPARA	24.08413	87.789827	8.11	150.3	45	57	64.8	143.9	2.6	1808	300.6	354	0.82	0.39457619	0.8118
NAMAKANDA	24.08578	87.779668	7.45	48.1	12.2	40	25.5	66.9	1.1	600	101.8	94	0.81	0.389764286	0.8019
MAJHARIPARA	24.07705	87.790713	8.4	24	12.2		0.6	49.9	2.3	403	127.5	62	0.77	0.370516667	0.7623
MAJHARIPARA	24.078	87.790667	8.08	124.2	7.3	24	0.5	50	2.2	1280	305.3	208	0.77	0.370516667	0.7623
PASCHIM GAMINI	24.07668	87.776405	7.71	70.1	25.5	47.5	25	69.9	1.9	820	154.9	130	0.63	0.30315	0.6237
SANDHIGARA	24.07748	87.798266	7.72	30.1	32.2	6.8	0.5	32	2	464	233.6	17	0.63	0.30315	0.6237
PASCHIM GAMINI	24.07761	87.774695	7.1	132.3	51		22.62	80.5	2.2	1278	336.6	195	0.62	0.298338095	0.6138
BILASPUR	24.08863	87.774105	7.1	84.2	31.6		6.6	49.9	3.7	777	234.6	109	0.61	0.29352619	0.6039
NAMAKANDA	24.08677	87.780438	6.69	57.7	8.7	25	0.43	24.7	3.9	528	176	55	0.61	0.29352619	0.6039
SANDHIGARA	24.0778	87.797863	7.6	32.1	6.1	5	2.59	22	2.5	281	129.5	19	0.61	0.29352619	0.6039
MAJHARIPARA	24.07393	87.790884	6.25	20.8	10	45	6.08	7.3	7.6	248	49	14	0.61	0.29352619	0.6039
MALLARPUR	24.08145	87.706189	7.55	44.1	10.9	22.5	67.9	64.9	1	572	134.1	85	0.61	0.29352619	0.6039
MATMAHULA	24.05348	87.682712	7.79	48.1	27.9	17.8	108.4	59.9	1.9	647	189.6	61	0.6	0.288714286	0.594
BILASPUR	24.08664	87.772915	7.79	48.1	27.9	17.8	108.4	59.9	1.9	647	189.6	61	0.59	0.283902381	0.5841
SANDHIGARA	24.07658	87.797372	6.55	9.6	4.4	4.3	5.17	18.1	0.5	164	58	14	0.58	0.279090476	0.5742
MAJHARIPARA	24.0847	87.791742	7.7	44.1	18.2	18.3	6.71	35	5.8	438	175.8	26	0.57	0.274278571	0.5643
SANDHIGARA	24.0774	87.796724	7.4	30.1	13.4		0.35	17.8	1	260	122.4	21	0.57	0.274278571	0.5643
MAJHARIPARA	24.07506	87.791728	6.96	19	8.5	7.5	15.2	56.9	28	460	85.6	75	0.57	0.274278571	0.5643
DAKSHIN GRAM	24.03447	87.812437	7.78	40.1	10.9	5	0.5	20.5	1.1	338	157.3	24	0.56	0.269466667	0.5544
RANGTARA	24.05489	87.876685	7.35	53.4	11.3		0.2	110.1	2.2	813	250.5	104	0.56	0.269466667	0.5544



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SANDHIGARA	24.07617	87.798016	8.11	25.1	11.5	6.8	0.5	51.9	4.4	405	191.9	19	0.56	0.269466667	0.5544
MAJHARIPARA	24.07357	87.792619	7.55	98.2	7.3	37	7.13	119.9	6.6	1144	296	182	0.56	0.269466667	0.5544
JHIKADDA	23.98945	87.73618	7.2	40.1	12.2		2.71	40.3	1.7	405	102	26	0.56	0.269466667	0.5544
NAMAKANDA	24.08422	87.778855	7.45	8	4.9	9.3	4.89	30	17	240	55.5	33	0.55	0.264654762	0.5445
SANDHIGARA	24.07615	87.795429	7.07	40.5	33.4		0.2	60.1	2.7	728	329.3	25	0.55	0.264654762	0.5445
PAHANA	24.03255	87.79372	7	4	4.9		0.63	20.4	9.4	146	40.8	19	0.53	0.255030952	0.5247
BILASPUR	24.08792	87.773655	7.26	32.4	14.7		0.2	96.8	2.1	588	220.2	48	0.53	0.255030952	0.5247
NANDURA	23.99685	87.690722	7.74	23.2	10.4	23	2.85	26.5	1.1	311	114	17	0.52	0.250219048	0.5148
DAKSHIN GRAM	24.03472	87.81282	7.77	15	10.3	30.5	1.49	90.9	13	503	208.1	21	0.52	0.250219048	0.5148
KAMRA	24.05453	87.770297	6.96	44.9	17.5	34	0.92	48.9	3.4	559	260	21	0.52	0.250219048	0.5148
NAMAKANDA	24.08778	87.781137	7.44	47.1	41.3	225	0.5	81.9	3.2	862	238.2	14	0.52	0.250219048	0.5148
BEGUNA	24.02036	87.823228	7.83	37.1	9.1	93	0.5	85.9	13.6	586	201.2	17	0.51	0.245407143	0.5049
MAJHARIPARA	24.08469	87.790637	7.3	128.3	20.7		0.68	187.5	2.2	1482	438.6	221	0.51	0.245407143	0.5049
NAMAKANDA	24.08529	87.779845	8.23	34.1	19.4	11	0.5	48	4.8	395	180.4	19	0.51	0.245407143	0.5049
MAJHARIPARA	24.07702	87.790699	7.39	6.5	2.9		0.2	134.5	1	402	163.6	19	0.51	0.245407143	0.5049
PATHAI	24.00623	87.675323	8.73	18	7.3	22	3.13	96.9	5.1	556	152.6	59	0.51	0.245407143	0.5049
JHIKADDA	23.98988	87.737924	8.18	20	3	36.5	1.25	131.9	3.8	708	157.3	87	0.51	0.245407143	0.5049
DANGAL	24.04675	87.726648	7.39	30.8	12.3		10.36	150.8	2.9	912	250.5	113	0.5	0.240595238	0.495
MAJHARIPARA	24.07461	87.790567	7.95	19.4	6.9		0.2	218.1	6.7	1106	254.5	183	0.5	0.240595238	0.495
BILASPUR	24.08637	87.771235	9.62	1	2.9								0.49	0.235783333	0.4851
PASCHIM GAMINI	24.07606	87.773382	7.83	28.1	8.5	7.5	7.12	25.6	1.3	379	143.4	35	0.49	0.235783333	0.4851
SABEK HARUKI	23.98723	87.71424	6.94	48.6	8.3		1.3	17.3	1.3	350	176.8	7.2	0.49	0.235783333	0.4851
DAKSHIN GRAM	24.03473	87.812937	6.94	48.6	8.3		1.3	17.3	1.3	350	176.8	7.2	0.48	0.230971429	0.4752
SEKHPUR	24.04522	87.689078	7.77	19	11.5	10.8	0.87	19	1.3	334	175.8	17	0.48	0.230971429	0.4752
SAMACHAR	24.06008	87.774428	7.68	108.2	28.6	78	96.5	110	24	1224	231.3	184	0.45	0.216535714	0.4455
MATMAHULA	24.05624	87.683028	6.92	11.33	2.9		0.33	5.6	6.2	104	40.4	7.2	0.45	0.216535714	0.4455
PARULIA	23.99581	87.703343	8.8	12	7.3		0.29	46.9	16.4	317	91.8	52	0.45	0.216535714	0.4455
BEGUNA	24.0206	87.825852	7.87	27.1	1.8	5	0.62	15.4	0.9	206	97.1	17	0.45	0.216535714	0.4455
MATMAHULA	24.05073	87.680753	8	35.1	11.5	5	1.06	10.2	2.7	273	131.8	19	0.44	0.21172381	0.4356
DWARURI	24.04436	87.773645	7.15	44.1	6.1	23.5	6.08	58.9	2.5	501	115.6	83	0.44	0.21172381	0.4356
BEGUNA	24.0192	87.82706	8.06	22	7.3	5	8.58	9.7	1.8	202	67.1	21	0.44	0.21172381	0.4356
MAJHARIPARA	24.0757	87.79101	8.15	38.1	15.8	34.3	0.8	60.9	141	919	270.6	99	0.44	0.21172381	0.4356
GOALA	24.09156	87.713974	7.67	67.1	14.6	26.8	0.98	53.9	8	1059	365.4	130	0.43	0.206911905	0.4257
SANDHIGARA	24.07664	87.794483	8.01	43.1	41.3	5.8	8.84	27	1.5	589	254.4	57	0.43	0.206911905	0.4257
MAJHARIPARA	24.07565	87.790087	7.77	30.1	4.3	5	5.31	10.1	2	232	94.8	14	0.43	0.206911905	0.4257
PATHAI	24.00498	87.677432	6.92	17.8	3.9		10.47	56	1.1	367		33	0.43	0.206911905	0.4257
SANAKPUR	24.01231	87.86205	7.35	16	5.5	5	0.44	24.7	1.8	226	71.7	24	0.43	0.206911905	0.4257
DAKSHIN GRAM	24.03527	87.81241	8.42	34.1	13.4	5	3.26	13.6	3.6	269	111	14	0.42	0.2021	0.4158
DAKSHIN GRAM	24.03588	87.810523	6.87	84.2	13.4	66	132.2	87.6	8.5	1025	200	101	0.42	0.2021	0.4158
SAMACHAR	24.06021	87.773528	7.29	42.1	15.7		0.23	86.6	1.2	475	228.3	9.6	0.42	0.2021	0.4158
KAMRA	24.04757	87.765485	7.29	42.1	15.7		0.23	86.6	1.2	475	228.3	9.6	0.42	0.2021	0.4158
MAHISAKURA	24.08435	87.695527	7.72	45.1	7.9	8.3	0.89	29	2.4	407	159.6	33	0.42	0.2021	0.4158
BEGUNA	24.02118	87.777563	7.83	28.1	8.5	7.5	7.12	25.6	1.3	379	143.4	35	0.42	0.2021	0.4158



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BEGUNA	24.01606	87.817142	6.94	48.6	8.3		1.3	17.3	1.3	350	176.8	7.2	0.42	0.2021	0.4158
BEGUNA	24.0186	87.828543	6.94	48.6	8.3		1.3	17.3	1.3	350	176.8	7.2	0.42	0.2021	0.4158
MAJHARIPARA	24.0765	87.791607	7.77	19	11.5	10.8	0.87	19	1.3	334	175.8	17	0.42	0.2021	0.4158
JHIKADDA	23.98917	87.738926	7.68	108.2	28.6	78	96.5	110	24	1224	231.3	184	0.42	0.2021	0.4158
JHIKADDA	23.98901	87.740253	6.92	11.33	2.9		0.33	5.6	6.2	104	40.4	7.2	0.42	0.2021	0.4158
SANAKPUR	24.01441	87.859504	8.8	12	7.3		0.29	46.9	16.4	317	91.8	52	0.42	0.2021	0.4158
SANAKPUR	24.01229	87.86212	7.87	27.1	1.8	5	0.62	15.4	0.9	206	97.1	17	0.42	0.2021	0.4158
BARATURIGRAM	24.03828	87.853537	8	35.1	11.5	5	1.06	10.2	2.7	273	131.8	19	0.41	0.197288095	0.4059
DAKSHIN GRAM	24.03725	87.808583	7.15	44.1	6.1	23.5	6.08	58.9	2.5	501	115.6	83	0.41	0.197288095	0.4059
RANGTARA	24.05474	87.868352	8.06	22	7.3	5	8.58	9.7	1.8	202	67.1	21	0.41	0.197288095	0.4059
SEKHPUR	24.03358	87.69743	8.15	38.1	15.8	34.3	0.8	60.9	141	919	270.6	99	0.41	0.197288095	0.4059
HATURIA	24.08443	87.772038	7.67	67.1	14.6	26.8	0.98	53.9	8	1059	365.4	130	0.41	0.197288095	0.4059
PASCHIM GAMINI	24.07538	87.773923	8.01	43.1	41.3	5.8	8.84	27	1.5	589	254.4	57	0.41	0.197288095	0.4059
RATMA	24.02422	87.808079	7.77	30.1	4.3	5	5.31	10.1	2	232	94.8	14	0.41	0.197288095	0.4059
PATHAI	24.00504	87.676408	6.92	17.8	3.9		10.47	56	1.1	367		33	0.41	0.197288095	0.4059
BARATURIGRAM	24.01098	87.858025	7.35	16	5.5	5	0.44	24.7	1.8	226	71.7	24	0.41	0.197288095	0.4059
LAYEKPUR	23.99571	87.739093	8.42	34.1	13.4	5	3.26	13.6	3.6	269	111	14	0.41	0.197288095	0.4059
JHIKADDA	23.98946	87.737167	6.87	84.2	13.4	66	132.2	87.6	8.5	1025	200	101	0.41	0.197288095	0.4059
DABUK	24.06379	87.817297	7.29	42.1	15.7		0.23	86.6	1.2	475	228.3	9.6	0.41	0.197288095	0.4059
SANAKPUR	24.01159	87.860586	7.29	42.1	15.7		0.23	86.6	1.2	475	228.3	9.6	0.41	0.197288095	0.4059
DAKSHIN GRAM	24.03254	87.809732	7.72	45.1	7.9	8.3	0.89	29	2.4	407	159.6	33	0.4	0.19247619	0.396
SANDHIGARA	24.07902	87.793629	7.35	53.4	11.3		0.2	110.1	2.2	813	250.5	104	0.4	0.19247619	0.396
MIRPUR	23.97577	87.733343	8.11	25.1	11.5	6.8	0.5	51.9	4.4	405	191.9	19	0.4	0.19247619	0.396
MATMAHULA	24.04721	87.683093	7.55	98.2	7.3	37	7.13	119.9	6.6	1144	296	182	0.39	0.187664286	0.3861
BEGUNA	24.02394	87.820597	7.2	40.1	12.2		2.71	40.3	1.7	405	102	26	0.39	0.187664286	0.3861
DHARANI NABAGRAM	23.99622	87.73851	7.45	8	4.9	9.3	4.89	30	17	240	55.5	33	0.39	0.187664286	0.3861
KANACHI	24.07623	87.762998	7.07	40.5	33.4		0.2	60.1	2.7	728	329.3	25	0.39	0.187664286	0.3861
GAYASPUR	24.05359	87.705179	7	4	4.9		0.63	20.4	9.4	146	40.8	19	0.39	0.187664286	0.3861
PASCHIM GAMINI	24.0749	87.773858	7.26	32.4	14.7		0.2	96.8	2.1	588	220.2	48	0.39	0.187664286	0.3861
BHALIAN	24.08869	87.757461	7.74	23.2	10.4	23	2.85	26.5	1.1	311	114	17	0.39	0.187664286	0.3861
RATMA	24.02329	87.807586	7.77	15	10.3	30.5	1.49	90.9	13	503	208.1	21	0.39	0.187664286	0.3861
PATHAI	24.0058	87.676286	6.96	44.9	17.5	34	0.92	48.9	3.4	559	260	21	0.39	0.187664286	0.3861
MALLARPUR	24.07501	87.720254	7.44	47.1	41.3	225	0.5	81.9	3.2	862	238.2	14	0.39	0.187664286	0.3861
JHIKADDA	23.989	87.739789	7.83	37.1	9.1	93	0.5	85.9	13.6	586	201.2	17	0.39	0.187664286	0.3861
FATEHPUR	24.07214	87.724966	7.3	128.3	20.7		0.68	187.5	2.2	1482	438.6	221	0.39	0.187664286	0.3861
SANAKPUR	24.01322	87.861429	8.23	34.1	19.4	11	0.5	48	4.8	395	180.4	19	0.39	0.187664286	0.3861
SANAKPUR	24.01322	87.860688	7.39	6.5	2.9		0.2	134.5	1	402	163.6	19	0.39	0.187664286	0.3861
BARATURIGRAM	24.01019	87.861201	8.73	18	7.3	22	3.13	96.9	5.1	556	152.6	59	0.39	0.187664286	0.3861
BARATURIGRAM	24.00793	87.861002	8.18	20	3	36.5	1.25	131.9	3.8	708	157.3	87	0.39	0.187664286	0.3861
DAKSHIN GRAM	24.00647	87.810718	7.39	30.8	12.3		10.36	150.8	2.9	912	250.5	113	0.39	0.187664286	0.3861
DABUK	24.06272	87.813837	7.95	19.4	6.9		0.2	218.1	6.7	1106	254.5	183	0.39	0.187664286	0.3861
BARATURIGRAM	24.03598	87.855568	9.62	1	2.9								0.38	0.182852381	0.3762
BARATURIGRAM	24.03729	87.851217	7.83	28.1	8.5	7.5	7.12	25.6	1.3	379	143.4	35	0.38	0.182852381	0.3762



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SEKHPUR	24.02967	87.701982	6.94	48.6	8.3		1.3	17.3	1.3	350	176.8	7.2	0.38	0.182852381	0.3762
DAKSHIN GRAM	24.03806	87.808322	6.94	48.6	8.3		1.3	17.3	1.3	350	176.8	7.2	0.38	0.182852381	0.3762
SAMACHAR	24.04999	87.777795	7.77	19	11.5	10.8	0.87	19	1.3	334	175.8	17	0.38	0.182852381	0.3762
MATMAHULA	24.0507	87.679212	7.68	108.2	28.6	78	96.5	110	24	1224	231.3	184	0.38	0.182852381	0.3762
SIPURA	24.00836	87.804691	6.92	11.33	2.9		0.33	5.6	6.2	104	40.4	7.2	0.38	0.182852381	0.3762
LAYEKPUR	23.99609	87.734635	8.8	12	7.3		0.29	46.9	16.4	317	91.8	52	0.38	0.182852381	0.3762
RATMA	24.02125	87.807465	7.87	27.1	1.8	5	0.62	15.4	0.9	206	97.1	17	0.38	0.182852381	0.3762
MALLARPUR	24.07836	87.706099	8	35.1	11.5	5	1.06	10.2	2.7	273	131.8	19	0.38	0.182852381	0.3762
MALLARPUR	24.07658	87.703617	6.53	13	4.9		8.08	23.6	2.1	187	74.7	7.2	0.38	0.182852381	0.3762
LAYEKPUR	23.99437	87.738507	6.53	13	4.9		8.08	23.6	2.1	187	74.7	7.2	0.38	0.182852381	0.3762
MIRPUR	23.97415	87.734994	6.53	13	4.9		8.08	23.6	2.1	187	74.7	7.2	0.38	0.182852381	0.3762
MIRPUR	23.97188	87.73528	7.4	49.1	6.1	5	7.37	5.8	3.3	290	117.9	19	0.38	0.182852381	0.3762
RAUTARA	23.97728	87.732577	6.84	10	9.1	5	5.82	8.7	8.6	163	37	28	0.38	0.182852381	0.3762
RAUTARA	23.97923	87.727948	7.97	18.7	1		0.69	7.8	0.8	119	55.5		0.38	0.182852381	0.3762
DARIHARUKI	23.97913	87.724113	5.68	111.7	27.5		11.1	56	3.4	1120	222.2	290	0.38	0.182852381	0.3762
KATIGRAM	24.04902	87.746062	6.5	20	2.4	13.5	58.8	14.2	6.6	202	23.1	26	0.38	0.182852381	0.3762
SANAKPUR	24.01309	87.860961	6.81	42.9	16.7		0.2	33.8	1.6	496	157.6	50	0.38	0.182852381	0.3762
BARATURIGRAM	24.01049	87.860697	7.8	47.1	16.4	12	13.7	28.5	23	461	143.4	47	0.38	0.182852381	0.3762
BARATURIGRAM	24.00988	87.861366	7.68	37.1	15.2	5	0.5	22.5	1.5	317	157.3	9.4	0.38	0.182852381	0.3762
DABUK	24.0619	87.814773	5.74	4	1.7	1	8.91	1	3.1	58	12	8.2	0.38	0.182852381	0.3762
SEKHPUR	24.02879	87.701965	6.51	61.5	22.6		0.2	41.6		626	195.9	65	0.37	0.178040476	0.3663
DAKSHIN GRAM	24.03661	87.809377	6.51	61.5	22.6		0.2	41.6		626	195.9	65	0.37	0.178040476	0.3663
KAMRA	24.04872	87.762668	7.46	50.1	18.2	16.5	66.5	26	3.2	433	10.8	52	0.37	0.178040476	0.3663
SEKHPUR	24.04523	87.688617	8.05	11	7.9	10	0.62	12.4	2.1	140	55.5	9.4	0.37	0.178040476	0.3663
MATMAHULA	24.05333	87.680882	7.61	20	7.3	5	0.5	10.5	0.8	178	87.9	12	0.37	0.178040476	0.3663
MATMAHULA	24.0557	87.682697	8.45	51.1	17.6	14	0.5	25.5	2.9	506	196.6	33	0.37	0.178040476	0.3663
GOURBAZAR	24.05549	87.776213	7.64	80.2	19.4	5	1.03	30	2.9	672	85.6	125	0.37	0.178040476	0.3663
BEGUNA	24.02466	87.820925	6.44	58.3	32.4		4.25	32.6	1.7	648	198	85	0.37	0.178040476	0.3663
SANAKPUR	24.01643	87.8538	7.73	21	6.5	7.5	0.5	17	1.3	262	122.6	14	0.37	0.178040476	0.3663
SANAKPUR	24.01501	87.854759	7.53	23	27.3	5	0.5	20	1.2	440	228.9	9.4	0.37	0.178040476	0.3663
BEGUNA	24.01929	87.825885	7.48	100.2	59.5	36	103.1	45.5	2.8	1196	171.1	236	0.37	0.178040476	0.3663
BEGUNA	24.01784	87.82655	6.58	31.6	13.3		4.34	91.7		286	103	24	0.37	0.178040476	0.3663
DHARANI NABAGRAM	23.99836	87.737117	7.19	30.1	4.9	29	16.3	46.5	2.4	418	48.6	68	0.37	0.178040476	0.3663
KANACHI	24.07233	87.760621	7.83	79.2	20.7	90	101.5	88.9	5.5	1395	219.7	257	0.37	0.178040476	0.3663
MALLARPUR	24.07761	87.706321	7.51	7	4.3	5.5	2.13	6.6	2.2	101	41.6	4.7	0.37	0.178040476	0.3663
MALLARPUR	24.08021	87.707567	7.8	59.1	12.8	15.8	10.8	23.2	3.2	535	161.9	64	0.37	0.178040476	0.3663
MALLARPUR	24.0819	87.707316	7.48	48.1	32.8	69	0.18	53.9	1.6	721	180.4	94	0.37	0.178040476	0.3663
LAYEKPUR	23.99342	87.738062	7.38	158.3	45	88	147.2	47	3.6	1319	224.3	222	0.37	0.178040476	0.3663
JHIKADDA	23.98902	87.738384	7.13	27.1	8.5	11.5	80.1	40	1.3	390	64.8	50	0.37	0.178040476	0.3663
TAUSIA	23.99872	87.825846	6.53	13	4.9		8.08	23.6	2.1	187	74.7	7.2	0.37	0.178040476	0.3663
MIRPUR	23.97034	87.73575	6.53	13	4.9		8.08	23.6	2.1	187	74.7	7.2	0.37	0.178040476	0.3663
RAUTARA	23.9769	87.734638	6.53	13	4.9		8.08	23.6	2.1	187	74.7	7.2	0.37	0.178040476	0.3663
RAUTARA	23.97869	87.729898	7.4	49.1	6.1	5	7.37	5.8	3.3	290	117.9	19	0.37	0.178040476	0.3663



