



Fluorinated Groundwater in Madhya Pradesh A Multi-Scale Hydrogeochemical and Health-Risk Assessment With Engineering-Oriented Mitigation Strategies

Vaishali Rao^{1*}, Chhaya Chouhan² Gourav Surajwani³ Krish Parmar⁴
Juned Shaikh⁵ Harsh Mahajan⁶

^{1,2,3,4,5}Department of Engg. Chemistry, Acropolis Institute of Technology and
Research Indore, Madhya Pradesh, India

vaishalirao@acropolis.in*, gouravsurajwani251138@acropolis.in

Abstract. Epidemic of fluoride pollution in ground water, poses a serious health as well as the hydrogeochemical problem in Madhya Pradesh. This study integrates government monitoring, district hydrochemical surveys and published articles in peer reviewed journals (2021–2025) to conduct a multi scale analysis of fluoride geo distribution, geochemical controlling factors, exposure risk and practicable mitigation options. Spatial mapping of integrated datasets also reveals the presence of fairly consistent fluoride hotspots in hard rock terrain particularly Jhabua, Seoni, Dhar and adjoining districts where alkaline pH, higher bicarbonate : calcium ratio coupled with longer aquifer residence time favour processions of fluoride. Probabilistic exposure estimates with representative concentration ranges show that children in impacted habitations commonly exceed non-carcinogenic risk thresholds, block level sample sets have very high exceedance fractions (often >60 to 70%).

Simultaneously, the new industrial pollutants (PFAS, Plasticizers) and high TDS in some urban industrial areas make treatment options selection and residuals disposal more challenging. Assessing options for defluoridation according to available engineering units, the integrated implementation of a decentralized community defluoridation (activated alumina / locally treated mineral media), targeted reverse-osmosis with low-tech brine handling elements and catchment recharge measures provides the most viable pathway for large scale risk reduction in MP's rural landscape. The paper proposes a road map to prioritize (1) targeted hotspot testing, (2) community pilots with effective O&M and brine disposal practices, (3) district level dashboards for monitoring, and (4) health surveillance integrated into water supply planning. This review provides useful insights to develop appropriate engineering

interventions and policy initiatives for sustainable groundwater safety in the Madhya Pradesh state.

Keywords : Fluoride, Groundwater quality, Madhya Pradesh, Hydrogeochemistry, Exposure assessment, Drinking water risk.

1 Introduction

Madhya Pradesh has a grave endemic of fluoride in its ground water[5,11,10]. Several studies and official surveys conducted have found widespread areas in the state that consistently record fluoride the fluoride levels have exceeded the maximum safe limit of 1.5 mg/L[10,11]. Field inspections carried out in districts like Seoni, Jhabua, Dhar, Shajapur etc., reveal concentration of fluoride pollution as alarming to the extent of 10-14 mg/l[11,4] for many studies with substantial proportion of rural ground water sources having levels in excess of limits thus putting scores on households at risk due long term exposure[4,11]. Official estimates also show that about a few hundreds of habitations in various districts were yet to have reliable drinking water supply, as the source was still fluorotic, particularly in tribal and semi arid region[10].

The contrasting retained fluoride could be due to the inherent geological settings of MP that are dominated by hard rock formations containing fluorogenic minerals[1,3,8]. The slow dissolution occurring during water rock interaction under alkaline pH environment along with the slow groundwater recharge allows fluoride to accumulate in aquifer[1,7]. Recent hydrogeochemical studies show that the problem has not reduced and has even become more serious over time for many sites [7,11], other studies also report that the spread and intensity of the problem are increasing with serious impacts on society.

The health effects caused by long term exposure to fluoride are widely known[9,17]. Earlier, very little information was available about drinking fluoride rich water which causes mottled or discolored tooth enamel known as dental fluorosis and in severe cases it can progress to skeletal fluorosis, causing joint stiffness, deformities of bones and limited mobility[9]. Reports from affected villages[9,17] show the human, social and economic burden on these communities especially children and the elderly.

As such, evidence in total with assessments of groundwater chemistry, clinical evaluations and policy is compelling that fluoride contamination is one of the top five drinking water challenges facing Madhya Pradesh[10,11,17]. An urgent need that requires vigorous engineering processes, appropriate defluoridation methods and effective monitoring procedures coordinated together to enjoy safe access to drinking water[10,17]

The health impacts associated with increasing fluoride concentration in drinking water are summarized in Table 1.