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RAUTARA	23.97859	87.728957	6.84	10	9.1	5	5.82	8.7	8.6	163	37	28	0.37	0.178040476	0.3663
KATIGRAM	24.04744	87.747754	7.97	18.7	1		0.69	7.8	0.8	119	55.5		0.37	0.178040476	0.3663
SANAKPUR	24.01077	87.861302	5.68	111.7	27.5		11.1	56	3.4	1120	222.2	290	0.37	0.178040476	0.3663
BARATURIGRAM	24.00891	87.861584	6.5	20	2.4	13.5	58.8	14.2	6.6	202	23.1	26	0.37	0.178040476	0.3663
SANAKPUR	24.01093	87.858745	6.81	42.9	16.7		0.2	33.8	1.6	496	157.6	50	0.37	0.178040476	0.3663
SANAKPUR	24.01251	87.857519	7.8	47.1	16.4	12	13.7	28.5	23	461	143.4	47	0.37	0.178040476	0.3663
DABUK	24.06377	87.812265	7.68	37.1	15.2	5	0.5	22.5	1.5	317	157.3	9.4	0.37	0.178040476	0.3663
BARATURIGRAM	24.03828	87.855905	5.74	4	1.7	1	8.91	1	3.1	58	12	8.2	0.36	0.173228571	0.3564
BARATURIGRAM	24.03809	87.85263	6.51	61.5	22.6		0.2	41.6		626	195.9	65	0.36	0.173228571	0.3564
SEKHPUR	24.03365	87.699462	6.51	61.5	22.6		0.2	41.6		626	195.9	65	0.36	0.173228571	0.3564
SEKHPUR	24.03322	87.698712	7.46	50.1	18.2	16.5	66.5	26	3.2	433	10.8	52	0.36	0.173228571	0.3564
JAMALPUR	24.05633	87.726032	8.05	11	7.9	10	0.62	12.4	2.1	140	55.5	9.4	0.36	0.173228571	0.3564
SAMACHAR	24.05367	87.768665	7.61	20	7.3	5	0.5	10.5	0.8	178	87.9	12	0.36	0.173228571	0.3564
SEKHPUR	24.04587	87.688845	8.45	51.1	17.6	14	0.5	25.5	2.9	506	196.6	33	0.36	0.173228571	0.3564
MATMAHULA	24.047	87.683553	7.64	80.2	19.4	5	1.03	30	2.9	672	85.6	125	0.36	0.173228571	0.3564
SUKNA	24.02466	87.780213	6.44	58.3	32.4		4.25	32.6	1.7	648	198	85	0.36	0.173228571	0.3564
SANAKPUR	24.01682	87.854056	7.73	21	6.5	7.5	0.5	17	1.3	262	122.6	14	0.36	0.173228571	0.3564
SANAKPUR	24.01166	87.854645	7.53	23	27.3	5	0.5	20	1.2	440	228.9	9.4	0.36	0.173228571	0.3564
BANASPUR	24.01737	87.836262	7.48	100.2	59.5	36	103.1	45.5	2.8	1196	171.1	236	0.36	0.173228571	0.3564
HATURIA	24.08966	87.766827	6.58	31.6	13.3		4.34	91.7		286	103	24	0.36	0.173228571	0.3564
DIGHALGRAM	24.04584	87.641275	7.19	30.1	4.9	29	16.3	46.5	2.4	418	48.6	68	7.26	3.493442857	7.1874
GANPUR	24.06926	87.66967	7.83	79.2	20.7	90	101.5	88.9	5.5	1395	219.7	257	3.14	1.510938095	3.1086
TANTULBARIA	24.00687	87.61221	7.51	7	4.3	5.5	2.13	6.6	2.2	101	41.6	4.7	2.31	1.11155	2.2869
DHAMARA	24.10285	87.675298	7.8	59.1	12.8	15.8	10.8	23.2	3.2	535	161.9	64	1.75	0.842083333	1.7325
RAUTARA	24.00487	87.598712	7.48	48.1	32.8	69	0.18	53.9	1.6	721	180.4	94	1.74	0.837271429	1.7226
DIGHALGRAM	24.04173	87.644152	7.38	158.3	45	88	147.2	47	3.6	1319	224.3	222	1.46	0.702538095	1.4454
DHAMARA	24.10173	87.675652	7.13	27.1	8.5	11.5	80.1	40	1.3	390	64.8	50	1.36	0.654419048	1.3464
TANTULBARIA	24.00304	87.622251	7.87	83.2	19.4	5	0.83	35	3.2	656	268.3	59	1.23	0.591864286	1.2177
CHAK RAIPUR	24.09995	87.646823	7.41	150.3	26.7	60	145.5	89.9	5	1359	134.1	290	1.02	0.490814286	1.0098
RAUTARA	24.00937	87.601622	7.69	32.1	18.2	15.5	10.2	29.5	1.5	735	185	127	1.02	0.490814286	1.0098
SONTHSAL	24.04744	87.620293	7.84	29.1	23.7	5	1.04	32	0.9	411	212.8	35	1.01	0.486002381	0.9999
BARA BATASPUR	24.04559	87.66261	7.3	86.2	35.2		1.57	43	1.4	610	78.6	99	1.01	0.486002381	0.9999
DEBAGRAM	24.04459	87.545163	7.66	61.1	28.6	18.5	1.51	29	6.6	600	203.5	71	1	0.481190476	0.99
CHAK RAIPUR	24.09458	87.64242	7.43	31.1	7.3	5	2.59	20.7	0.8	268	131.8	9.4	1	0.481190476	0.99
USHKA	24.02934	87.601955	7.71	132.3	14.6	85	12.4	53.9	6.9	1487	372.3	236	0.94	0.452319048	0.9306
BHAGABANDHA	24.09217	87.502642	7.95	87.2	48	38	90.9	33	2.6	897	198.9	139	0.92	0.442695238	0.9108
HATGHACHHA	24.10172	87.583445	6.83	111.7	13.7		8.13	40.8	1.7	860	166.7	154	0.91	0.437883333	0.9009
BAHADURGANJA	24.04085	87.584938	7.46	16	4.9	5	0.5	13.4	1	144	67.1	12	0.91	0.437883333	0.9009
SALAMATPUR	23.95291	87.617665	7.66	24	9.1	6.3	0.5	20.5	1.5	373	189.6	12	0.91	0.437883333	0.9009
CHAK RAIPUR	24.10039	87.646477	7.37	356.7	66.8	185	256.5	234.8	5.1	3808	344.6	790	0.91	0.437883333	0.9009
KULKURI	24.02002	87.531757	6.5	80.2	26.7		64.99	103.9	52.3	1085	158.1	202	0.79	0.380140476	0.7821
BAHADURGANJA	24.04416	87.581735	8.49	36.1	10.9	5	5.67	27	1.1	343	127.2	26	0.79	0.380140476	0.7821
BHAGABANDHA	24.09253	87.503267	7.47	157.3	9.1	82	5.28	54.9	5.7	1315	284.4	219	0.79	0.380140476	0.7821



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PURANA	24.05625	87.495903	7.83	28.1	8.5	7.5	7.12	25.6	1.3	379	143.4	35	0.79	0.380140476	0.7821
JINDHARPUR	24.0641	87.513323	6.94	48.6	8.3		1.3	17.3	1.3	350	176.8	7.2	0.79	0.380140476	0.7821
KHAYRAKURI	23.95657	87.519392	6.94	48.6	8.3		1.3	17.3	1.3	350	176.8	7.2	0.78	0.375328571	0.7722
DEBAGRAM	24.04805	87.547523	7.77	19	11.5	10.8	0.87	19	1.3	334	175.8	17	0.76	0.365704762	0.7524
SONTHSAL	24.04765	87.621923	7.68	108.2	28.6	78	96.5	110	24	1224	231.3	184	0.76	0.365704762	0.7524
BALIHARPUR	24.09437	87.513978	6.92	11.33	2.9		0.33	5.6	6.2	104	40.4	7.2	0.76	0.365704762	0.7524
HATGHACHHA	24.10287	87.581918	8.8	12	7.3		0.29	46.9	16.4	317	91.8	52	0.73	0.351269048	0.7227
HATGHACHHA	24.10291	87.597442	7.87	27.1	1.8	5	0.62	15.4	0.9	206	97.1	17	0.73	0.351269048	0.7227
KULKURI	24.01544	87.53003	8	35.1	11.5	5	1.06	10.2	2.7	273	131.8	19	0.73	0.351269048	0.7227
SAREDA	24.06552	87.546308	7.15	44.1	6.1	23.5	6.08	58.9	2.5	501	115.6	83	0.73	0.351269048	0.7227
JINDHARPUR	24.06459	87.51492	8.06	22	7.3	5	8.58	9.7	1.8	202	67.1	21	0.73	0.351269048	0.7227
KULKURI	24.01526	87.5284	8.15	38.1	15.8	34.3	0.8	60.9	141	919	270.6	99	0.72	0.346457143	0.7128
DEUCHA	24.04549	87.578665	7.67	67.1	14.6	26.8	0.98	53.9	8	1059	365.4	130	0.72	0.346457143	0.7128
MURALPUR	24.0967	87.504368	8.01	43.1	41.3	5.8	8.84	27	1.5	589	254.4	57	0.72	0.346457143	0.7128
JINDHARPUR	24.06099	87.514725	7.77	30.1	4.3	5	5.31	10.1	2	232	94.8	14	0.72	0.346457143	0.7128
TAJPUR	24.03738	87.582652	7.87	83.2	19.4	5	0.83	35	3.2	656	268.3	59	0.72	0.346457143	0.7128
DUBRAJPUR	24.03598	87.58374	7.41	150.3	26.7	60	145.5	89.9	5	1359	134.1	290	0.72	0.346457143	0.7128
NISCHINTAPUR	24.05246	87.574948	7.69	32.1	18.2	15.5	10.2	29.5	1.5	735	185	127	0.72	0.346457143	0.7128
KULKURI	24.01541	87.52818	7.84	29.1	23.7	5	1.04	32	0.9	411	212.8	35	0.71	0.341645238	0.7029
MURALPUR	24.09631	87.506437	7.3	86.2	35.2		1.57	43	1.4	610	78.6	99	0.71	0.341645238	0.7029
BHAGABANDHA	24.09332	87.503358	7.66	61.1	28.6	18.5	1.51	29	6.6	600	203.5	71	0.71	0.341645238	0.7029
HARIDASPUR	24.07226	87.630057	7.43	31.1	7.3	5	2.59	20.7	0.8	268	131.8	9.4	0.71	0.341645238	0.7029
HATGHACHHA	24.11136	87.598503	7.71	132.3	14.6	85	12.4	53.9	6.9	1487	372.3	236	0.71	0.341645238	0.7029
NISCHINTAPUR	24.04994	87.57502	7.95	87.2	48	38	90.9	33	2.6	897	198.9	139	0.71	0.341645238	0.7029
KORAPUKUR	24.06016	87.543202	6.83	111.7	13.7		8.13	40.8	1.7	860	166.7	154	0.69	0.332021429	0.6831
MALADANGA	23.96801	87.541652	7.46	16	4.9	5	0.5	13.4	1	144	67.1	12	0.69	0.332021429	0.6831
KORAPUKUR	24.06087	87.544655	7.66	24	9.1	6.3	0.5	20.5	1.5	373	189.6	12	0.67	0.322397619	0.6633
KORAPUKUR	24.05352	87.54344	7.37	356.7	66.8	185	256.5	234.8	5.1	3808	344.6	790	0.67	0.322397619	0.6633
JETHIA	24.10644	87.622375	6.5	80.2	26.7		64.99	103.9	52.3	1085	158.1	202	0.61	0.29352619	0.6039
KULKURI	24.01636	87.528812	8.49	36.1	10.9	5	5.67	27	1.1	343	127.2	26	0.61	0.29352619	0.6039
BHAGABANDHA	24.09596	87.503655	7.47	157.3	9.1	82	5.28	54.9	5.7	1315	284.4	219	0.61	0.29352619	0.6039
SAREDA	24.0665	87.5434	7.83	28.1	8.5	7.5	7.12	25.6	1.3	379	143.4	35	0.61	0.29352619	0.6039
PURANA	24.05748	87.49752	6.94	48.6	8.3		1.3	17.3	1.3	350	176.8	7.2	0.61	0.29352619	0.6039
MALADANGA	23.96694	87.544488	6.94	48.6	8.3		1.3	17.3	1.3	350	176.8	7.2	0.61	0.29352619	0.6039
HATGHACHHA	24.09271	87.589662	7.77	19	11.5	10.8	0.87	19	1.3	334	175.8	17	0.61	0.29352619	0.6039
HATGHACHHA	24.08817	87.602573	7.68	108.2	28.6	78	96.5	110	24	1224	231.3	184	0.61	0.29352619	0.6039
KABILPUR	23.97951	87.616338	6.92	11.33	2.9		0.33	5.6	6.2	104	40.4	7.2	0.61	0.29352619	0.6039
HATGHACHHA	24.11044	87.595658	8.8	12	7.3		0.29	46.9	16.4	317	91.8	52	0.61	0.29352619	0.6039
HARINSINGA	24.0802	87.571382	7.87	27.1	1.8	5	0.62	15.4	0.9	206	97.1	17	0.61	0.29352619	0.6039
ABDARPUR	24.02065	87.51721	8	35.1	11.5	5	1.06	10.2	2.7	273	131.8	19	0.59	0.283902381	0.5841
PALAN	24.08362	87.552695	7.15	44.1	6.1	23.5	6.08	58.9	2.5	501	115.6	83	0.59	0.283902381	0.5841
RAUTARA	24.00695	87.599878	8.06	22	7.3	5	8.58	9.7	1.8	202	67.1	21	0.57	0.274278571	0.5643
BIRUPUR	23.98933	87.533625	8.15	38.1	15.8	34.3	0.8	60.9	141	919	270.6	99	0.57	0.274278571	0.5643



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RAUTARA	24.01115	87.597895	7.67	67.1	14.6	26.8	0.98	53.9	8	1059	365.4	130	0.56	0.269466667	0.5544
KULKURI	24.01884	87.532367	8.01	43.1	41.3	5.8	8.84	27	1.5	589	254.4	57	0.56	0.269466667	0.5544
SALUKA	24.03444	87.616388	7.77	30.1	4.3	5	5.31	10.1	2	232	94.8	14	0.52	0.250219048	0.5148
KULKURI	24.01805	87.531918	6.92	17.8	3.9		10.47	56	1.1	367		33	0.52	0.250219048	0.5148
TAJPUR	24.03683	87.585287	7.35	16	5.5	5	0.44	24.7	1.8	226	71.7	24	0.51	0.245407143	0.5049
KHAYRAKURI	23.95931	87.517598	8.42	34.1	13.4	5	3.26	13.6	3.6	269	111	14	0.49	0.235783333	0.4851
SONTHSAL	24.0462	87.618137	6.87	84.2	13.4	66	132.2	87.6	8.5	1025	200	101	0.49	0.235783333	0.4851
SONTHSAL	24.04802	87.621237	7.29	42.1	15.7		0.23	86.6	1.2	475	228.3	9.6	0.49	0.235783333	0.4851
HATGHACHHA	24.09734	87.62059	7.29	42.1	15.7		0.23	86.6	1.2	475	228.3	9.6	0.49	0.235783333	0.4851
JETHIA	24.09884	87.621232	7.72	45.1	7.9	8.3	0.89	29	2.4	407	159.6	33	0.49	0.235783333	0.4851
JETHIA	24.09837	87.621443	7.9	46.1	13.4	5	0.5	24.7	1.6	426	92.5	80	0.49	0.235783333	0.4851
ABDARPUR	24.0186	87.516048	7.8	17	6.1	17.5	5.41	78.9	2.6	426	185	19	0.49	0.235783333	0.4851
BAHADURGANJA	24.04181	87.586003	8.23	59.1	8.5	18.3	3.36	50	16.5	565	256.7	26	0.49	0.235783333	0.4851
BALIHARPUR	24.09479	87.510653	7.48	30.1	8.5	11	77.4	22.5	2.5	312	55.5	42	0.49	0.235783333	0.4851
PURANA	24.04905	87.50852	7.13	35.6	6.9		0.2	17.5	1.3	296	131.3	9.6	0.49	0.235783333	0.4851
RAYPUR	24.0214	87.578135	6.9	44.1	8.5		0.42	43.8	10.4	455	142.8	62	0.49	0.235783333	0.4851
DHAMARA	24.10269	87.67229	6.5	12	14.6		4.48	14	5.8	188	61.2	26	0.49	0.235783333	0.4851
TANTULBARIA	24.00962	87.615265	7.43	52.1	7.9	5	1.67	22.5	0.5	384	187.3	17	0.49	0.235783333	0.4851
BARA BATASPUR	24.04566	87.662685	7.8	82.2	23.1	20	129.5	42	1.6	607	226.6	68	0.49	0.235783333	0.4851
HATGHACHHA	24.08698	87.602367	7.78	50.1	10.9	16.5	3.31	28	1.8	399	203.5	21	0.49	0.235783333	0.4851
HATGHACHHA	24.08529	87.607678	7.23	21	3.6	7.5	13	9.7	2.2	179	60.1	17	0.49	0.235783333	0.4851
DHAMARA	24.106	87.66316	7.62	102.2	7.3	14.3	0.81	52.9	3.7	901	300.6	106	0.49	0.235783333	0.4851
DEUCHA	24.04432	87.580095	8.1	2	1.2		0.5	9.5	3.1	63	20.4	14	0.47	0.226159524	0.4653
KENDSARAIL	24.0801	87.52774	7.07	58.3	14.7		2.08	38.7	1.2	529	270.7	9.6	0.47	0.226159524	0.4653
HATGHACHHA	24.10172	87.583993	7.07	58.3	14.7		2.08	38.7	1.2	529	270.7	9.6	0.46	0.221347619	0.4554
HATGHACHHA	24.10747	87.599797	7.29	80.2	18.8	19	107.5	35	5.7	735	113.3	123	0.46	0.221347619	0.4554
ABDARPUR	24.02105	87.516717	7.19	38.9	9.8		0.2	44.8	2.2	419	200	14	0.46	0.221347619	0.4554
ABDARPUR	24.01899	87.517317	7.19	38.9	9.8		0.2	44.8	2.2	419	200	14	0.46	0.221347619	0.4554
BAHADURGANJA	24.03747	87.590362	6.5	112.2	34		85.8	64.2	3.3	1080	91.8	240	0.46	0.221347619	0.4554
BAHADURGANJA	24.04125	87.58342	7.5	154.3	35.2	77	102.5	101.9	3.8	1477	201.2	278	0.46	0.221347619	0.4554
DEUCHA	24.04439	87.577943	7.89	88.2	17	30.8	15.3	42	1.2	682	198.9	92	0.46	0.221347619	0.4554
BALIHARPUR	24.09169	87.519932	7.1	88.2	36.5		33.25	31.6	7.6	771	219.3	102	0.46	0.221347619	0.4554
PALAN	24.08161	87.550625	7.62	38.1	4.3	14.8	24.2	49	0.7	423	111	47	0.46	0.221347619	0.4554
BHERAPATHAR	24.05114	87.520072	7.52	12	2.4	5	5.02	14.2	2	127	60.1	9.4	0.46	0.221347619	0.4554
BEJORA	23.99041	87.569619	7.81	64.1	21.9	5	2.22	31	3.1	521	231.3	38	0.46	0.221347619	0.4554
RAYPUR	24.02232	87.576773	8.08	60.1	14	17.3	12.7	27.5	3.2	484	175.8	40	0.46	0.221347619	0.4554
RAYPUR	24.02118	87.57809	7.79	48.1	27.9	17.8	108.4	59.9	1.9	647	189.6	61	0.46	0.221347619	0.4554
HUSAIPUR	24.07659	87.528107	7.3	32.1	9.7	6.5	15.9	29	1.5	292	74	47	0.46	0.221347619	0.4554
GANPUR	24.07104	87.67099	7.78	60.1	14.6	8.8	105.3	13.8	2.4	437	106.4	47	0.46	0.221347619	0.4554
DIGHALGRAM	24.04882	87.643492	7.87	40.1	8.5	14.3	1.09	76.9	3.4	782	383.9	42	0.46	0.221347619	0.4554
CHAK RAIPUR	24.09814	87.653207	7.71	124.2	42.5	87	93.3	94.9	12	1476	289.1	248	0.46	0.221347619	0.4554
USHKA	24.01795	87.60927	8.44	50.1	16.4	14.5	94.2	31.5	1.7	487	101.8	57	0.46	0.221347619	0.4554
KULKURI	24.01632	87.528788	8.58	48.1	24.3	5	2.35	44	0.7	471	235.9	17	0.46	0.221347619	0.4554



Integrated approach on discerning fluoride contamination mechanisms in the groundwater and formulating remedial strategies for potential health hazards in Birbhum District, West Bengal'.

BARA BATASPUR	24.04625	87.662818	6.3	156.3	43.7		5.08	62.2	8.4	1253	255	240	0.46	0.221347619	0.4554
CHANDA	24.08263	87.587295	7.57	26.1	12.2	5	4.22	13.8	1.4	254	115.6	14	0.46	0.221347619	0.4554
BARA BATASPUR	24.04422	87.656753	7.62	118.2	17	44	7.51	52.9	8.1	1051	245.1	165	0.46	0.221347619	0.4554
BARA BATASPUR	24.04596	87.654843	8.05	28.1	4.9	5	10.3	28	3.8	268	129.5	12	0.46	0.221347619	0.4554
DIGHALGRAM	24.04215	87.648318	6.9	144.3	43.7		25.09	142.6	8.9	1603	402.9	238	0.46	0.221347619	0.4554
DHAMARA	24.10468	87.669077	6.6	68.1	26.7		0.95	61	3.4	738	163.2	114	0.46	0.221347619	0.4554
DHAMARA	24.10507	87.668308	7.88	18	3.6	5	2.91	21.7	0.9	203	83.3	14	0.46	0.221347619	0.4554
DHAMARA	24.10625	87.662668	7.33	16	12.2	6.3	5.57	21.9	1.8	230	230	13	0.46	0.221347619	0.4554
MURALPUR	24.09753	87.506557	7.5	74.1	20.7		0.72	50.9	8.2	701	173.4	112	0.46	0.221347619	0.4554
KATUNIA	23.95132	87.608008	7.99	40.1	20.7	6	1.36	32.5	0.9	456	231.3	19	0.46	0.221347619	0.4554
BALIHARPUR	24.09507	87.50854	7.77	40.1	15.2	5	1.03	24	1.2	332	166.5	12	0.41	0.197288095	0.4059
HINGLA	24.07563	87.536743	6.8	20	4.9		17.27	44.8	1	312	81.6	38	0.41	0.197288095	0.4059
MALDIHA	23.98187	87.600523	7.72	110.2	22.5	17.8	5.81	58.9	4.4	1037	245.1	156	0.41	0.197288095	0.4059
BAGALPUR	24.01994	87.553223	6.8	60.1	19.4		10.36	32.6	3.2	566	153	76	0.41	0.197288095	0.4059
CHAK BAHARAKURI	24.00577	87.5175	8.2	36.1	18.2	5	0.62	50	6.2	441	238.2	12	0.41	0.197288095	0.4059
DIGHALGRAM	24.04295	87.641122	6.61	34.5	9.2	21	0.94	9.8	2.9	295	112	26	0.41	0.197288095	0.4059
DIGHALGRAM	24.0442	87.644663	6.82	56.1	9.2	42	1.08	43.8	19	558	252	25	0.41	0.197288095	0.4059
RAYPUR	24.01479	87.580775	7.64	32.1	1.8		0.5	20	1.3	262	129.5		0.41	0.197288095	0.4059
RAYPUR	24.01869	87.581912	7.66	45.1	8.5	5	128.3	26.5	1.2	366	157.3	26	0.41	0.197288095	0.4059
KENDSARAIL	24.08589	87.5278	7.5	60.1	26.7		1.25	50.9	2.6	554	316.2	19	0.41	0.197288095	0.4059
HUSAIPUR	24.0762	87.527723	6.8	60.1	17		5.02	32.6	1.5	528	158.1	74	0.41	0.197288095	0.4059
GANPUR	24.06711	87.670878	6.8	8	6.1		5.37	5.37	1	105	51	7.1	0.41	0.197288095	0.4059
TAJPUR	24.03705	87.582027	7.55	40.1	17	5	0.5	4.7	1.7	355	189.6	12	0.41	0.197288095	0.4059
KULKURI	24.01849	87.535188	7.65	106.2	16.4	11.5	0.62	60.9	4.5	938	349.2	99	0.41	0.197288095	0.4059
KULKURI	24.01524	87.52841	6.92	17.8	3.9		10.47	56	1.1	367		33	0.41	0.197288095	0.4059
HATGHACHHA	24.08248	87.601607	7.35	16	5.5	5	0.44	24.7	1.8	226	71.7	24	0.41	0.197288095	0.4059
DIGHALGRAM	24.04306	87.647943	8.42	34.1	13.4	5	3.26	13.6	3.6	269	111	14	0.41	0.197288095	0.4059
RAUTARA	24.00962	87.599397	6.87	84.2	13.4	66	132.2	87.6	8.5	1025	200	101	0.41	0.197288095	0.4059
RAUTARA	24.00502	87.598017	7.29	42.1	15.7		0.23	86.6	1.2	475	228.3	9.6	0.41	0.197288095	0.4059
JAYRAMPUR	23.998	87.63274	7.29	42.1	15.7		0.23	86.6	1.2	475	228.3	9.6	0.41	0.197288095	0.4059
DHAMARA	24.10561	87.665167	7.72	45.1	7.9	8.3	0.89	29	2.4	407	159.6	33	0.41	0.197288095	0.4059
MURALPUR	24.09628	87.506042	7.9	46.1	13.4	5	0.5	24.7	1.6	426	92.5	80	0.41	0.197288095	0.4059
PURUSOTTAMPUR	23.97743	87.612647	7.8	17	6.1	17.5	5.41	78.9	2.6	426	185	19	0.41	0.197288095	0.4059
NISCHINTAPUR	24.05395	87.557275	8.23	59.1	8.5	18.3	3.36	50	16.5	565	256.7	26	0.41	0.197288095	0.4059
DEUCHA	24.0397	87.586758	7.48	30.1	8.5	11	77.4	22.5	2.5	312	55.5	42	0.4	0.19247619	0.396
DIGHALGRAM	24.04244	87.643405	7.13	35.6	6.9		0.2	17.5	1.3	296	131.3	9.6	0.4	0.19247619	0.396
SONTHSAL	24.04933	87.615115	6.9	44.1	8.5		0.42	43.8	10.4	455	142.8	62	0.39	0.187664286	0.3861
SONTHSAL	24.04755	87.621283	6.5	12	14.6		4.48	14	5.8	188	61.2	26	0.39	0.187664286	0.3861
HATGHACHHA	24.10349	87.581222	7.43	52.1	7.9	5	1.67	22.5	0.5	384	187.3	17	0.39	0.187664286	0.3861
ABDARPUR	24.01863	87.516383	7.8	82.2	23.1	20	129.5	42	1.6	607	226.6	68	0.39	0.187664286	0.3861
BAHADURGANJA	24.04049	87.588542	7.78	50.1	10.9	16.5	3.31	28	1.8	399	203.5	21	0.39	0.187664286	0.3861
DEUCHA	24.04504	87.578943	7.23	21	3.6	7.5	13	9.7	2.2	179	60.1	17	0.39	0.187664286	0.3861
BAHADURGANJA	24.04232	87.58329	7.62	102.2	7.3	14.3	0.81	52.9	3.7	901	300.6	106	0.39	0.187664286	0.3861



Integrated approach on discerning fluoride contamination mechanisms in the groundwater and formulating remedial strategies for potential health hazards in Birbhum District, West Bengal.

BAHADURGANJA	24.0408	87.585848	8.1	2	1.2		0.5	9.5	3.1	63	20.4	14	0.39	0.187664286	0.3861
MURALPUR	24.09784	87.502985	7.07	58.3	14.7		2.08	38.7	1.2	529	270.7	9.6	0.39	0.187664286	0.3861
HINGLA	24.07838	87.536538	7.07	58.3	14.7		2.08	38.7	1.2	529	270.7	9.6	0.39	0.187664286	0.3861
PALAN	24.08321	87.551675	7.29	80.2	18.8	19	107.5	35	5.7	735	113.3	123	0.39	0.187664286	0.3861
MALDIHA	23.97951	87.601987	7.19	38.9	9.8		0.2	44.8	2.2	419	200	14	0.39	0.187664286	0.3861
RAJYADHARPUR	23.98018	87.592457	7.19	38.9	9.8		0.2	44.8	2.2	419	200	14	0.39	0.187664286	0.3861
BHERAPATHAR	24.05315	87.521472	6.5	112.2	34		85.8	64.2	3.3	1080	91.8	240	0.39	0.187664286	0.3861
JINDHARPUR	24.06288	87.51563	7.5	154.3	35.2	77	102.5	101.9	3.8	1477	201.2	278	0.39	0.187664286	0.3861
KAPISHTA	24.05908	87.518525	7.89	88.2	17	30.8	15.3	42	1.2	682	198.9	92	0.39	0.187664286	0.3861
BAGALPUR	24.01802	87.551847	7.1	88.2	36.5		33.25	31.6	7.6	771	219.3	102	0.39	0.187664286	0.3861
BEJORA	24.00854	87.546426	7.62	38.1	4.3	14.8	24.2	49	0.7	423	111	47	0.39	0.187664286	0.3861
LANGALBHANGA	24.03432	87.566003	7.52	12	2.4	5	5.02	14.2	2	127	60.1	9.4	0.39	0.187664286	0.3861
LANGALBHANGA	24.03637	87.563962	7.81	64.1	21.9	5	2.22	31	3.1	521	231.3	38	0.39	0.187664286	0.3861
LANGALBHANGA	24.03343	87.565052	8.08	60.1	14	17.3	12.7	27.5	3.2	484	175.8	40	0.39	0.187664286	0.3861
BISHNUPUR	24.02379	87.528112	7.79	48.1	27.9	17.8	108.4	59.9	1.9	647	189.6	61	0.39	0.187664286	0.3861
HINGLA	24.07521	87.536165	7.3	32.1	9.7	6.5	15.9	29	1.5	292	74	47	0.39	0.187664286	0.3861
DIGHALGRAM	24.04341	87.643083	7.78	60.1	14.6	8.8	105.3	13.8	2.4	437	106.4	47	0.39	0.187664286	0.3861
DIGHALGRAM	24.04519	87.641478	7.87	40.1	8.5	14.3	1.09	76.9	3.4	782	383.9	42	0.39	0.187664286	0.3861
DHAMARA	24.10098	87.673527	7.71	124.2	42.5	87	93.3	94.9	12	1476	289.1	248	0.39	0.187664286	0.3861
DHAMARA	24.10299	87.672793	8.44	50.1	16.4	14.5	94.2	31.5	1.7	487	101.8	57	0.39	0.187664286	0.3861
DHAMARA	24.10347	87.673323	8.58	48.1	24.3	5	2.35	44	0.7	471	235.9	17	0.39	0.187664286	0.3861
DHAMARA	24.10217	87.674458	6.3	156.3	43.7		5.08	62.2	8.4	1253	255	240	0.39	0.187664286	0.3861
DHAMARA	24.1019	87.673995	7.57	26.1	12.2	5	4.22	13.8	1.4	254	115.6	14	0.39	0.187664286	0.3861
CHAK RAIPUR	24.09505	87.652015	7.62	118.2	17	44	7.51	52.9	8.1	1051	245.1	165	0.39	0.187664286	0.3861
CHAK RAIPUR	24.09293	87.638823	8.05	28.1	4.9	5	10.3	28	3.8	268	129.5	12	0.39	0.187664286	0.3861
TANTULBARIA	24.0146	87.611732	6.9	144.3	43.7		25.09	142.6	8.9	1603	402.9	238	0.39	0.187664286	0.3861
TANTULBARIA	24.01318	87.613032	6.6	68.1	26.7		0.95	61	3.4	738	163.2	114	0.39	0.187664286	0.3861
USHKA	24.01707	87.610425	7.88	18	3.6	5	2.91	21.7	0.9	203	83.3	14	0.39	0.187664286	0.3861
BENACHAPAR	24.02037	87.49306	7.33	16	12.2	6.3	5.57	21.9	1.8	230	230	13	0.39	0.187664286	0.3861
ASENGA	23.96592	87.61549	7.5	74.1	20.7		0.72	50.9	8.2	701	173.4	112	0.39	0.187664286	0.3861
KULKURI	24.01904	87.534475	7.99	40.1	20.7	6	1.36	32.5	0.9	456	231.3	19	0.39	0.187664286	0.3861
KULKURI	24.01876	87.532308	7.77	40.1	15.2	5	1.03	24	1.2	332	166.5	12	0.39	0.187664286	0.3861
KULKURI	24.0181	87.531958	6.8	20	4.9		17.27	44.8	1	312	81.6	38	0.39	0.187664286	0.3861
BARA BATASPUR	24.04821	87.65923	7.72	110.2	22.5	17.8	5.81	58.9	4.4	1037	245.1	156	0.39	0.187664286	0.3861
ATLA	24.10597	87.784317	6.8	60.1	19.4		10.36	32.6	3.2	566	153	76	9.5	4.571309524	9.405
CHHORA	24.21342	87.713745	8.2	36.1	18.2	5	0.62	50	6.2	441	238.2	12	4.7	2.261595238	4.653
JUNIDPUR	24.09982	87.78311	6.61	34.5	9.2	21	0.94	9.8	2.9	295	112	26	1.9	0.914261905	1.881
CHAKPARA	24.1206	87.753747	6.82	56.1	9.2	42	1.08	43.8	19	558	252	25	1.9	0.914261905	1.881
JUNIDPUR	24.09925	87.781755	7.64	32.1	1.8		0.5	20	1.3	262	129.5		1.85	0.890202381	1.8315
JUNIDPUR	24.09847	87.782735	7.66	45.1	8.5	5	128.3	26.5	1.2	366	157.3	26	1.85	0.890202381	1.8315
JUNIDPUR	24.09995	87.782943	7.5	60.1	26.7		1.25	50.9	2.6	554	316.2	19	1.85	0.890202381	1.8315
JUNIDPUR	24.0992	87.781775	6.8	60.1	17		5.02	32.6	1.5	528	158.1	74	1.83	0.880578571	1.8117
CHANDPUR	24.19793	87.683413	6.8	8	6.1		5.37	5.37	1	105	51	7.1	0.67	0.322397619	0.6633



Integrated approach on discerning fluoride contamination mechanisms in the groundwater and formulating remedial strategies for potential health hazards in Birbhum District, West Bengal.

GUG	24.1379	87.726352	7.55	40.1	17	5	0.5	4.7	1.7	355	189.6	12	0.66	0.317585714	0.6534
PANISAIL	24.23018	87.77774	7.65	106.2	16.4	11.5	0.62	60.9	4.5	938	349.2	99	0.66	0.317585714	0.6534
MURADDA	24.12357	87.729634	7.77	78.2	37.7	51	20.3	49	4	815	245.1	90	0.66	0.317585714	0.6534
SAONSA	24.11058	87.720353	7.21	53.1	16.4	16.5	10.6	34	4.8	508	131.8	71	0.66	0.317585714	0.6534
HARIOKA	24.15071	87.75648	8.1	51.1	29.2	6.3	0.8	46	6	695	314.5	47	0.65	0.31277381	0.6435
AKHIRA	24.19485	87.778933	8.41	62.1	34	7.5	1.06	80.9	3.2	488	235.9	12	0.65	0.31277381	0.6435
SAONSA	24.10888	87.717498	7.04	48.6	13.7		0.2	46.9	2.1	475	222.2	15	0.65	0.31277381	0.6435
SAONSA	24.11074	87.718742	6.8	32.1	12.2		16.65	50.9	1.5	446	255	50	0.65	0.31277381	0.6435
BARSHAL	24.15028	87.78263	8.26	26.1	17.6	12.5	0.5	59.9	7.3	626	321.4	21	0.64	0.307961905	0.6336
EKPARA	24.23935	87.686755	6.46	76.2	24.3		1.22	25.9	2.3	581	209.1	78	0.64	0.307961905	0.6336
SAONSA	24.11115	87.716723	6.94	92.2	34	56	2.33	51	4.5	942	300	104	0.64	0.307961905	0.6336
BARSHAL	24.14917	87.783582	7.78	158.3	15.8	65	3.05	111.9	7	1967	351.5	401	0.63	0.30315	0.6237
RAMRAMPUR	24.18804	87.789553	6.9	220.4	58.3		38.1	78.5	6.1	1597	413.1	261	0.63	0.30315	0.6237
SERPUR	24.18351	87.835215	7.7	54.1	60.8	35	1.21	69.9	6.4	1029	261.3	156	0.63	0.30315	0.6237
MADHYA GOPALPUR	24.14434	87.786482	7.75	28.1	5.5	5	14.8	16.2	0.8	250	87.9	24	0.62	0.298338095	0.6138
BARSHAL	24.1451	87.784113	7.73	54.1	18.2	20.5	0.5	43	3.6	520	203.5	33	0.62	0.298338095	0.6138
RADIPUR	24.1516	87.725898	8.11	150.3	45	57	64.8	143.9	2.6	1808	300.6	354	0.62	0.298338095	0.6138
BAMDEBPUR	24.17753	87.84223	7.45	48.1	12.2	40	25.5	66.9	1.1	600	101.8	94	0.62	0.298338095	0.6138
BAMDEBPUR	24.18021	87.843682	8.4	24	12.2		0.6	49.9	2.3	403	127.5	62	0.62	0.298338095	0.6138
JOYKRISHNAPUR	24.1832	87.801423	8.08	124.2	7.3	24	0.5	50	2.2	1280	305.3	208	0.61	0.29352619	0.6039
JOYKRISHNAPUR	24.18257	87.798173	7.71	70.1	25.5	47.5	25	69.9	1.9	820	154.9	130	0.61	0.29352619	0.6039
TELDAHA	24.10954	87.728822	7.72	30.1	32.2	6.8	0.5	32	2	464	233.6	17	0.6	0.288714286	0.594
JOYKRISHNAPUR	24.18809	87.79986	7.1	132.3	51		22.62	80.5	2.2	1278	336.6	195	0.6	0.288714286	0.594
BARSHAL	24.15035	87.783753	7.1	84.2	31.6		6.6	49.9	3.7	777	234.6	109	0.6	0.288714286	0.594
BARSHAL	24.15044	87.786227	6.69	57.7	8.7	25	0.43	24.7	3.9	528	176	55	0.6	0.288714286	0.594
CHANDPUR	24.19926	87.693988	7.6	32.1	6.1	5	2.59	22	2.5	281	129.5	19	0.6	0.288714286	0.594
SAONSA	24.11273	87.719266	6.25	20.8	10	45	6.08	7.3	7.6	248	49	14	0.6	0.288714286	0.594
SAONSA	24.11103	87.717644	7.55	44.1	10.9	22.5	67.9	64.9	1	572	134.1	85	0.6	0.288714286	0.594
SAONSA	24.11051	87.715732	7.79	48.1	27.9	17.8	108.4	59.9	1.9	647	189.6	61	0.6	0.288714286	0.594
SAONSA	24.1094	87.716927	7.79	48.1	27.9	17.8	108.4	59.9	1.9	647	189.6	61	0.6	0.288714286	0.594
BAMDEBPUR	24.18043	87.840933	6.55	9.6	4.4	4.3	5.17	18.1	0.5	164	58	14	0.6	0.288714286	0.594
SAKIRPUR	24.14619	87.780403	7.7	44.1	18.2	18.3	6.71	35	5.8	438	175.8	26	0.59	0.283902381	0.5841
GUG	24.13826	87.727788	7.4	30.1	13.4		0.35	17.8	1	260	122.4	21	0.59	0.283902381	0.5841
CHAKPARA	24.12125	87.754265	6.96	19	8.5	7.5	15.2	56.9	28	460	85.6	75	0.59	0.283902381	0.5841
CHAKPARA	24.12543	87.754167	7.78	40.1	10.9	5	0.5	20.5	1.1	338	157.3	24	0.59	0.283902381	0.5841
AYAS	24.25664	87.800132	7.35	53.4	11.3		0.2	110.1	2.2	813	250.5	104	0.59	0.283902381	0.5841
SAONSA	24.11015	87.71723	8.11	25.1	11.5	6.8	0.5	51.9	4.4	405	191.9	19	0.59	0.283902381	0.5841
CHAKPARA	24.12632	87.754383	7.55	98.2	7.3	37	7.13	119.9	6.6	1144	296	182	0.58	0.279090476	0.5742
GOPALPUR	24.11549	87.712962	7.2	40.1	12.2		2.71	40.3	1.7	405	102	26	0.58	0.279090476	0.5742
AYAS	24.25573	87.794817	7.45	8	4.9	9.3	4.89	30	17	240	55.5	33	0.58	0.279090476	0.5742
SAONSA	24.1112	87.718492	7.07	40.5	33.4		0.2	60.1	2.7	728	329.3	25	0.58	0.279090476	0.5742
TELDAHA	24.10877	87.727687	7	4	4.9		0.63	20.4	9.4	146	40.8	19	0.55	0.264654762	0.5445
JOYKRISHNAPUR	24.18676	87.804902	7.26	32.4	14.7		0.2	96.8	2.1	588	220.2	48	0.55	0.264654762	0.5445



Integrated approach on discerning fluoride contamination mechanisms in the groundwater and formulating remedial strategies for potential health hazards in Birbhum District, West Bengal'.

SAKIRPUR	24.14509	87.779875	7.74	23.2	10.4	23	2.85	26.5	1.1	311	114	17	0.55	0.264654762	0.5445
SAIPUR	24.23107	87.792936	7.77	15	10.3	30.5	1.49	90.9	13	503	208.1	21	0.55	0.264654762	0.5445
CHAKAIPUR	24.19919	87.713377	6.96	44.9	17.5	34	0.92	48.9	3.4	559	260	21	0.55	0.264654762	0.5445
RADIPUR	24.14948	87.726328	7.44	47.1	41.3	225	0.5	81.9	3.2	862	238.2	14	0.55	0.264654762	0.5445
MURADDA	24.12106	87.731835	7.83	37.1	9.1	93	0.5	85.9	13.6	586	201.2	17	0.55	0.264654762	0.5445
SADINPUR	24.2301	87.794128	7.3	128.3	20.7		0.68	187.5	2.2	1482	438.6	221	0.55	0.264654762	0.5445
SAONSA	24.11108	87.717355	8.23	34.1	19.4	11	0.5	48	4.8	395	180.4	19	0.55	0.264654762	0.5445
SAONSA	24.10994	87.720558	7.39	6.5	2.9		0.2	134.5	1	402	163.6	19	0.55	0.264654762	0.5445
JOYKRISHNAPUR	24.18712	87.80509	8.73	18	7.3	22	3.13	96.9	5.1	556	152.6	59	0.54	0.259842857	0.5346
JOYKRISHNAPUR	24.18732	87.804675	8.18	20	3	36.5	1.25	131.9	3.8	708	157.3	87	0.54	0.259842857	0.5346
PANISAIL	24.23289	87.78552	7.39	30.8	12.3		10.36	150.8	2.9	912	250.5	113	0.54	0.259842857	0.5346
MADHYA GOPALPUR	24.14461	87.78605	7.95	19.4	6.9		0.2	218.1	6.7	1106	254.5	183	0.54	0.259842857	0.5346
SAKIRPUR	24.14461	87.779907	9.62	1	2.9								0.54	0.259842857	0.5346
CHAKAIPUR	24.20591	87.710272	7.77	78.2	37.7	51	20.3	49	4	815	245.1	90	0.54	0.259842857	0.5346
BARSHAL	24.14983	87.784123	7.21	53.1	16.4	16.5	10.6	34	4.8	508	131.8	71	0.54	0.259842857	0.5346
JOYKRISHNAPUR	24.18429	87.796305	8.1	51.1	29.2	6.3	0.8	46	6	695	314.5	47	0.54	0.259842857	0.5346
AKHIRA	24.19781	87.776251	8.41	62.1	34	7.5	1.06	80.9	3.2	488	235.9	12	0.54	0.259842857	0.5346
CHITURI	24.13985	87.750014	7.04	48.6	13.7		0.2	46.9	2.1	475	222.2	15	0.54	0.259842857	0.5346
SERPUR	24.1827	87.833203	6.8	32.1	12.2		16.65	50.9	1.5	446	255	50	0.54	0.259842857	0.5346
SAKIRPUR	24.14499	87.78061	8.26	26.1	17.6	12.5	0.5	59.9	7.3	626	321.4	21	0.53	0.255030952	0.5247
BARSHAL	24.14422	87.784525	6.46	76.2	24.3		1.22	25.9	2.3	581	209.1	78	0.53	0.255030952	0.5247
BARSHAL	24.14842	87.78314	6.94	92.2	34	56	2.33	51	4.5	942	300	104	0.53	0.255030952	0.5247
JOYKRISHNAPUR	24.18308	87.797232	7.78	158.3	15.8	65	3.05	111.9	7	1967	351.5	401	0.53	0.255030952	0.5247
BARSHAL	24.15099	87.782925	6.9	220.4	58.3		38.1	78.5	6.1	1597	413.1	261	0.53	0.255030952	0.5247
AKHIRA	24.19537	87.776963	7.7	54.1	60.8	35	1.21	69.9	6.4	1029	261.3	156	0.53	0.255030952	0.5247
AKHIRA	24.19301	87.780664	7.75	28.1	5.5	5	14.8	16.2	0.8	250	87.9	24	0.53	0.255030952	0.5247
BAMDEBPUR	24.17922	87.841013	7.73	54.1	18.2	20.5	0.5	43	3.6	520	203.5	33	0.53	0.255030952	0.5247
JOYKRISHNAPUR	24.18668	87.80379	8.11	150.3	45	57	64.8	143.9	2.6	1808	300.6	354	0.52	0.250219048	0.5148
SAKIRPUR	24.14568	87.78137	7.45	48.1	12.2	40	25.5	66.9	1.1	600	101.8	94	0.52	0.250219048	0.5148
SADINPUR	24.23332	87.79407	8.4	24	12.2		0.6	49.9	2.3	403	127.5	62	0.52	0.250219048	0.5148
JOYKRISHNAPUR	24.18453	87.796523	8.08	124.2	7.3	24	0.5	50	2.2	1280	305.3	208	0.52	0.250219048	0.5148
JOYKRISHNAPUR	24.18562	87.794032	7.71	70.1	25.5	47.5	25	69.9	1.9	820	154.9	130	0.52	0.250219048	0.5148
JOYKRISHNAPUR	24.18476	87.803928	7.72	30.1	32.2	6.8	0.5	32	2	464	233.6	17	0.52	0.250219048	0.5148
MASANPUR	24.24004	87.687883	7.1	132.3	51		22.62	80.5	2.2	1278	336.6	195	0.52	0.250219048	0.5148
CHITURI	24.13775	87.749809	7.1	84.2	31.6		6.6	49.9	3.7	777	234.6	109	0.52	0.250219048	0.5148
AYAS	24.25377	87.788603	6.69	57.7	8.7	25	0.43	24.7	3.9	528	176	55	0.45	0.216535714	0.4455
JOYKRISHNAPUR	24.18525	87.802607	7.6	32.1	6.1	5	2.59	22	2.5	281	129.5	19	0.45	0.216535714	0.4455
GUG	24.13804	87.729145	6.25	20.8	10	45	6.08	7.3	7.6	248	49	14	0.45	0.216535714	0.4455
SAKIRPUR	24.14727	87.780563	7.55	44.1	10.9	22.5	67.9	64.9	1	572	134.1	85	0.45	0.216535714	0.4455
CHAKPARA	24.12023	87.755225	7.79	48.1	27.9	17.8	108.4	59.9	1.9	647	189.6	61	0.45	0.216535714	0.4455
BARSHAL	24.14803	87.780648	7.79	48.1	27.9	17.8	108.4	59.9	1.9	647	189.6	61	0.45	0.216535714	0.4455
RAMRAMPUR	24.18788	87.789525	6.55	9.6	4.4	4.3	5.17	18.1	0.5	164	58	14	0.45	0.216535714	0.4455
SADINPUR	24.23193	87.79399	7.7	44.1	18.2	18.3	6.71	35	5.8	438	175.8	26	0.45	0.216535714	0.4455



'Integrated approach on discerning fluoride contamination mechanisms in the groundwater and formulating remedial strategies for potential health hazards in Birbhum District, West Bengal'.

CHITURI	24.13917	87.74987	7.4	30.1	13.4		0.35	17.8	1	260	122.4	21	0.45	0.216535714	0.4455
AKHIRA	24.194	87.780602	6.96	19	8.5	7.5	15.2	56.9	28	460	85.6	75	0.45	0.216535714	0.4455
SAONSA	24.1109	87.720132	7.78	40.1	10.9	5	0.5	20.5	1.1	338	157.3	24	0.45	0.216535714	0.4455
SERPUR	24.18236	87.833905	7.35	53.4	11.3		0.2	110.1	2.2	813	250.5	104	0.45	0.216535714	0.4455
AYAS	24.25272	87.791823	8.11	25.1	11.5	6.8	0.5	51.9	4.4	405	191.9	19	0.44	0.21172381	0.4356
CHAKAIPUR	24.21115	87.732518	7.55	98.2	7.3	37	7.13	119.9	6.6	1144	296	182	0.44	0.21172381	0.4356
JOYKRISHNAPUR	24.18324	87.802232	7.2	40.1	12.2		2.71	40.3	1.7	405	102	26	0.44	0.21172381	0.4356
CHAKAIPUR	24.20137	87.714267	7.45	8	4.9	9.3	4.89	30	17	240	55.5	33	0.44	0.21172381	0.4356
RANAPUR	24.12756	87.818483	7.07	40.5	33.4		0.2	60.1	2.7	728	329.3	25	1.4	0.673666667	1.386
RANAPUR	24.12777	87.819903	7	4	4.9		0.63	20.4	9.4	146	40.8	19	1.4	0.673666667	1.386
RANAPUR	24.12824	87.818287	7.26	32.4	14.7		0.2	96.8	2.1	588	220.2	48	1.3	0.625547619	1.287
RANAPUR	24.12708	87.817462	7.74	23.2	10.4	23	2.85	26.5	1.1	311	114	17	1.3	0.625547619	1.287
RANAPUR	24.12631	87.823113	7.77	15	10.3	30.5	1.49	90.9	13	503	208.1	21	1.3	0.625547619	1.287
RANAPUR	24.12857	87.818567	6.96	44.9	17.5	34	0.92	48.9	3.4	559	260	21	1.2	0.577428571	1.188
RANAPUR	24.12681	87.82389	7.44	47.1	41.3	225	0.5	81.9	3.2	862	238.2	14	1.2	0.577428571	1.188
RANAPUR	24.12717	87.821408	7.83	37.1	9.1	93	0.5	85.9	13.6	586	201.2	17	0.91	0.437883333	0.9009
NABAGRAM	24.12777	87.81037	7.3	128.3	20.7		0.68	187.5	2.2	1482	438.6	221	0.9	0.433071429	0.891
BUDHIGRAM	24.08962	87.884555	8.23	34.1	19.4	11	0.5	48	4.8	395	180.4	19	0.85	0.409011905	0.8415
BUDHIGRAM	24.09112	87.885822	7.39	6.5	2.9		0.2	134.5	1	402	163.6	19	0.85	0.409011905	0.8415
SANTOSHPUR	24.21276	87.879175	8.73	18	7.3	22	3.13	96.9	5.1	556	152.6	59	0.84	0.4042	0.8316
BUDHIGRAM	24.08785	87.883265	8.18	20	3	36.5	1.25	131.9	3.8	708	157.3	87	0.84	0.4042	0.8316
BUDHIGRAM	24.0905	87.88615	7.39	30.8	12.3		10.36	150.8	2.9	912	250.5	113	0.84	0.4042	0.8316
MARGRAM	24.144	87.84266	7.95	19.4	6.9		0.2	218.1	6.7	1106	254.5	183	0.84	0.4042	0.8316
BUDHIGRAM	24.09183	87.883497	9.62	1	2.9								0.83	0.399388095	0.8217
BUDHIGRAM	24.0903	87.887508	7.83	28.1	8.5	7.5	7.12	25.6	1.3	379	143.4	35	0.83	0.399388095	0.8217
BUDHIGRAM	24.09051	87.884463	6.94	48.6	8.3		1.3	17.3	1.3	350	176.8	7.2	0.83	0.399388095	0.8217
BUDHIGRAM	24.0892	87.885862	6.94	48.6	8.3		1.3	17.3	1.3	350	176.8	7.2	0.83	0.399388095	0.8217
BUDHIGRAM	24.0916	87.885808	7.77	19	11.5	10.8	0.87	19	1.3	334	175.8	17	0.83	0.399388095	0.8217
BUDHIGRAM	24.09151	87.88488	7.68	108.2	28.6	78	96.5	110	24	1224	231.3	184	0.82	0.39457619	0.8118
BUDHIGRAM	24.09031	87.889443	6.92	11.33	2.9		0.33	5.6	6.2	104	40.4	7.2	0.82	0.39457619	0.8118
RANAPUR	24.12717	87.822182	8.8	12	7.3		0.29	46.9	16.4	317	91.8	52	0.82	0.39457619	0.8118
RANAPUR	24.12698	87.822995	7.87	27.1	1.8	5	0.62	15.4	0.9	206	97.1	17	0.82	0.39457619	0.8118
RANAPUR	24.1262	87.825145	8	35.1	11.5	5	1.06	10.2	2.7	273	131.8	19	0.82	0.39457619	0.8118
BUDHIGRAM	24.09079	87.88498	7.15	44.1	6.1	23.5	6.08	58.9	2.5	501	115.6	83	0.81	0.389764286	0.8019
BUDHIGRAM	24.08817	87.886605	8.06	22	7.3	5	8.58	9.7	1.8	202	67.1	21	0.81	0.389764286	0.8019
NINGA	24.20823	87.889372	8.15	38.1	15.8	34.3	0.8	60.9	141	919	270.6	99	0.8	0.384952381	0.792
CHAKBATI	24.22915	87.89104	7.67	67.1	14.6	26.8	0.98	53.9	8	1059	365.4	130	0.8	0.384952381	0.792
RANAPUR	24.1269	87.817952	8.01	43.1	41.3	5.8	8.84	27	1.5	589	254.4	57	0.8	0.384952381	0.792
NABAGRAM	24.12679	87.810497	7.77	30.1	4.3	5	5.31	10.1	2	232	94.8	14	0.8	0.384952381	0.792
KHAMEDDA	24.07162	87.873472	6.92	17.8	3.9		10.47	56	1.1	367		33	0.63	0.30315	0.6237
KHAMEDDA	24.07062	87.874852	7.35	16	5.5	5	0.44	24.7	1.8	226	71.7	24	0.63	0.30315	0.6237
UTTAR NARAYANPUR	24.18023	87.852567	8.42	34.1	13.4	5	3.26	13.6	3.6	269	111	14	0.62	0.298338095	0.6138
UTTAR NARAYANPUR	24.18	87.849957	6.87	84.2	13.4	66	132.2	87.6	8.5	1025	200	101	0.62	0.298338095	0.6138



Integrated approach on discerning fluoride contamination mechanisms in the groundwater and formulating remedial strategies for potential health hazards in Birbhum District, West Bengal.

KHAMEDDA	24.07189	87.875088	7.29	42.1	15.7		0.23	86.6	1.2	475	228.3	9.6	0.62	0.298338095	0.6138
KHAMEDDA	24.07119	87.873003	7.29	42.1	15.7		0.23	86.6	1.2	475	228.3	9.6	0.62	0.298338095	0.6138
KHAMEDDA	24.07083	87.874918	7.72	45.1	7.9	8.3	0.89	29	2.4	407	159.6	33	0.62	0.298338095	0.6138
NINGA	24.214	87.887217	7.83	28.1	8.5	7.5	7.12	25.6	1.3	379	143.4	35	0.62	0.298338095	0.6138
KHAMEDDA	24.07179	87.872467	6.94	48.6	8.3		1.3	17.3	1.3	350	176.8	7.2	0.62	0.298338095	0.6138
MARA BASAHAR	24.19496	87.849483	6.94	48.6	8.3		1.3	17.3	1.3	350	176.8	7.2	0.62	0.298338095	0.6138
NINGA	24.2169	87.8913	7.77	19	11.5	10.8	0.87	19	1.3	334	175.8	17	0.62	0.298338095	0.6138
UTTAR NARAYANPUR	24.17797	87.854103	7.68	108.2	28.6	78	96.5	110	24	1224	231.3	184	0.61	0.29352619	0.6039
MARGRAM	24.14942	87.844452	6.92	11.33	2.9		0.33	5.6	6.2	104	40.4	7.2	0.61	0.29352619	0.6039
NINGA	24.21526	87.886648	8.8	12	7.3		0.29	46.9	16.4	317	91.8	52	0.61	0.29352619	0.6039
NINGA	24.21589	87.884533	7.87	27.1	1.8	5	0.62	15.4	0.9	206	97.1	17	0.61	0.29352619	0.6039
MARA BASAHAR	24.19732	87.850395	8	35.1	11.5	5	1.06	10.2	2.7	273	131.8	19	0.61	0.29352619	0.6039
CHAKBATI	24.22805	87.88853	7.15	44.1	6.1	23.5	6.08	58.9	2.5	501	115.6	83	0.6	0.288714286	0.594
UTTAR NARAYANPUR	24.18086	87.851135	8.06	22	7.3	5	8.58	9.7	1.8	202	67.1	21	0.6	0.288714286	0.594
RANAPUR	24.1258	87.823067	8.15	38.1	15.8	34.3	0.8	60.9	141	919	270.6	99	0.6	0.288714286	0.594
RANAPUR	24.12534	87.824918	7.67	67.1	14.6	26.8	0.98	53.9	8	1059	365.4	130	0.6	0.288714286	0.594
JAGADISHPUR	24.20249	87.84972	8.01	43.1	41.3	5.8	8.84	27	1.5	589	254.4	57	0.6	0.288714286	0.594
JAGADISHPUR	24.20441	87.850725	7.77	30.1	4.3	5	5.31	10.1	2	232	94.8	14	0.6	0.288714286	0.594
NABAGRAM	24.12782	87.809563	6.92	17.8	3.9		10.47	56	1.1	367		33	0.6	0.288714286	0.594
CHHOTA KANAIPUR	24.23006	87.896865	7.35	16	5.5	5	0.44	24.7	1.8	226	71.7	24	0.59	0.283902381	0.5841
UTTAR NARAYANPUR	24.17922	87.853112	8.42	34.1	13.4	5	3.26	13.6	3.6	269	111	14	0.59	0.283902381	0.5841
UTTAR NARAYANPUR	24.18019	87.851885	6.87	84.2	13.4	66	132.2	87.6	8.5	1025	200	101	0.59	0.283902381	0.5841
UTTAR NARAYANPUR	24.18118	87.853383	7.29	42.1	15.7		0.23	86.6	1.2	475	228.3	9.6	0.59	0.283902381	0.5841
MARGRAM	24.14838	87.846795	7.29	42.1	15.7		0.23	86.6	1.2	475	228.3	9.6	0.59	0.283902381	0.5841
KURULA	24.18917	87.834255	7.72	45.1	7.9	8.3	0.89	29	2.4	407	159.6	33	0.59	0.283902381	0.5841
BALSA	24.21771	87.9428	7.35	53.4	11.3		0.2	110.1	2.2	813	250.5	104	0.59	0.283902381	0.5841
HATPARA	24.21921	87.872431	8.11	25.1	11.5	6.8	0.5	51.9	4.4	405	191.9	19	0.59	0.283902381	0.5841
BEJURI	24.08808	87.808258	7.55	98.2	7.3	37	7.13	119.9	6.6	1144	296	182	0.58	0.279090476	0.5742
CHHOTA KANAIPUR	24.23078	87.896982	7.2	40.1	12.2		2.71	40.3	1.7	405	102	26	0.58	0.279090476	0.5742
UTTAR NARAYANPUR	24.17976	87.851945	7.45	8	4.9	9.3	4.89	30	17	240	55.5	33	0.58	0.279090476	0.5742
MARGRAM	24.14791	87.84297	7.07	40.5	33.4		0.2	60.1	2.7	728	329.3	25	0.58	0.279090476	0.5742
MARGRAM	24.14865	87.84893	7	4	4.9		0.63	20.4	9.4	146	40.8	19	0.58	0.279090476	0.5742
HATPARA	24.2202	87.871494	7.26	32.4	14.7		0.2	96.8	2.1	588	220.2	48	0.58	0.279090476	0.5742
MARA BASAHAR	24.19385	87.848753	7.74	23.2	10.4	23	2.85	26.5	1.1	311	114	17	0.58	0.279090476	0.5742
KALIDHAHA	24.14798	87.888047	7.77	15	10.3	30.5	1.49	90.9	13	503	208.1	21	0.57	0.274278571	0.5643
CHAKBATI	24.23006	87.89379	6.96	44.9	17.5	34	0.92	48.9	3.4	559	260	21	0.57	0.274278571	0.5643
CHHOTA KANAIPUR	24.22861	87.894133	7.44	47.1	41.3	225	0.5	81.9	3.2	862	238.2	14	0.57	0.274278571	0.5643
BISHNUPUR	24.13141	87.891845	7.83	37.1	9.1	93	0.5	85.9	13.6	586	201.2	17	0.57	0.274278571	0.5643
BISHNUPUR	24.13401	87.88993	7.3	128.3	20.7		0.68	187.5	2.2	1482	438.6	221	0.57	0.274278571	0.5643
NINGA	24.2174	87.890097	8.23	34.1	19.4	11	0.5	48	4.8	395	180.4	19	0.57	0.274278571	0.5643
BEJURI	24.09011	87.80461	7.39	6.5	2.9		0.2	134.5	1	402	163.6	19	0.56	0.269466667	0.5544
BEJURI	24.08936	87.804683	8.73	18	7.3	22	3.13	96.9	5.1	556	152.6	59	0.55	0.264654762	0.5445
KALIDHAHA	24.14842	87.889383	8.18	20	3	36.5	1.25	131.9	3.8	708	157.3	87	0.55	0.264654762	0.5445



Integrated approach on discerning fluoride contamination mechanisms in the groundwater and formulating remedial strategies for potential health hazards in Birbhum District, West Bengal.

CHHOTA KANAIPUR	24.22961	87.89614	7.39	30.8	12.3		10.36	150.8	2.9	912	250.5	113	0.55	0.264654762	0.5445
MARGRAM	24.14635	87.84337	7.95	19.4	6.9		0.2	218.1	6.7	1106	254.5	183	0.55	0.264654762	0.5445
MARGRAM	24.14814	87.843375	9.62	1	2.9								0.55	0.264654762	0.5445
PANCH PUKHURIA	23.9342	87.568872	7.83	28.1	8.5	7.5	7.12	25.6	1.3	379	143.4	35	5.1	2.454071429	5.049
DHULLA	23.93417	87.568887	6.94	48.6	8.3		1.3	17.3	1.3	350	176.8	7.2	4.86	2.338585714	4.8114
MALLICKPUR	23.8672	87.50492	6.94	48.6	8.3		1.3	17.3	1.3	350	176.8	7.2	3.4	1.636047619	3.366
MALLICKPUR	23.86432	87.512616	7.77	19	11.5	10.8	0.87	19	1.3	334	175.8	17	3.21	1.544621429	3.1779
MALLICKPUR	23.86482	87.513621	7.68	108.2	28.6	78	96.5	110	24	1224	231.3	184	2.92	1.40507619	2.8908
KUKHURDIHI	23.92444	87.566153	6.92	11.33	2.9		0.33	5.6	6.2	104	40.4	7.2	2.9	1.395452381	2.871
MALLICKPUR	23.86489	87.51342	8.8	12	7.3		0.29	46.9	16.4	317	91.8	52	2.9	1.395452381	2.871
KUTURA	23.87622	87.535853	7.87	27.1	1.8	5	0.62	15.4	0.9	206	97.1	17	2.9	1.395452381	2.871
MALLICKPUR	23.86549	87.513221	8	35.1	11.5	5	1.06	10.2	2.7	273	131.8	19	2.36	1.135609524	2.3364
GAJALPUR	23.86177	87.52132	6.53	13	4.9		8.08	23.6	2.1	187	74.7	7.2	2.3	1.106738095	2.277
ITAGARIA	23.92432	87.566163	6.53	13	4.9		8.08	23.6	2.1	187	74.7	7.2	2.7	1.299214286	2.673
MALLICKPUR	23.86487	87.513537	6.53	13	4.9		8.08	23.6	2.1	187	74.7	7.2	2.69	1.294402381	2.6631
GOBINDAPUR	23.89038	87.482766	7.4	49.1	6.1	5	7.37	5.8	3.3	290	117.9	19	2.66	1.279966667	2.6334
ITAGARIA	23.92417	87.56613	6.84	10	9.1	5	5.82	8.7	8.6	163	37	28	2.66	1.279966667	2.6334
ADDA	23.87698	87.533487	7.97	18.7	1		0.69	7.8	0.8	119	55.5		2.55	1.227035714	2.5245
ADDA	23.87701	87.533568	5.68	111.7	27.5		11.1	56	3.4	1120	222.2	290	2.5	1.20297619	2.475
GOBINDAPUR	23.89363	87.481688	6.5	20	2.4	13.5	58.8	14.2	6.6	202	23.1	26	1.6	0.769904762	1.584
MAMREZPUR	23.8878	87.47954	6.81	42.9	16.7		0.2	33.8	1.6	496	157.6	50	1.54	0.741033333	1.5246
GOBINDAPUR	23.89321	87.481733	7.8	47.1	16.4	12	13.7	28.5	23	461	143.4	47	1.43	0.688102381	1.4157
ITAGARIA	23.92412	87.564183	7.68	37.1	15.2	5	0.5	22.5	1.5	317	157.3	9.4	2.18	1.048995238	2.1582
MAHESHPUR	23.92874	87.566845	5.74	4	1.7	1	8.91	1	3.1	58	12	8.2	2.1	1.0105	2.079
GOBINDAPUR	23.89516	87.483618	6.51	61.5	22.6		0.2	41.6		626	195.9	65	1.3	0.625547619	1.287
UPARJOL	23.92653	87.466958	6.51	61.5	22.6		0.2	41.6		626	195.9	65	1.22	0.587052381	1.2078
CHANDANPUR	23.8673	87.517063	7.46	50.1	18.2	16.5	66.5	26	3.2	433	10.8	52	1.2	0.577428571	1.188
MAMREZPUR	23.88957	87.480078	8.05	11	7.9	10	0.62	12.4	2.1	140	55.5	9.4	1.2	0.577428571	1.188
GOBINDAPUR	23.89501	87.483662	7.61	20	7.3	5	0.5	10.5	0.8	178	87.9	12	1.14	0.548557143	1.1286
CHANDANPUR	23.86545	87.515968	8.45	51.1	17.6	14	0.5	25.5	2.9	506	196.6	33	1.1	0.529309524	1.089
CHANDANPUR	23.86548	87.517948	7.64	80.2	19.4	5	1.03	30	2.9	672	85.6	125	1.1	0.529309524	1.089
UPARJOL	23.92136	87.469147	6.44	58.3	32.4		4.25	32.6	1.7	648	198	85	1.1	0.529309524	1.089
LAKSHMONDARPUR	23.90413	87.492145	7.73	21	6.5	7.5	0.5	17	1.3	262	122.6	14	0.84	0.4042	0.8316
KARIDHYA	23.90889	87.503555	7.53	23	27.3	5	0.5	20	1.2	440	228.9	9.4	0.83	0.399388095	0.8217
MAHULA	23.96145	87.436203	7.48	100.2	59.5	36	103.1	45.5	2.8	1196	171.1	236	0.83	0.399388095	0.8217
LAKSHMANDIHI	23.8245	87.465133	6.58	31.6	13.3		4.34	91.7		286	103	24	0.82	0.39457619	0.8118
BROJERGRAM	23.90715	87.515482	7.19	30.1	4.9	29	16.3	46.5	2.4	418	48.6	68	0.81	0.389764286	0.8019
BHURKUNA	23.83447	87.508487	7.83	79.2	20.7	90	101.5	88.9	5.5	1395	219.7	257	0.81	0.389764286	0.8019
TASARKATA	23.92458	87.495338	7.51	7	4.3	5.5	2.13	6.6	2.2	101	41.6	4.7	0.8	0.384952381	0.792
BHURKUNA	23.83211	87.501062	7.8	59.1	12.8	15.8	10.8	23.2	3.2	535	161.9	64	0.78	0.375328571	0.7722
BHURKUNA	23.83443	87.498812	7.48	48.1	32.8	69	0.18	53.9	1.6	721	180.4	94	0.78	0.375328571	0.7722
LANGULIA	23.97118	87.455787	7.38	158.3	45	88	147.2	47	3.6	1319	224.3	222	0.77	0.370516667	0.7623
BHURKUNA	23.83397	87.495361	7.13	27.1	8.5	11.5	80.1	40	1.3	390	64.8	50	0.77	0.370516667	0.7623



Integrated approach on discerning fluoride contamination mechanisms in the groundwater and formulating remedial strategies for potential health hazards in Birbhum District, West Bengal.

UPARJOL	23.91634	87.465203	6.53	13	4.9		8.08	23.6	2.1	187	74.7	7.2	0.76	0.365704762	0.7524
HARIDASPUR	23.89534	87.479235	6.53	13	4.9		8.08	23.6	2.1	187	74.7	7.2	0.72	0.346457143	0.7128
KALIPUR	23.90625	87.5068	6.53	13	4.9		8.08	23.6	2.1	187	74.7	7.2	0.71	0.341645238	0.7029
CHHORA	23.91739	87.486587	7.4	49.1	6.1	5	7.37	5.8	3.3	290	117.9	19	0.71	0.341645238	0.7029
UPARJOL	23.92381	87.470573	6.84	10	9.1	5	5.82	8.7	8.6	163	37	28	0.71	0.341645238	0.7029
MOHANPUR	23.81875	87.490283	7.97	18.7	1		0.69	7.8	0.8	119	55.5		0.7	0.336833333	0.693
CHHORA	23.91565	87.488935	5.68	111.7	27.5		11.1	56	3.4	1120	222.2	290	0.7	0.336833333	0.693
CHHORA	23.91469	87.495195	6.5	20	2.4	13.5	58.8	14.2	6.6	202	23.1	26	0.7	0.336833333	0.693
JIBDHARPUR	23.88607	87.500425	6.81	42.9	16.7		0.2	33.8	1.6	496	157.6	50	0.7	0.336833333	0.693
SAHABAZAR	23.91924	87.440408	7.8	47.1	16.4	12	13.7	28.5	23	461	143.4	47	0.69	0.332021429	0.6831
BARIHAT	23.8353	87.502753	7.68	37.1	15.2	5	0.5	22.5	1.5	317	157.3	9.4	0.69	0.332021429	0.6831
MURAMATH	23.8526	87.49415	5.74	4	1.7	1	8.91	1	3.1	58	12	8.2	0.69	0.332021429	0.6831
BHURKUNA	23.83253	87.499881	6.51	61.5	22.6		0.2	41.6		626	195.9	65	0.66	0.317585714	0.6534
BHURKUNA	23.83584	87.498817	6.51	61.5	22.6		0.2	41.6		626	195.9	65	0.66	0.317585714	0.6534
CHANDANPUR	23.87627	87.512192	7.46	50.1	18.2	16.5	66.5	26	3.2	433	10.8	52	0.65	0.31277381	0.6435
KUSTOR	23.97817	87.456607	8.05	11	7.9	10	0.62	12.4	2.1	140	55.5	9.4	0.65	0.31277381	0.6435
BHURKUNA	23.83151	87.501656	7.61	20	7.3	5	0.5	10.5	0.8	178	87.9	12	0.65	0.31277381	0.6435
CHAKDAHA	23.88042	87.496405	8.45	51.1	17.6	14	0.5	25.5	2.9	506	196.6	33	0.64	0.307961905	0.6336
AGAR	23.84225	87.503407	7.64	80.2	19.4	5	1.03	30	2.9	672	85.6	125	0.64	0.307961905	0.6336
RANPUR	23.93382	87.506134	6.44	58.3	32.4		4.25	32.6	1.7	648	198	85	0.64	0.307961905	0.6336
PARSIMULIA	23.94641	87.584445	7.73	21	6.5	7.5	0.5	17	1.3	262	122.6	14	0.63	0.30315	0.6237
CHHORA	23.91473	87.496017	7.53	23	27.3	5	0.5	20	1.2	440	228.9	9.4	0.63	0.30315	0.6237
LATABANI	23.9453	87.41674	7.48	100.2	59.5	36	103.1	45.5	2.8	1196	171.1	236	0.62	0.298338095	0.6138
KARIDHYA	23.91474	87.505358	6.58	31.6	13.3		4.34	91.7		286	103	24	0.62	0.298338095	0.6138
KARIDHYA	23.91196	87.50361	7.19	30.1	4.9	29	16.3	46.5	2.4	418	48.6	68	0.62	0.298338095	0.6138
BARIHAT	23.83399	87.503845	7.83	79.2	20.7	90	101.5	88.9	5.5	1395	219.7	257	0.62	0.298338095	0.6138
TILPARA	23.92007	87.527025	7.51	7	4.3	5.5	2.13	6.6	2.2	101	41.6	4.7	0.62	0.298338095	0.6138
NABAGRAM	23.95577	87.448225	7.8	59.1	12.8	15.8	10.8	23.2	3.2	535	161.9	64	0.61	0.29352619	0.6039
CHHORA	23.91642	87.487127	7.48	48.1	32.8	69	0.18	53.9	1.6	721	180.4	94	0.61	0.29352619	0.6039
CHHORA	23.91461	87.49664	7.38	158.3	45	88	147.2	47	3.6	1319	224.3	222	0.61	0.29352619	0.6039
CHORMARA	23.90244	87.485907	7.13	27.1	8.5	11.5	80.1	40	1.3	390	64.8	50	0.61	0.29352619	0.6039
NAGARI	23.9305	87.460642	7.87	83.2	19.4	5	0.83	35	3.2	656	268.3	59	0.61	0.29352619	0.6039
LAKSHMANDIHI	23.8248	87.470545	7.41	150.3	26.7	60	145.5	89.9	5	1359	134.1	290	0.61	0.29352619	0.6039
LAKSHMANDIHI	23.82515	87.466025	7.69	32.1	18.2	15.5	10.2	29.5	1.5	735	185	127	0.61	0.29352619	0.6039
KAKURIA	23.92083	87.57258	7.84	29.1	23.7	5	1.04	32	0.9	411	212.8	35	0.6	0.288714286	0.594
KARIDHYA	23.90844	87.504916	7.3	86.2	35.2		1.57	43	1.4	610	78.6	99	0.6	0.288714286	0.594
RANPUR	23.93471	87.506038	7.66	61.1	28.6	18.5	1.51	29	6.6	600	203.5	71	0.6	0.288714286	0.594
DHARAMPUR	23.93247	87.432328	7.43	31.1	7.3	5	2.59	20.7	0.8	268	131.8	9.4	0.6	0.288714286	0.594
CHANGURIA	23.87559	87.53936	7.71	132.3	14.6	85	12.4	53.9	6.9	1487	372.3	236	0.59	0.283902381	0.5841
KUSTOR	23.97753	87.457067	7.95	87.2	48	38	90.9	33	2.6	897	198.9	139	0.59	0.283902381	0.5841
KUSTOR	23.97718	87.456563	6.83	111.7	13.7		8.13	40.8	1.7	860	166.7	154	0.59	0.283902381	0.5841
KENDULI	23.97775	87.4491	7.46	16	4.9	5	0.5	13.4	1	144	67.1	12	0.59	0.283902381	0.5841
BHURKUNA	23.83627	87.498143	7.66	24	9.1	6.3	0.5	20.5	1.5	373	189.6	12	0.59	0.283902381	0.5841



Integrated approach on discerning fluoride contamination mechanisms in the groundwater and formulating remedial strategies for potential health hazards in Birbhum District, West Bengal'.

TILPARA	23.92199	87.518888	7.37	356.7	66.8	185	256.5	234.8	5.1	3808	344.6	790	0.59	0.283902381	0.5841
AMGACHHI	23.92237	87.472645	6.5	80.2	26.7		64.99	103.9	52.3	1085	158.1	202	0.58	0.279090476	0.5742
PATHAR CHAPRI	23.92596	87.432313	8.49	36.1	10.9	5	5.67	27	1.1	343	127.2	26	0.57	0.274278571	0.5643
MURULIA CHAK	23.96849	87.45356	7.47	157.3	9.1	82	5.28	54.9	5.7	1315	284.4	219	0.56	0.269466667	0.5544
SAHABAZAR	23.92034	87.452085	7.83	28.1	8.5	7.5	7.12	25.6	1.3	379	143.4	35	0.56	0.269466667	0.5544
AMRAPALAN	23.88586	87.495763	6.94	48.6	8.3		1.3	17.3	1.3	350	176.8	7.2	0.56	0.269466667	0.5544
KACHUJOR	23.83271	87.470099	6.94	48.6	8.3		1.3	17.3	1.3	350	176.8	7.2	0.56	0.269466667	0.5544
RANPUR	23.93324	87.504328	7.77	19	11.5	10.8	0.87	19	1.3	334	175.8	17	0.56	0.269466667	0.5544
CHHORA	23.9164	87.493512	7.68	108.2	28.6	78	96.5	110	24	1224	231.3	184	0.55	0.264654762	0.5445
NIMTIKURI	23.87297	87.49127	6.92	11.33	2.9		0.33	5.6	6.2	104	40.4	7.2	0.55	0.264654762	0.5445
TASARKATA	23.92309	87.494187	8.8	12	7.3		0.29	46.9	16.4	317	91.8	52	0.55	0.264654762	0.5445
TASARKATA	23.92658	87.495602	7.87	27.1	1.8	5	0.62	15.4	0.9	206	97.1	17	0.55	0.264654762	0.5445
BHURKUNA	23.83439	87.496948	8	35.1	11.5	5	1.06	10.2	2.7	273	131.8	19	0.55	0.264654762	0.5445
AGAR	23.83715	87.503537	7.15	44.1	6.1	23.5	6.08	58.9	2.5	501	115.6	83	0.55	0.264654762	0.5445
RANPUR	23.93289	87.503453	8.06	22	7.3	5	8.58	9.7	1.8	202	67.1	21	0.55	0.264654762	0.5445
KALIPUR	23.90423	87.507188	8.15	38.1	15.8	34.3	0.8	60.9	141	919	270.6	99	0.54	0.259842857	0.5346
LANGULIA	23.97072	87.453312	7.67	67.1	14.6	26.8	0.98	53.9	8	1059	365.4	130	0.54	0.259842857	0.5346
LANGULIA	23.97126	87.452073	8.01	43.1	41.3	5.8	8.84	27	1.5	589	254.4	57	0.54	0.259842857	0.5346
SAHABAZAR	23.9164	87.447637	7.77	30.1	4.3	5	5.31	10.1	2	232	94.8	14	0.54	0.259842857	0.5346
LATABANI	23.94562	87.416092	7.87	83.2	19.4	5	0.83	35	3.2	656	268.3	59	0.54	0.259842857	0.5346
CHAKDAHA	23.88236	87.495815	7.41	150.3	26.7	60	145.5	89.9	5	1359	134.1	290	0.54	0.259842857	0.5346
JIBDHARPUR	23.88517	87.497515	7.69	32.1	18.2	15.5	10.2	29.5	1.5	735	185	127	0.54	0.259842857	0.5346
TARAPUR	23.93389	87.505293	7.84	29.1	23.7	5	1.04	32	0.9	411	212.8	35	0.46	0.221347619	0.4554
UPARJOL	23.9161	87.46613	7.3	86.2	35.2		1.57	43	1.4	610	78.6	99	0.46	0.221347619	0.4554
TILPARA	23.91811	87.50778	7.66	61.1	28.6	18.5	1.51	29	6.6	600	203.5	71	0.46	0.221347619	0.4554
LAKSHMANDIHI	23.82438	87.465716	7.43	31.1	7.3	5	2.59	20.7	0.8	268	131.8	9.4	0.46	0.221347619	0.4554
LAKSHMANDIHI	23.8315	87.46542	7.71	132.3	14.6	85	12.4	53.9	6.9	1487	372.3	236	0.46	0.221347619	0.4554
KARIDHYA	23.90973	87.500674	7.95	87.2	48	38	90.9	33	2.6	897	198.9	139	0.46	0.221347619	0.4554
RANPUR	23.93369	87.504634	6.83	111.7	13.7		8.13	40.8	1.7	860	166.7	154	0.46	0.221347619	0.4554
KARIDHYA	23.91062	87.500963	7.46	16	4.9	5	0.5	13.4	1	144	67.1	12	0.45	0.216535714	0.4455
PARBATIPUR	23.81534	87.564377	7.66	24	9.1	6.3	0.5	20.5	1.5	373	189.6	12	2	0.962380952	1.98
FATEPUR (P)	23.88127	87.537697	7.37	356.7	66.8	185	256.5	234.8	5.1	3808	344.6	790	1.18	0.567804762	1.1682
KOMA	23.84311	87.531977	6.5	80.2	26.7		64.99	103.9	52.3	1085	158.1	202	1.03	0.49562619	1.0197
BANSHANKA	23.79914	87.531408	8.49	36.1	10.9	5	5.67	27	1.1	343	127.2	26	1	0.481190476	0.99
PALSHITA	23.83207	87.565136	7.47	157.3	9.1	82	5.28	54.9	5.7	1315	284.4	219	0.97	0.466754762	0.9603
FATEPUR (P)	23.88238	87.538258	7.83	28.1	8.5	7.5	7.12	25.6	1.3	379	143.4	35	0.96	0.461942857	0.9504
MURADPUR	23.81977	87.530632	6.94	48.6	8.3		1.3	17.3	1.3	350	176.8	7.2	0.95	0.457130952	0.9405
DUBASHANKA	23.79419	87.524846	6.94	48.6	8.3		1.3	17.3	1.3	350	176.8	7.2	0.82	0.39457619	0.8118
DUBASHANKA	23.79282	87.523748	7.77	19	11.5	10.8	0.87	19	1.3	334	175.8	17	0.82	0.39457619	0.8118
JAMURI	23.80028	87.528557	7.68	108.2	28.6	78	96.5	110	24	1224	231.3	184	0.82	0.39457619	0.8118
JAMURI	23.79692	87.53325	6.92	11.33	2.9		0.33	5.6	6.2	104	40.4	7.2	0.79	0.380140476	0.7821
JAMURI	23.79984	87.524313	8.8	12	7.3		0.29	46.9	16.4	317	91.8	52	0.79	0.380140476	0.7821
JAMAL	23.88331	87.541795	7.87	27.1	1.8	5	0.62	15.4	0.9	206	97.1	17	0.78	0.375328571	0.7722



Integrated approach on discerning fluoride contamination mechanisms in the groundwater and formulating remedial strategies for potential health hazards in Birbhum District, West Bengal.

BANSHANKA	23.79911	87.533099	8	35.1	11.5	5	1.06	10.2	2.7	273	131.8	19	0.78	0.375328571	0.7722
JAMURI	23.80024	87.528572	7.15	44.1	6.1	23.5	6.08	58.9	2.5	501	115.6	83	0.78	0.375328571	0.7722
BANSHANKA	23.79828	87.534129	8.06	22	7.3	5	8.58	9.7	1.8	202	67.1	21	0.77	0.370516667	0.7623
BANSHANKA	23.79628	87.533264	8.15	38.1	15.8	34.3	0.8	60.9	141	919	270.6	99	0.77	0.370516667	0.7623
JAMURI	23.79634	87.5323	7.67	67.1	14.6	26.8	0.98	53.9	8	1059	365.4	130	0.76	0.365704762	0.7524
KOMA	23.84229	87.535182	8.01	43.1	41.3	5.8	8.84	27	1.5	589	254.4	57	0.75	0.360892857	0.7425
BANSRA	23.88892	87.617333	7.77	30.1	4.3	5	5.31	10.1	2	232	94.8	14	0.75	0.360892857	0.7425
KOMA	23.83925	87.532885	6.92	17.8	3.9		10.47	56	1.1	367		33	0.74	0.356080952	0.7326
KOMA	23.83852	87.529633	7.35	16	5.5	5	0.44	24.7	1.8	226	71.7	24	0.73	0.351269048	0.7227
RAJNAGAR	23.84032	87.529138	8.42	34.1	13.4	5	3.26	13.6	3.6	269	111	14	0.73	0.351269048	0.7227
DHALTIKRI	23.86882	87.596339	6.87	84.2	13.4	66	132.2	87.6	8.5	1025	200	101	0.72	0.346457143	0.7128
JAMURI	23.79701	87.527198	7.29	42.1	15.7		0.23	86.6	1.2	475	228.3	9.6	0.72	0.346457143	0.7128
KOMA	23.83992	87.532552	7.29	42.1	15.7		0.23	86.6	1.2	475	228.3	9.6	0.69	0.332021429	0.6831
KOMA	23.83942	87.529752	7.72	45.1	7.9	8.3	0.89	29	2.4	407	159.6	33	0.69	0.332021429	0.6831
PIASHALA	23.84884	87.607042	7.9	46.1	13.4	5	0.5	24.7	1.6	426	92.5	80	0.67	0.322397619	0.6633
KOMA	23.84023	87.533275	7.8	17	6.1	17.5	5.41	78.9	2.6	426	185	19	0.67	0.322397619	0.6633
KOMA	23.83999	87.530065	8.23	59.1	8.5	18.3	3.36	50	16.5	565	256.7	26	0.65	0.31277381	0.6435
BANSHANKA	23.798	87.527517	7.48	30.1	8.5	11	77.4	22.5	2.5	312	55.5	42	0.65	0.31277381	0.6435
BANSHANKA	23.79749	87.523968	7.13	35.6	6.9		0.2	17.5	1.3	296	131.3	9.6	0.65	0.31277381	0.6435
BANSHANKA	23.80624	87.527757	6.9	44.1	8.5		0.42	43.8	10.4	455	142.8	62	0.65	0.31277381	0.6435
IKRA	23.8956	87.609329	6.5	12	14.6		4.48	14	5.8	188	61.2	26	0.65	0.31277381	0.6435
PURANDARPUR	23.85729	87.587045	7.43	52.1	7.9	5	1.67	22.5	0.5	384	187.3	17	0.64	0.307961905	0.6336
RAJNAGAR	23.84107	87.529618	7.8	82.2	23.1	20	129.5	42	1.6	607	226.6	68	0.63	0.30315	0.6237
MURADPUR	23.81994	87.528927	7.78	50.1	10.9	16.5	3.31	28	1.8	399	203.5	21	0.63	0.30315	0.6237
KULERA	23.91219	87.545418	7.23	21	3.6	7.5	13	9.7	2.2	179	60.1	17	0.63	0.30315	0.6237
PIASHALA	23.85053	87.614485	7.62	102.2	7.3	14.3	0.81	52.9	3.7	901	300.6	106	0.63	0.30315	0.6237
BANSHANKA	23.79777	87.526161	8.1	2	1.2		0.5	9.5	3.1	63	20.4	14	0.63	0.30315	0.6237
DUBASHANKA	23.79359	87.523623	7.07	58.3	14.7		2.08	38.7	1.2	529	270.7	9.6	0.63	0.30315	0.6237
IKRA	23.89454	87.608421	7.07	58.3	14.7		2.08	38.7	1.2	529	270.7	9.6	0.63	0.30315	0.6237
RAJNAGAR	23.81985	87.528917	7.29	80.2	18.8	19	107.5	35	5.7	735	113.3	123	0.62	0.298338095	0.6138
IKRA	23.89296	87.607676	7.19	38.9	9.8		0.2	44.8	2.2	419	200	14	0.62	0.298338095	0.6138
PURANDARPUR	23.85312	87.586427	7.19	38.9	9.8		0.2	44.8	2.2	419	200	14	0.61	0.29352619	0.6039
DHALTIKRI	23.86883	87.596615	6.5	112.2	34		85.8	64.2	3.3	1080	91.8	240	0.61	0.29352619	0.6039
DHALTIKRI	23.87414	87.60241	7.5	154.3	35.2	77	102.5	101.9	3.8	1477	201.2	278	0.61	0.29352619	0.6039
DUBASHANKA	23.79209	87.525623	7.89	88.2	17	30.8	15.3	42	1.2	682	198.9	92	0.61	0.29352619	0.6039
BANSHANKA	23.80072	87.53057	7.1	88.2	36.5		33.25	31.6	7.6	771	219.3	102	0.61	0.29352619	0.6039
IKRA	23.89461	87.606958	7.62	38.1	4.3	14.8	24.2	49	0.7	423	111	47	0.61	0.29352619	0.6039
KOMA	23.83884	87.530858	7.52	12	2.4	5	5.02	14.2	2	127	60.1	9.4	0.6	0.288714286	0.594
IKRA	23.89649	87.609785	7.81	64.1	21.9	5	2.22	31	3.1	521	231.3	38	0.6	0.288714286	0.594
IKRA	23.89454	87.608283	8.08	60.1	14	17.3	12.7	27.5	3.2	484	175.8	40	0.6	0.288714286	0.594
IKRA	23.89296	87.60773	7.79	48.1	27.9	17.8	108.4	59.9	1.9	647	189.6	61	0.6	0.288714286	0.594
IKRA	23.89673	87.609746	7.3	32.1	9.7	6.5	15.9	29	1.5	292	74	47	0.59	0.283902381	0.5841
DHALTIKRI	23.87447	87.602926	7.78	60.1	14.6	8.8	105.3	13.8	2.4	437	106.4	47	0.58	0.279090476	0.5742



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BANSHANKA	23.79607	87.529731	7.87	40.1	8.5	14.3	1.09	76.9	3.4	782	383.9	42	0.58	0.279090476	0.5742
BANSHANKA	23.79614	87.529259	7.71	124.2	42.5	87	93.3	94.9	12	1476	289.1	248	0.57	0.274278571	0.5643
DUBASHANKA	23.79331	87.527674	8.44	50.1	16.4	14.5	94.2	31.5	1.7	487	101.8	57	0.57	0.274278571	0.5643
IKRA	23.89712	87.608576	8.58	48.1	24.3	5	2.35	44	0.7	471	235.9	17	0.57	0.274278571	0.5643
PIASHALA	23.84694	87.606712	6.3	156.3	43.7		5.08	62.2	8.4	1253	255	240	0.56	0.269466667	0.5544
PURANDARPUR	23.85567	87.589557	7.57	26.1	12.2	5	4.22	13.8	1.4	254	115.6	14	0.56	0.269466667	0.5544
USHGRAM	23.84252	87.580547	7.62	118.2	17	44	7.51	52.9	8.1	1051	245.1	165	0.56	0.269466667	0.5544
KOMA	23.84242	87.536268	8.05	28.1	4.9	5	10.3	28	3.8	268	129.5	12	0.55	0.264654762	0.5445
KOMA	23.8403	87.534305	6.9	144.3	43.7		25.09	142.6	8.9	1603	402.9	238	0.55	0.264654762	0.5445
MURADPUR	23.82259	87.538272	6.6	68.1	26.7		0.95	61	3.4	738	163.2	114	0.55	0.264654762	0.5445
PURANDARPUR	23.85264	87.587753	7.88	18	3.6	5	2.91	21.7	0.9	203	83.3	14	0.55	0.264654762	0.5445
PURANDARPUR	23.84685	87.58902	7.33	16	12.2	6.3	5.57	21.9	1.8	230	230	13	0.55	0.264654762	0.5445
HATIKRA	23.82572	87.58721	7.5	74.1	20.7		0.72	50.9	8.2	701	173.4	112	0.55	0.264654762	0.5445
DHALTIKRI	23.87433	87.60536	7.99	40.1	20.7	6	1.36	32.5	0.9	456	231.3	19	0.55	0.264654762	0.5445
KODAIKUR	23.8462	87.594807	7.77	40.1	15.2	5	1.03	24	1.2	332	166.5	12	0.55	0.264654762	0.5445
KOMA	23.83851	87.533192	6.8	20	4.9		17.27	44.8	1	312	81.6	38	0.54	0.259842857	0.5346
IKRA	23.89354	87.61264	7.72	110.2	22.5	17.8	5.81	58.9	4.4	1037	245.1	156	0.54	0.259842857	0.5346
KANSHPAI	23.83012	87.543745	6.8	60.1	19.4		10.36	32.6	3.2	566	153	76	0.51	0.245407143	0.5049
PURANDARPUR	23.85178	87.587848	8.2	36.1	18.2	5	0.62	50	6.2	441	238.2	12	0.51	0.245407143	0.5049
PURANDARPUR	23.85512	87.588798	6.61	34.5	9.2	21	0.94	9.8	2.9	295	112	26	0.51	0.245407143	0.5049
SAJINA	23.84446	87.57554	6.82	56.1	9.2	42	1.08	43.8	19	558	252	25	0.51	0.245407143	0.5049
BANSHANKA	23.80023	87.528006	7.64	32.1	1.8		0.5	20	1.3	262	129.5		0.51	0.245407143	0.5049
FATEPUR (P)	23.88397	87.532158	7.66	45.1	8.5	5	128.3	26.5	1.2	366	157.3	26	0.51	0.245407143	0.5049
JAMAL	23.88388	87.54875	7.5	60.1	26.7		1.25	50.9	2.6	554	316.2	19	0.5	0.240595238	0.495
PURANDARPUR	23.85413	87.590265	6.8	60.1	17		5.02	32.6	1.5	528	158.1	74	0.49	0.235783333	0.4851
PURANDARPUR	23.852	87.590228	6.8	8	6.1		5.37	5.37	1	105	51	7.1	0.49	0.235783333	0.4851
BANSRA	23.88804	87.61736	7.55	40.1	17	5	0.5	4.7	1.7	355	189.6	12	0.49	0.235783333	0.4851
DHALTIKRI	23.87692	87.600498	7.65	106.2	16.4	11.5	0.62	60.9	4.5	938	349.2	99	0.49	0.235783333	0.4851
BANSHANKA	23.80003	87.528982	6.92	17.8	3.9		10.47	56	1.1	367		33	0.49	0.235783333	0.4851
FATEPUR (P)	23.88441	87.531268	7.35	16	5.5	5	0.44	24.7	1.8	226	71.7	24	0.49	0.235783333	0.4851
BHOLAIPUR	23.81265	87.568343	8.42	34.1	13.4	5	3.26	13.6	3.6	269	111	14	0.48	0.230971429	0.4752
PURANDARPUR	23.853	87.591097	6.87	84.2	13.4	66	132.2	87.6	8.5	1025	200	101	0.48	0.230971429	0.4752
TENTULDIHI	23.84601	87.62443	7.29	42.1	15.7		0.23	86.6	1.2	475	228.3	9.6	4.07	1.958445238	4.0293
BHABANIPUR	23.96435	87.367702	7.29	42.1	15.7		0.23	86.6	1.2	475	228.3	9.6	3.07	1.477254762	3.0393
BHABANIPUR	23.97078	87.374514	7.72	45.1	7.9	8.3	0.89	29	2.4	407	159.6	33	2.67	1.284778571	2.6433
RANIGRAM	23.96262	87.307152	7.9	46.1	13.4	5	0.5	24.7	1.6	426	92.5	80	1.82	0.875766667	1.8018
PATADANGA	23.91991	87.438607	7.8	17	6.1	17.5	5.41	78.9	2.6	426	185	19	1.68	0.8084	1.6632
PATADANGA	23.91834	87.441233	8.23	59.1	8.5	18.3	3.36	50	16.5	565	256.7	26	1.68	0.8084	1.6632
RASAIKUR	23.78902	87.60647	7.48	30.1	8.5	11	77.4	22.5	2.5	312	55.5	42	1.58	0.760280952	1.5642
MADHAIPUR	23.90789	87.413202	7.13	35.6	6.9		0.2	17.5	1.3	296	131.3	9.6	1.52	0.731409524	1.5048
TABADUMRA	23.99318	87.347807	6.9	44.1	8.5		0.42	43.8	10.4	455	142.8	62	1.42	0.683290476	1.4058
MADHAIPUR	23.9089	87.411638	6.5	12	14.6		4.48	14	5.8	188	61.2	26	1.4	0.673666667	1.386
SAHABAD	23.9712	87.275324	7.43	52.1	7.9	5	1.67	22.5	0.5	384	187.3	17	1.4	0.673666667	1.386



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TANTIPARA	23.90408	87.372342	7.8	82.2	23.1	20	129.5	42	1.6	607	226.6	68	1.38	0.664042857	1.3662
RAOTARA	23.95884	87.380926	7.78	50.1	10.9	16.5	3.31	28	1.8	399	203.5	21	1.37	0.659230952	1.3563
MADHAIPUR	23.90506	87.415962	7.23	21	3.6	7.5	13	9.7	2.2	179	60.1	17	1.36	0.654419048	1.3464
TANTIPARA	23.91054	87.370978	7.62	102.2	7.3	14.3	0.81	52.9	3.7	901	300.6	106	1.36	0.654419048	1.3464
RAJNAGAR	23.94359	87.32445	8.1	2	1.2		0.5	9.5	3.1	63	20.4	14	1.35	0.649607143	1.3365
CHANDRAPUR	23.92678	87.385298	7.07	58.3	14.7		2.08	38.7	1.2	529	270.7	9.6	1.24	0.59667619	1.2276
TANTIPARA	23.90274	87.369652	7.07	58.3	14.7		2.08	38.7	1.2	529	270.7	9.6	1.24	0.59667619	1.2276
BHABANIPUR	23.96697	87.377991	7.29	80.2	18.8	19	107.5	35	5.7	735	113.3	123	1.21	0.582240476	1.1979
RAJNAGAR	23.94881	87.305323	7.19	38.9	9.8		0.2	44.8	2.2	419	200	14	1.21	0.582240476	1.1979
TANTIPARA	23.90236	87.369293	7.19	38.9	9.8		0.2	44.8	2.2	419	200	14	1.2	0.577428571	1.188
JAHANABAD	23.96901	87.281107	6.5	112.2	34		85.8	64.2	3.3	1080	91.8	240	1.2	0.577428571	1.188
JAHANABAD	23.96781	87.281684	7.5	154.3	35.2	77	102.5	101.9	3.8	1477	201.2	278	1.2	0.577428571	1.188
BHABANIPUR	23.97079	87.374553	7.89	88.2	17	30.8	15.3	42	1.2	682	198.9	92	1.19	0.572616667	1.1781
KABILASHPUR	23.96047	87.369437	7.1	88.2	36.5		33.25	31.6	7.6	771	219.3	102	1.16	0.558180952	1.1484
ARALI	23.95334	87.32523	7.62	38.1	4.3	14.8	24.2	49	0.7	423	111	47	1.15	0.553369048	1.1385
PATHARGHATA	23.83759	87.639717	7.52	12	2.4	5	5.02	14.2	2	127	60.1	9.4	1.15	0.553369048	1.1385
ARALI	23.95942	87.329862	7.81	64.1	21.9	5	2.22	31	3.1	521	231.3	38	1.14	0.548557143	1.1286
BHABANIPUR	23.97127	87.374485	8.08	60.1	14	17.3	12.7	27.5	3.2	484	175.8	40	1.14	0.548557143	1.1286
GULALGACHHI	23.9346	87.336348	7.79	48.1	27.9	17.8	108.4	59.9	1.9	647	189.6	61	1.13	0.543745238	1.1187
MADHAIPUR	23.91354	87.395265	7.3	32.1	9.7	6.5	15.9	29	1.5	292	74	47	1.13	0.543745238	1.1187
KHAYRADIHI	23.9007	87.363507	7.78	60.1	14.6	8.8	105.3	13.8	2.4	437	106.4	47	1.12	0.538933333	1.1088
BHABANIPUR	23.97126	87.37438	7.87	40.1	8.5	14.3	1.09	76.9	3.4	782	383.9	42	1.11	0.534121429	1.0989
KHAYRADIHI	23.90121	87.362605	7.71	124.2	42.5	87	93.3	94.9	12	1476	289.1	248	1.1	0.529309524	1.089
KATHGHARIA	23.91347	87.318658	8.44	50.1	16.4	14.5	94.2	31.5	1.7	487	101.8	57	1.1	0.529309524	1.089
KHAYRADIHI	23.90171	87.361395	8.58	48.1	24.3	5	2.35	44	0.7	471	235.9	17	1.1	0.529309524	1.089
PATADANGA	23.91809	87.442315	6.3	156.3	43.7		5.08	62.2	8.4	1253	255	240	1.05	0.50525	1.0395
ARALI	23.95962	87.32804	7.57	26.1	12.2	5	4.22	13.8	1.4	254	115.6	14	1.04	0.500438095	1.0296
CHANDRAPUR	23.91785	87.399999	7.62	118.2	17	44	7.51	52.9	8.1	1051	245.1	165	1.04	0.500438095	1.0296
SAHABAD	23.97042	87.276315	8.05	28.1	4.9	5	10.3	28	3.8	268	129.5	12	1.04	0.500438095	1.0296
SAHABAD	23.96961	87.282488	6.9	144.3	43.7		25.09	142.6	8.9	1603	402.9	238	1.04	0.500438095	1.0296
GANUTIA	23.90582	87.619415	6.6	68.1	26.7		0.95	61	3.4	738	163.2	114	1.04	0.500438095	1.0296
TANTIPARA	23.91498	87.369773	7.88	18	3.6	5	2.91	21.7	0.9	203	83.3	14	1.04	0.500438095	1.0296
TANTIPARA	23.91522	87.372	7.33	16	12.2	6.3	5.57	21.9	1.8	230	230	13	1.04	0.500438095	1.0296
GOBRA	23.97638	87.311688	7.5	74.1	20.7		0.72	50.9	8.2	701	173.4	112	1.04	0.500438095	1.0296
KUSAIPUR	23.97399	87.378499	7.99	40.1	20.7	6	1.36	32.5	0.9	456	231.3	19	1.03	0.49562619	1.0197
GANUTIA	23.9065	87.619702	7.77	40.1	15.2	5	1.03	24	1.2	332	166.5	12	1.03	0.49562619	1.0197
INDIRA	23.90245	87.740047	6.8	20	4.9		17.27	44.8	1	312	81.6	38	1.02	0.490814286	1.0098
LAUBERIA	24.02402	87.32249	7.72	110.2	22.5	17.8	5.81	58.9	4.4	1037	245.1	156	1.02	0.490814286	1.0098
TABADUMRA	23.99245	87.348107	6.8	60.1	19.4		10.36	32.6	3.2	566	153	76	1.01	0.486002381	0.9999
SAHABAD	23.96953	87.27797	8.2	36.1	18.2	5	0.62	50	6.2	441	238.2	12	1.01	0.486002381	0.9999
GHASBERA	23.94449	87.6041	6.61	34.5	9.2	21	0.94	9.8	2.9	295	112	26	1	0.481190476	0.99
PATADANGA	23.91966	87.437007	6.82	56.1	9.2	42	1.08	43.8	19	558	252	25	0.99	0.476378571	0.9801
RAJNAGAR	23.94477	87.325198	7.64	32.1	1.8		0.5	20	1.3	262	129.5		0.99	0.476378571	0.9801



'Integrated approach on discerning fluoride contamination mechanisms in the groundwater and formulating remedial strategies for potential health hazards in Birbhum District, West Bengal'.

NANUBAZAR	23.8412	87.647937	7.66	45.1	8.5	5	128.3	26.5	1.2	366	157.3	26	0.98	0.471566667	0.9702
TRIPURARIPUR	23.83699	87.647168	7.5	60.1	26.7		1.25	50.9	2.6	554	316.2	19	0.97	0.466754762	0.9603
PATHARGHATA	23.83813	87.63796	6.8	60.1	17		5.02	32.6	1.5	528	158.1	74	0.96	0.461942857	0.9504
TANTIPARA	23.90192	87.371804	6.8	8	6.1		5.37	5.37	1	105	51	7.1	0.96	0.461942857	0.9504
MADHAIPUR	23.90616	87.414408	7.55	40.1	17	5	0.5	4.7	1.7	355	189.6	12	0.95	0.457130952	0.9405
MADHAIPUR	23.90774	87.411242	7.65	106.2	16.4	11.5	0.62	60.9	4.5	938	349.2	99	0.95	0.457130952	0.9405
KUSAIPUR	23.97494	87.373769	7.77	78.2	37.7	51	20.3	49	4	815	245.1	90	0.95	0.457130952	0.9405
GANGMURI	23.96043	87.321952	7.21	53.1	16.4	16.5	10.6	34	4.8	508	131.8	71	0.9	0.433071429	0.891
NANUBAZAR	23.83967	87.652018	8.1	51.1	29.2	6.3	0.8	46	6	695	314.5	47	0.9	0.433071429	0.891
PATADANGA	23.91802	87.442473	8.41	62.1	34	7.5	1.06	80.9	3.2	488	235.9	12	0.89	0.428259524	0.8811
CHANDRAPUR	23.93088	87.383412	7.04	48.6	13.7		0.2	46.9	2.1	475	222.2	15	0.89	0.428259524	0.8811
RAJNAGAR	23.9449	87.326547	6.8	32.1	12.2		16.65	50.9	1.5	446	255	50	0.89	0.428259524	0.8811
RAJNAGAR	23.9467	87.33021	8.26	26.1	17.6	12.5	0.5	59.9	7.3	626	321.4	21	0.89	0.428259524	0.8811
TANTIPARA	23.90264	87.37152	6.46	76.2	24.3		1.22	25.9	2.3	581	209.1	78	0.88	0.423447619	0.8712
PERUL	23.96901	87.385088	6.94	92.2	34	56	2.33	51	4.5	942	300	104	0.87	0.418635714	0.8613
JOLLO	23.88502	87.647295	7.78	158.3	15.8	65	3.05	111.9	7	1967	351.5	401	0.87	0.418635714	0.8613
KHAMARTORA	23.90631	87.618688	6.9	220.4	58.3		38.1	78.5	6.1	1597	413.1	261	0.87	0.418635714	0.8613
KATHGHARIA	23.91383	87.3194	7.7	54.1	60.8	35	1.21	69.9	6.4	1029	261.3	156	0.86	0.41382381	0.8514
BHABANIPUR	23.96775	87.379219	7.75	28.1	5.5	5	14.8	16.2	0.8	250	87.9	24	0.86	0.41382381	0.8514
CHANDRAPUR	23.93065	87.384782	7.73	54.1	18.2	20.5	0.5	43	3.6	520	203.5	33	0.86	0.41382381	0.8514
UTTAR TILPARA	23.94138	87.73292	8.11	150.3	45	57	64.8	143.9	2.6	1808	300.6	354	0.86	0.41382381	0.8514
ABHIRAMPUR	23.88655	87.638102	7.45	48.1	12.2	40	25.5	66.9	1.1	600	101.8	94	0.86	0.41382381	0.8514
HATARA	23.89717	87.643822	8.4	24	12.2		0.6	49.9	2.3	403	127.5	62	0.86	0.41382381	0.8514
CHAKTULSI	23.92041	87.415732	8.08	124.2	7.3	24	0.5	50	2.2	1280	305.3	208	0.85	0.409011905	0.8415
CHANDRAPUR	23.91768	87.401029	7.71	70.1	25.5	47.5	25	69.9	1.9	820	154.9	130	0.85	0.409011905	0.8415
ABHIRAMPUR	23.8868	87.637008	7.72	30.1	32.2	6.8	0.5	32	2	464	233.6	17	0.85	0.409011905	0.8415
TANTIPARA	23.90163	87.376287	7.1	132.3	51		22.62	80.5	2.2	1278	336.6	195	0.85	0.409011905	0.8415
KHAYRADIHI	23.90167	87.363571	7.1	84.2	31.6		6.6	49.9	3.7	777	234.6	109	0.84	0.4042	0.8316
JOLLO	23.88358	87.645178	6.69	57.7	8.7	25	0.43	24.7	3.9	528	176	55	0.84	0.4042	0.8316
TANTIPARA	23.90333	87.371877	7.6	32.1	6.1	5	2.59	22	2.5	281	129.5	19	0.84	0.4042	0.8316
BARSHAL	23.89779	87.32567	6.25	20.8	10	45	6.08	7.3	7.6	248	49	14	0.84	0.4042	0.8316
TANTIPARA	23.89964	87.374378	7.55	44.1	10.9	22.5	67.9	64.9	1	572	134.1	85	0.84	0.4042	0.8316
KULTOR	23.93601	87.616173	7.79	48.1	27.9	17.8	108.4	59.9	1.9	647	189.6	61	0.83	0.399388095	0.8217
HARIPUR	23.98269	87.429148	7.79	48.1	27.9	17.8	108.4	59.9	1.9	647	189.6	61	0.83	0.399388095	0.8217
JOLLO	23.8844	87.646627	6.55	9.6	4.4	4.3	5.17	18.1	0.5	164	58	14	0.83	0.399388095	0.8217
PATHARGHATA	23.83754	87.630713	7.7	44.1	18.2	18.3	6.71	35	5.8	438	175.8	26	0.83	0.399388095	0.8217
RAOTARA	23.95999	87.378277	7.4	30.1	13.4		0.35	17.8	1	260	122.4	21	0.82	0.39457619	0.8118
LAUJOR	23.94302	87.354735	6.96	19	8.5	7.5	15.2	56.9	28	460	85.6	75	0.82	0.39457619	0.8118
UTTAR KHAYERBUNI	23.87982	87.667828	7.78	40.1	10.9	5	0.5	20.5	1.1	338	157.3	24	0.82	0.39457619	0.8118
JOLLO	23.88467	87.645663	7.35	53.4	11.3		0.2	110.1	2.2	813	250.5	104	0.82	0.39457619	0.8118
TENTULDIHI	23.84324	87.624537	8.11	25.1	11.5	6.8	0.5	51.9	4.4	405	191.9	19	0.82	0.39457619	0.8118
KABILASHPUR	23.95842	87.369682	7.55	98.2	7.3	37	7.13	119.9	6.6	1144	296	182	0.81	0.389764286	0.8019
GOBRA	23.97127	87.315282	7.2	40.1	12.2		2.71	40.3	1.7	405	102	26	0.81	0.389764286	0.8019



Integrated approach on discerning fluoride contamination mechanisms in the groundwater and formulating remedial strategies for potential health hazards in Birbhum District, West Bengal.

KHAYRADIHI	23.90223	87.363313	7.45	8	4.9	9.3	4.89	30	17	240	55.5	33	0.81	0.389764286	0.8019
GULALGACHHI	23.9314	87.341663	7.07	40.5	33.4		0.2	60.1	2.7	728	329.3	25	0.8	0.384952381	0.792
KUSAIPUR	23.964	87.380448	7	4	4.9		0.63	20.4	9.4	146	40.8	19	0.8	0.384952381	0.792
GANGMURI	23.95957	87.317547	7.26	32.4	14.7		0.2	96.8	2.1	588	220.2	48	0.8	0.384952381	0.792
CHANDRAPUR	23.91705	87.401463	7.74	23.2	10.4	23	2.85	26.5	1.1	311	114	17	0.8	0.384952381	0.792
MRITADASPUR	23.83967	87.646798	7.77	15	10.3	30.5	1.49	90.9	13	503	208.1	21	0.8	0.384952381	0.792
RASAIPUR	23.78432	87.608907	6.96	44.9	17.5	34	0.92	48.9	3.4	559	260	21	0.8	0.384952381	0.792
TANTIPARA	23.90199	87.376494	7.44	47.1	41.3	225	0.5	81.9	3.2	862	238.2	14	0.8	0.384952381	0.792
GANESHPUR	23.97546	87.40287	7.83	37.1	9.1	93	0.5	85.9	13.6	586	201.2	17	0.79	0.380140476	0.7821
DAKSHIN SIJA	23.87665	87.670653	7.3	128.3	20.7		0.68	187.5	2.2	1482	438.6	221	0.79	0.380140476	0.7821
RAJNAGAR	23.94385	87.325467	8.23	34.1	19.4	11	0.5	48	4.8	395	180.4	19	0.79	0.380140476	0.7821
RAJNAGAR	23.94743	87.329442	7.39	6.5	2.9		0.2	134.5	1	402	163.6	19	0.79	0.380140476	0.7821
TARASOL	23.94427	87.390258	8.73	18	7.3	22	3.13	96.9	5.1	556	152.6	59	0.79	0.380140476	0.7821
JOLLO	23.88516	87.647337	8.18	20	3	36.5	1.25	131.9	3.8	708	157.3	87	0.79	0.380140476	0.7821
ABHIRAMPUR	23.88649	87.639317	7.39	30.8	12.3		10.36	150.8	2.9	912	250.5	113	0.79	0.380140476	0.7821
MRITADASPUR	23.84016	87.646385	7.95	19.4	6.9		0.2	218.1	6.7	1106	254.5	183	0.79	0.380140476	0.7821
MRITADASPUR	23.83992	87.647592	9.62	1	2.9								0.79	0.380140476	0.7821
BHOLAGARIA	23.78542	87.600765	7.77	78.2	37.7	51	20.3	49	4	815	245.1	90	0.79	0.380140476	0.7821
TENTULDIHI	23.84745	87.6297	7.21	53.1	16.4	16.5	10.6	34	4.8	508	131.8	71	0.78	0.375328571	0.7722
ARALI	23.94752	87.317082	8.1	51.1	29.2	6.3	0.8	46	6	695	314.5	47	0.76	0.365704762	0.7524
PASHOA	23.82611	87.650525	8.41	62.1	34	7.5	1.06	80.9	3.2	488	235.9	12	0.76	0.365704762	0.7524
BADURIA	23.76124	87.723863	7.04	48.6	13.7		0.2	46.9	2.1	475	222.2	15	0.76	0.365704762	0.7524
BANGJITA	23.79929	87.607593	6.8	32.1	12.2		16.65	50.9	1.5	446	255	50	0.76	0.365704762	0.7524
LAUJOR	23.94195	87.354862	8.26	26.1	17.6	12.5	0.5	59.9	7.3	626	321.4	21	0.75	0.360892857	0.7425
MADHAIPUR	23.90906	87.413173	6.46	76.2	24.3		1.22	25.9	2.3	581	209.1	78	0.75	0.360892857	0.7425
DALDALA	23.99233	87.415733	6.94	92.2	34	56	2.33	51	4.5	942	300	104	0.75	0.360892857	0.7425
CHAKTULSI	23.91834	87.416038	7.78	158.3	15.8	65	3.05	111.9	7	1967	351.5	401	0.75	0.360892857	0.7425
KHAYRADIHI	23.90053	87.362035	6.9	220.4	58.3		38.1	78.5	6.1	1597	413.1	261	0.75	0.360892857	0.7425
JOLLO	23.88304	87.644703	7.7	54.1	60.8	35	1.21	69.9	6.4	1029	261.3	156	0.75	0.360892857	0.7425
RANIGRAM	23.962	87.301773	7.75	28.1	5.5	5	14.8	16.2	0.8	250	87.9	24	0.75	0.360892857	0.7425
INDIRA	23.8881	87.742137	7.73	54.1	18.2	20.5	0.5	43	3.6	520	203.5	33	0.75	0.360892857	0.7425
KUSAIPUR	23.97216	87.379533	8.11	150.3	45	57	64.8	143.9	2.6	1808	300.6	354	0.74	0.356080952	0.7326
RAJNAGAR	23.94361	87.326698	7.45	48.1	12.2	40	25.5	66.9	1.1	600	101.8	94	0.74	0.356080952	0.7326
LAYEKPUR	23.82759	87.640925	8.4	24	12.2		0.6	49.9	2.3	403	127.5	62	0.74	0.356080952	0.7326
ARALI	23.95505	87.324975	8.08	124.2	7.3	24	0.5	50	2.2	1280	305.3	208	0.73	0.351269048	0.7227
NIMRA	23.77297	87.884559	7.71	70.1	25.5	47.5	25	69.9	1.9	820	154.9	130	0.73	0.351269048	0.7227
CHAKTULSI	23.91832	87.413403	7.72	30.1	32.2	6.8	0.5	32	2	464	233.6	17	0.71	0.341645238	0.7029
UTTAR BAMNIGAON	23.94426	87.71685	7.1	132.3	51		22.62	80.5	2.2	1278	336.6	195	0.71	0.341645238	0.7029
GANGMURI	23.96103	87.318449	7.1	84.2	31.6		6.6	49.9	3.7	777	234.6	109	0.71	0.341645238	0.7029
GANGMURI	23.96031	87.3208	6.69	57.7	8.7	25	0.43	24.7	3.9	528	176	55	0.71	0.341645238	0.7029
UTTAR KHAYERBUNI	23.87974	87.6693	7.6	32.1	6.1	5	2.59	22	2.5	281	129.5	19	0.71	0.341645238	0.7029
TENTULIA BANDH	23.90569	87.337873	6.25	20.8	10	45	6.08	7.3	7.6	248	49	14	0.71	0.341645238	0.7029
RASAIPUR	23.78292	87.60921	7.55	44.1	10.9	22.5	67.9	64.9	1	572	134.1	85	0.71	0.341645238	0.7029



Integrated approach on discerning fluoride contamination mechanisms in the groundwater and formulating remedial strategies for potential health hazards in Birbhum District, West Bengal.

MEHERPUR	23.77014	87.665813	7.79	48.1	27.9	17.8	108.4	59.9	1.9	647	189.6	61	0.71	0.341645238	0.7029
UTTAR BAMNIGAON	23.94058	87.724045	7.79	48.1	27.9	17.8	108.4	59.9	1.9	647	189.6	61	0.7	0.336833333	0.693
UTTAR BAMNIGAON	23.94385	87.715567	6.55	9.6	4.4	4.3	5.17	18.1	0.5	164	58	14	0.7	0.336833333	0.693
KANMORA	24.00363	87.385795	7.7	44.1	18.2	18.3	6.71	35	5.8	438	175.8	26	0.7	0.336833333	0.693
AKUDIHI	23.87963	87.67238	7.4	30.1	13.4		0.35	17.8	1	260	122.4	21	0.7	0.336833333	0.693
GAISARA	23.90372	87.33293	6.96	19	8.5	7.5	15.2	56.9	28	460	85.6	75	0.7	0.336833333	0.693
PASHOA	23.82917	87.65009	7.78	40.1	10.9	5	0.5	20.5	1.1	338	157.3	24	0.7	0.336833333	0.693
NANUBAZAR	23.84184	87.643485	7.35	53.4	11.3		0.2	110.1	2.2	813	250.5	104	0.7	0.336833333	0.693
NETURI	23.77631	87.600542	8.11	25.1	11.5	6.8	0.5	51.9	4.4	405	191.9	19	0.7	0.336833333	0.693
TANTIPARA	23.90233	87.370357	7.55	98.2	7.3	37	7.13	119.9	6.6	1144	296	182	0.69	0.332021429	0.6831
RASAIPUR	23.78331	87.606215	7.2	40.1	12.2		2.71	40.3	1.7	405	102	26	0.69	0.332021429	0.6831
RASAIPUR	23.78318	87.609823	7.45	8	4.9	9.3	4.89	30	17	240	55.5	33	0.69	0.332021429	0.6831
PALASHDANGA	23.77065	87.67551	7.07	40.5	33.4		0.2	60.1	2.7	728	329.3	25	0.69	0.332021429	0.6831
TENTULDIHI	23.84797	87.628367	7	4	4.9		0.63	20.4	9.4	146	40.8	19	0.69	0.332021429	0.6831
GULALGACHHI	23.93465	87.343097	7.26	32.4	14.7		0.2	96.8	2.1	588	220.2	48	0.68	0.327209524	0.6732
CHAKTULSI	23.91823	87.414628	7.74	23.2	10.4	23	2.85	26.5	1.1	311	114	17	0.68	0.327209524	0.6732
CHAKTULSI	23.91903	87.41448	7.77	15	10.3	30.5	1.49	90.9	13	503	208.1	21	0.68	0.327209524	0.6732
ARALI	23.9608	87.322828	6.96	44.9	17.5	34	0.92	48.9	3.4	559	260	21	0.68	0.327209524	0.6732
KHAYRADIHI	23.90067	87.363439	7.44	47.1	41.3	225	0.5	81.9	3.2	862	238.2	14	0.68	0.327209524	0.6732
AKUDIHI	23.88003	87.674813	7.83	37.1	9.1	93	0.5	85.9	13.6	586	201.2	17	0.68	0.327209524	0.6732
PATHARGHATA	23.83785	87.638692	7.3	128.3	20.7		0.68	187.5	2.2	1482	438.6	221	0.68	0.327209524	0.6732
TENTULDIHI	23.84655	87.629578	8.23	34.1	19.4	11	0.5	48	4.8	395	180.4	19	0.68	0.327209524	0.6732
KULTOR	23.93583	87.61583	7.39	6.5	2.9		0.2	134.5	1	402	163.6	19	0.67	0.322397619	0.6633
BAGDAHARI	23.98367	87.646913	8.73	18	7.3	22	3.13	96.9	5.1	556	152.6	59	0.67	0.322397619	0.6633
DALDALA	23.99044	87.416238	8.18	20	3	36.5	1.25	131.9	3.8	708	157.3	87	0.67	0.322397619	0.6633
HARIPUR	23.9789	87.435408	7.39	30.8	12.3		10.36	150.8	2.9	912	250.5	113	0.67	0.322397619	0.6633
BELERA	23.96936	87.388928	7.95	19.4	6.9		0.2	218.1	6.7	1106	254.5	183	0.67	0.322397619	0.6633
RANIGRAM	23.9632	87.304785	9.62	1	2.9								0.67	0.322397619	0.6633
RASAIPUR	23.7832	87.607067	7.83	28.1	8.5	7.5	7.12	25.6	1.3	379	143.4	35	0.67	0.322397619	0.6633
BHABANIPUR	23.96672	87.379341	6.94	48.6	8.3		1.3	17.3	1.3	350	176.8	7.2	0.66	0.317585714	0.6534
MADANPUR	23.79848	87.63004	6.94	48.6	8.3		1.3	17.3	1.3	350	176.8	7.2	0.66	0.317585714	0.6534
UTTAR BAMNIGAON	23.94329	87.719647	7.77	19	11.5	10.8	0.87	19	1.3	334	175.8	17	0.66	0.317585714	0.6534
GANGMURI	23.95995	87.311637	7.68	108.2	28.6	78	96.5	110	24	1224	231.3	184	0.66	0.317585714	0.6534
RASAIPUR	23.78239	87.609523	6.92	11.33	2.9		0.33	5.6	6.2	104	40.4	7.2	0.66	0.317585714	0.6534
MALIGRAM	23.84898	87.63175	8.8	12	7.3		0.29	46.9	16.4	317	91.8	52	0.66	0.317585714	0.6534
DALDALA	23.9927	87.414797	7.87	27.1	1.8	5	0.62	15.4	0.9	206	97.1	17	0.64	0.307961905	0.6336
HARIPUR	23.97696	87.426108	8	35.1	11.5	5	1.06	10.2	2.7	273	131.8	19	0.64	0.307961905	0.6336
RAOTARA	23.96044	87.378534	7.15	44.1	6.1	23.5	6.08	58.9	2.5	501	115.6	83	0.64	0.307961905	0.6336
RAJNAGAR	23.94664	87.326202	8.06	22	7.3	5	8.58	9.7	1.8	202	67.1	21	0.64	0.307961905	0.6336
RAJNAGAR	23.94416	87.322605	8.15	38.1	15.8	34.3	0.8	60.9	141	919	270.6	99	0.64	0.307961905	0.6336
TENTULIA BANDH	23.90431	87.339617	7.67	67.1	14.6	26.8	0.98	53.9	8	1059	365.4	130	0.64	0.307961905	0.6336
BARSHAL	23.89652	87.327526	8.01	43.1	41.3	5.8	8.84	27	1.5	589	254.4	57	0.64	0.307961905	0.6336
RASAIPUR	23.78408	87.608438	7.77	30.1	4.3	5	5.31	10.1	2	232	94.8	14	0.64	0.307961905	0.6336



'Integrated approach on discerning fluoride contamination mechanisms in the groundwater and formulating remedial strategies for potential health hazards in Birbhum District, West Bengal'.

NETURI	23.77677	87.601045	6.92	17.8	3.9		10.47	56	1.1	367		33	0.64	0.307961905	0.6336
PADAMPUR	23.94024	87.352078	7.35	16	5.5	5	0.44	24.7	1.8	226	71.7	24	0.64	0.307961905	0.6336
JHIKRA	23.9214	87.356595	8.42	34.1	13.4	5	3.26	13.6	3.6	269	111	14	0.64	0.307961905	0.6336
MEHERPUR	23.77087	87.667875	6.87	84.2	13.4	66	132.2	87.6	8.5	1025	200	101	0.64	0.307961905	0.6336
LAUBERIA	24.02116	87.322855	7.29	42.1	15.7		0.23	86.6	1.2	475	228.3	9.6	0.64	0.307961905	0.6336
LAKSHMINARAYANPUR	24.27533	87.715193	7.29	42.1	15.7		0.23	86.6	1.2	475	228.3	9.6	9.65	4.643488095	9.5535
LAKSHMINARAYANPUR	24.27696	87.71567	7.72	45.1	7.9	8.3	0.89	29	2.4	407	159.6	33	9.31	4.479883333	9.2169
LAKSHMINARAYANPUR	24.26707	87.738022	7.83	28.1	8.5	7.5	7.12	25.6	1.3	379	143.4	35	8.93	4.297030952	8.8407
LAKSHMINARAYANPUR	24.28379	87.7292	6.94	48.6	8.3		1.3	17.3	1.3	350	176.8	7.2	7.76	3.734038095	7.6824
SONARKUNDU	24.26576	87.782885	6.94	48.6	8.3		1.3	17.3	1.3	350	176.8	7.2	7.72	3.714790476	7.6428
LAKSHMINARAYANPUR	24.283	87.731752	7.77	19	11.5	10.8	0.87	19	1.3	334	175.8	17	7.64	3.676295238	7.5636
LAKSHMINARAYANPUR	24.28343	87.732183	7.68	108.2	28.6	78	96.5	110	24	1224	231.3	184	7.52	3.618552381	7.4448
LAKSHMINARAYANPUR	24.2827	87.731606	6.92	11.33	2.9		0.33	5.6	6.2	104	40.4	7.2	7.36	3.541561905	7.2864
LAKSHMINARAYANPUR	24.27714	87.715917	8.8	12	7.3		0.29	46.9	16.4	317	91.8	52	6.24	3.002628571	6.1776
LAKSHMINARAYANPUR	24.30339	87.730993	7.87	27.1	1.8	5	0.62	15.4	0.9	206	97.1	17	5.54	2.665795238	5.4846
SANTOSHPUR	24.22569	87.714221	8	35.1	11.5	5	1.06	10.2	2.7	273	131.8	19	1.13	0.543745238	1.1187
SANTOSHPUR	24.26078	87.712257	7.15	44.1	6.1	23.5	6.08	58.9	2.5	501	115.6	83	0.95	0.457130952	0.9405
GOBINDAPUR	24.34751	87.772968	8.06	22	7.3	5	8.58	9.7	1.8	202	67.1	21	0.89	0.428259524	0.8811
MADNA	24.33723	87.771752	8.15	38.1	15.8	34.3	0.8	60.9	141	919	270.6	99	0.83	0.399388095	0.8217
LAKSHMINARAYANPUR	24.30305	87.728748	7.67	67.1	14.6	26.8	0.98	53.9	8	1059	365.4	130	0.81	0.389764286	0.8019
RADIPUR	24.24555	87.931865	8.01	43.1	41.3	5.8	8.84	27	1.5	589	254.4	57	0.8	0.384952381	0.792
SHAILMAIL	24.3244	87.981917	7.77	30.1	4.3	5	5.31	10.1	2	232	94.8	14	2.69	1.294402381	2.6631
UTTAR RAMPUR	24.35088	87.9288	6.92	17.8	3.9		10.47	56	1.1	367		33	1.5	0.721785714	1.485
NAWAPARA	24.27759	87.999708	7.35	16	5.5	5	0.44	24.7	1.8	226	71.7	24	1	0.481190476	0.99
JESHTHA BHABANIPUR	24.33163	87.950587	8.42	34.1	13.4	5	3.26	13.6	3.6	269	111	14	0.84	0.4042	0.8316
SHAILMAIL	24.32459	87.982605	6.87	84.2	13.4	66	132.2	87.6	8.5	1025	200	101	0.81	0.389764286	0.8019
JESHTHA BHABANIPUR	24.33012	87.951758	7.29	42.1	15.7		0.23	86.6	1.2	475	228.3	9.6	0.79	0.380140476	0.7821
BARA	24.32292	87.974405	7.29	42.1	15.7		0.23	86.6	1.2	475	228.3	9.6	0.78	0.375328571	0.7722
JESHTHA BHABANIPUR	24.33821	87.947851	7.72	45.1	7.9	8.3	0.89	29	2.4	407	159.6	33	0.77	0.370516667	0.7623
JESHTHA BHABANIPUR	24.32598	87.956443	7.35	53.4	11.3		0.2	110.1	2.2	813	250.5	104	0.76	0.365704762	0.7524
CHAKGOPAL	24.22188	87.99533	8.11	25.1	11.5	6.8	0.5	51.9	4.4	405	191.9	19	0.53	0.255030952	0.5247
CHAKGOPAL	24.21658	88.00021	7.55	98.2	7.3	37	7.13	119.9	6.6	1144	296	182	0.53	0.255030952	0.5247
NAKPUR	24.28789	88.005483	7.2	40.1	12.2		2.71	40.3	1.7	405	102	26	0.56	0.269466667	0.5544
CHAKGOPAL	24.22188	87.99533	7.45	8	4.9	9.3	4.89	30	17	240	55.5	33	0.53	0.255030952	0.5247
CHAKGOPAL	24.21658	88.00021	7.07	40.5	33.4		0.2	60.1	2.7	728	329.3	25	0.53	0.255030952	0.5247
KHALILPUR	24.27016	88.008763	7	4	4.9		0.63	20.4	9.4	146	40.8	19	0.52	0.250219048	0.5148
SALISANDA	24.30086	88.00135	7.26	32.4	14.7		0.2	96.8	2.1	588	220.2	48	0.51	0.245407143	0.5049
NAKPUR	24.28891	88.007797	7.74	23.2	10.4	23	2.85	26.5	1.1	311	114	17	0.48	0.230971429	0.4752
KHALILPUR	24.27007	88.009591	7.77	15	10.3	30.5	1.49	90.9	13	503	208.1	21	0.47	0.226159524	0.4653
SALISANDA	24.30051	88.000282	6.96	44.9	17.5	34	0.92	48.9	3.4	559	260	21	0.46	0.221347619	0.4554
SALISANDA	24.30431	88.002753	7.44	47.1	41.3	225	0.5	81.9	3.2	862	238.2	14	0.46	0.221347619	0.4554
BHATRA	24.51699	87.864585	7.83	37.1	9.1	93	0.5	85.9	13.6	586	201.2	17	1.72	0.827647619	1.7028
BHATRA	24.51651	87.863817	7.3	128.3	20.7		0.68	187.5	2.2	1482	438.6	221	1.64	0.789152381	1.6236



'Integrated approach on discerning fluoride contamination mechanisms in the groundwater and formulating remedial strategies for potential health hazards in Birbhum District, West Bengal'.

KASHIMNAGAR	24.4368	87.924409	8.23	34.1	19.4	11	0.5	48	4.8	395	180.4	19	1.25	0.601488095	1.2375
BISOR	24.38454	87.957144	7.39	6.5	2.9		0.2	134.5	1	402	163.6	19	0.94	0.452319048	0.9306
BISOR	24.38482	87.956196	8.73	18	7.3	22	3.13	96.9	5.1	556	152.6	59	0.92	0.442695238	0.9108
KASHIMNAGAR	24.42754	87.913092	8.18	20	3	36.5	1.25	131.9	3.8	708	157.3	87	0.89	0.428259524	0.8811
PERA	24.52428	87.886778	7.39	30.8	12.3		10.36	150.8	2.9	912	250.5	113	0.88	0.423447619	0.8712
KALITARA	24.53723	87.8962	7.95	19.4	6.9		0.2	218.1	6.7	1106	254.5	183	0.88	0.423447619	0.8712
BISOR	24.3835	87.959556	9.62	1	2.9								0.85	0.409011905	0.8415
BISOR	24.38248	87.956316	7.83	28.1	8.5	7.5	7.12	25.6	1.3	379	143.4	35	0.83	0.399388095	0.8217
BISOR	24.38333	87.96016	6.94	48.6	8.3		1.3	17.3	1.3	350	176.8	7.2	0.82	0.39457619	0.8118
ABDULLAPUR	24.49962	87.868206	6.94	48.6	8.3		1.3	17.3	1.3	350	176.8	7.2	0.82	0.39457619	0.8118
BISOR	24.38858	87.954197	7.77	19	11.5	10.8	0.87	19	1.3	334	175.8	17	0.81	0.389764286	0.8019
BISOR	24.38599	87.955627	7.68	108.2	28.6	78	96.5	110	24	1224	231.3	184	0.79	0.380140476	0.7821
BISOR	24.3885	87.954994	6.92	11.33	2.9		0.33	5.6	6.2	104	40.4	7.2	0.79	0.380140476	0.7821
BISOR	24.38687	87.955087	8.8	12	7.3		0.29	46.9	16.4	317	91.8	52	0.77	0.370516667	0.7623
BISOR	24.38717	87.955211	7.87	27.1	1.8	5	0.62	15.4	0.9	206	97.1	17	0.77	0.370516667	0.7623
BISOR	24.38815	87.955491	8	35.1	11.5	5	1.06	10.2	2.7	273	131.8	19	0.77	0.370516667	0.7623



ANNEXURE B- Primary Data (Pre- Monsoon- 2019)

Sample No.	Name of Village	Latitude (N)	Longitude(E)	Fluoride (mg/L)	THQ Adult	THQ Child
1	Chinpai Tapaspur	23.81166	87.45177	1.63	0.857690476	1.6137
2	Chinpai Goraipara	23.80986	87.4515	0.3	0.157857143	0.297
3	Chinpai Mandalpara	23.8113889	87.45283	1.75	0.920833333	1.7325
4	Chinpai JP School	23.8116944	87.45425	3.78	1.989	3.7422
5	Chinapai Binainagar	23.81363889	87.46663611	1.42	0.747190476	1.4058
6	Elama GP office	23.81363889	87.45933	1.68	0.884	1.6632
7	Elama Primary School	23.81130556	87.45933	1.22	0.641952381	1.2078
8	Elama Near House of Lalu Bauri	23.81088889	87.4411944	2.28	1.199714286	2.2572
9	Elama near House of Jaharlal Ghosh	23.80952778	87.441778	4	2.104761905	3.96
10	Elama Gouranga Mandir	23.809333	87.39277778	3.9	2.052142857	3.861
11	Kendula GP Das Para	23.76913889	87.442333	0.88	0.463047619	0.8712
12	Kendula near Nimai Das house	23.76863889	87.3925833	1.06	0.557761905	1.0494
13	Kendula near Sadhan Das' House	23.7695	87.39425	1.06	0.557761905	1.0494
14	Hetampur GP Hattala Young Lions Club	23.77558889	87.3991111	0.84	0.442	0.8316
15	Hetampur Hattala Saraswati Mandir	23.77519444	87.39836111	1.33	0.699833333	1.3167
16	Hetampur Kalitala	23.77616667	87.39705556	2.25	1.183928571	2.2275
17	Dakkhin Kalitala	23.776666	87.3963333	2.18	1.147095238	2.1582
18	Jashpur GP shibtala	23.77375	87.43236111	0.32	0.168380952	0.3168
19	Akkora Sanapara	23.77233	87.43163889	0.34	0.178904762	0.3366
20	Bagdipara Mitali Sangha	23.7736667	87.43136111	1.34	0.705095238	1.3266
21	Jashpur Manashatala	23.7739444	87.43041667	0.63	0.3315	0.6237
22	Gohialiara behind GP office	23.88247222	87.42019444	0.84	0.442	0.8316
23	Japtala 1	23.87261111	87.37002778	1.12	0.589333333	1.1088
24	Japtala 2	23.87236111	87.37072222	0.94	0.494619048	0.9306
25	Japtala Nepal Mondal House	23.87205556	87.37136111	1.66	0.87347619	1.6434
26	Japtala Talpukur	23.87208333	87.37197222	1.08	0.568285714	1.0692
27	Japtala Near P Mondal House	23.8708333	87.3694722	1.22	0.641952381	1.2078
28	Adibashipara GP Parulia	23.88475	87.4063889	0.98	0.515666667	0.9702
29	Shrimpur FP School Adibasipara	23.8916667	87.4085556	1.18	0.620904762	1.1682
30	Bakreshwar Junior Basic High School	23.88141667	87.367444	0.7	0.368333333	0.693
31	Bakreshwar Junior Basic High School 2	23.880889	87.36780556	1.2	0.631428571	1.188
32	Bakreshwar hot spring snaner ghat	23.881111	87.375056	16	8.419047619	15.84
33	Bakreshwar Agnikundo	23.881194	87.3758055	17	8.945238095	16.83
34	Bakreshwar Mahasashan	23.88002778	87.3786111	3.2	1.683809524	3.168
35	Kabichandrapur Primary School	24.11458333	87.79355556	1.95	1.026071429	1.9305
36	Padel Nagar Chalk Mine	23.99152778	87.61938889	2.43	1.278642857	2.4057
37	Angargaria BDO Office (New Tube Well)	23.9805	87.59005556	5.88	3.094	5.8212
38	Rajnagar Duckbungalow	23.9805	87.5894	1.78	0.936619048	1.7622
39	Fatehpur	23.88119	87.53756	1.75	0.920833333	1.7325
40	Noapara t/w- 0613011005	24.107583	87.78483	1.75	0.920833333	1.7325



ANNEXURE B- Primary Water Quality Data (Post- Monsoon- 2019)

Sample no.	Name of Village	Latitude (N)	Longitude(E)	Fluoride Content (mg/L)	THQ - Adult	THQ- Child
1	Chinpai Tapaspur	23.81166	87.45177	1.12	0.589333333	1.1088
2	Chinpai Goraipara	23.80986	87.4515	0.3	0.157857143	0.297
3	Chinpai Mandalpara	23.7713889	87.1883	1.16	0.610380952	1.1484
4	Chinpai JP School	23.8116944	87.45425	3.45	1.815357143	3.4155
5	Chinapai Binainagar	23.82363889	87.26663611	1.42	0.747190476	1.4058
6	Elama GP office	24.0363889	87.55933	1.68	0.884	1.6632
7	Elama Primary School	23.81130556	87.55933	0.84	0.442	0.8316
8	Elama Near House of Lalu Bauri	24.23088889	87.5411944	2.16	1.136571429	2.1384
9	Elama near House of Jaharlal Ghosh	23.80952778	87.441778	4	2.104761905	3.96
10	Elama Gouranga Mandir	23.809333	87.39277778	3.9	2.052142857	3.861
11	Kendula GP Das Para	23.76913889	87.342333	0.76	0.399904762	0.7524
12	Kendula near Nimai Das house	23.76863889	87.3925833	0.92	0.484095238	0.9108
13	Kendula near Sadhan Das' House	23.7695	87.39425	1.06	0.557761905	1.0494
14	Hetampur GP Hattala Young Lions Club	23.77558889	87.3991111	0.72	0.378857143	0.7128
15	Hetampur Hattala Saraswati Mandir	23.77519444	87.39836111	0.82	0.43147619	0.8118
16	Hetampur Kalitala	23.77616667	87.39705556	2.02	1.062904762	1.9998
17	Dakkhin Kalitala	23.776666	87.3963333	2.18	1.147095238	2.1582
18	Jashpur GP shibtala	23.77375	87.43236111	0.32	0.168380952	0.3168
19	Akkora Sanapara	23.77233	87.43163889	0.34	0.178904762	0.3366
20	Bagdipara Mitali Sangha	23.7736667	87.43136111	1.34	0.705095238	1.3266
21	Jashpur Manashatala	23.7739444	87.43041667	0.44	0.23152381	0.4356
22	Gohialiara behind GP office	23.88247222	87.42019444	0.56	0.294666667	0.5544
23	Japtala 1	23.87261111	87.37002778	1.12	0.589333333	1.1088
24	Japtala 2	23.85236111	87.3857	0.72	0.378857143	0.7128
25	Japtala Nepal Mondal House	23.87205556	87.37136111	1.02	0.536714286	1.0098
26	Japtala Talpukur	23.87208333	87.37197222	1.08	0.568285714	1.0692
27	Japtala Near P Mondal House	23.8608333	87.3594722	1.04	0.547238095	1.0296
28	Adibashipara GP Parulia	23.88475	87.4063889	0.98	0.515666667	0.9702
29	Shrimpur FP School Adibasipara	23.8916667	87.4085556	0.68	0.357809524	0.6732
30	Bakreshwar Junior Basic High School	23.88141667	87.367444	0.7	0.368333333	0.693
31	Bakreshwar Junior Basic High School 2	23.880889	87.36780556	1.2	0.631428571	1.188
32	Bakreshwar hot spring snaner ghat	23.881111	87.375056	16	8.419047619	15.84
33	Bakreshwar Agnikundo	23.881194	87.3758055	17	8.945238095	16.83
34	Bakreshwar Mahasashan	23.88002778	87.3786111	3.2	1.683809524	3.168
35	Kabichandrapur Primary School	24.11458333	87.79355556	1.95	1.026071429	1.9305
36	Padel Nagar Chalk Mine	23.99152778	87.61938889	2.43	1.278642857	2.4057
37	Angargaria BDO Office (New Tube Well)	23.9805	87.59005556	5.48	2.88352381	5.4252
38	Rajnagar Duckbunglow	23.9805	87.5894	1.78	0.936619048	1.7622
39	Fatehpur	23.88119	87.53756	1.75	0.920833333	1.7325
40	Noapara t/w- 0613011005	24.107583	87.78483	1.75	0.920833333	1.7325



41	Surul Ruppur	23.6666948	87.6640833	0.65	0.34202381	0.6435
42	Adda kali Mandir	23.876945	87.53355	2.8	1.473333333	2.772
43	Bharkuna GP	23.832528	87.499861	0.75	0.394642857	0.7425
44	Mallikpur Village	23.86438	87.512972	2.4	1.262857143	2.376
45	Gobindapur Muslim Para	23.892694	87.482	1.8	0.947142857	1.782
46	Itagaria HMM School	23.927028	87.59847	0.75	0.394642857	0.7425
47	Surul Uttarpara	23.666	87.664	0.25	0.131547619	0.2475
48	Parbatipur Kayasthapara	23.822473	87.56044	0.21	0.1105	0.2079
49	Kendua Ekdala More	23.883861	87.548361	0.13	0.068404762	0.1287
50	Kendua GP Office	23.895361	87.558472	0.67	0.352547619	0.6633