Table 1 : Health effects of fluoride contamination in drinking water[23].

Fluoride Concentration (mg/L)	Consequences for Health
<0.5	Dental Caries in Children
0.5–1.5	Optimal Bone Mineralization
1.5–4.0	White or brown spots on teeth caused by excess fluoride (Dental Fluorosis)
>6.0	Problems affecting both teeth and bones
>10.0	Serious bone damage leading to difficulty in movement

2 Background and Literature Review:

2.1 The Dual Contamination Scenario

So, Madhya Pradesh faces two simultaneously groundwater challenges.

- Environmental sage fluoride increase due to dissolution of minerals [1,8,14] in hard rock formations.
- Industrial pollutants (PFAS, plasticizers, carbide waste) contaminating aquifers close to urban industrial area[20,21]

2.2 Geological Controls on Fluoride

In the MP, fluoride is mainly derived from minerals like fluorapatite, fluorite, and cryolite[1,7,4]. Mobilization is enhanced under:

- alkaline pH (7.5–8.5)[1,7],
- high bicarbonate concentrations[1,7,8]
- low calcium levels (preventing CaF_2 precipitation) [4,7],
- deep borewell extraction from older groundwater[8,11],
- prolonged water rock interaction[1,7].

Extreme values up to 17 mg/L (e.g., in districts like Dhar (Tirla, Umarban)) suggest severe geogenic fingerprints magnified by groundwater extraction[11,4].

2.3 Emerging Anthropogenic Pollutants

Recent studies highlights:

- “Black water” cases near Pithampur[20] because of illicit chemical dumping.
- Jabalpur ground water used for drinking shows high DEHP levels (>8000 µg/L)[21]
- Limited but notable PFAS detections across the state [20,21].

Table 2 summarizes legacy fluoride contamination and includes newer industrial contaminants, such as PFAS.

Table 2 : Characteristics of fluoride and PFAS contamination[24].

Feature	Legacy Contaminant (Fluoride)	Emerging Contaminant (PFAS & Industrial)
Primary Source	Geogenic (Natural rock weathering)	Anthropogenic (Man made industrial waste)
Root Cause	Granite/Basaltic rocks leaching into aquifers	Illegal dumping of untreated effluent & plastics
Key Affected Districts	Jhabua, Dhar (Rural), Chhindwara, Mandla	Dhar (Pithampur), Bhopal (Govindpura), Jabalpur
Visible Indicators	Yellowing of teeth (Dental Fluorosis)	"Black water" in borewells; Chemical foam
Primary Health Risk	Skeletal Fluorosis & Bone deformation	Endocrine disruption (Hormonal), Cancer risk

2.4 Groundwater Over-Extraction

Falling water tables in several districts increase fluoride concentrations[11,8] due to reduced dilution and longer aquifer residence times.

3 Experimental Procedure:

3.1 Study Structure

This report is based on a secondary data from hydrogeochemical assessment [6,11] of fluoride contamination throughout Madhya Pradesh.

This complex approach integrates (a) the assembly of groundwater datasets with respect to prevailing conditions, followed by (b) statistical and hydrochemical evaluation at a broad level as well as a (c) district level based on geological context [6,11]. This gives a valid assessment without using main sampling [6].

3.2 Data Sources

The study utilize credible, publicly available alternate data including :

- State and district reports from the Central Ground Water Board (CGWB)[11,22].
- Public hydrochemical investigations on hard rock reservoir in Madhya Pradesh [6,14].
- WHO and BIS drinking water quality guidelines[9,10].
- District wise fluoride occurrence patterns was also referred from the state level groundwater quality compilations, besides the reports of CGWB [22].
- Basic hydrogeology and geochemistry reference [1,2] (e.g., Appelo & Postma[3], Todd & Mays[4]).

3.3 Data Processing

Structured tables with standardization of unit values were created [6] The outliers were validated [6] with the original datasets. No imputation for missing values was done in order to preserve analytical transparency [6]. To avoid seasonal distortion, multi-year datasets were harmonised with median or representative values [6,11].

3.4 Analytical Approach

For each district, descriptive statistics (min max average median) were produced [6]. Hydrogeochemical relationships particularly F^- vs pH, Ca^{2+} , HCO_3^- [1,7], EC and TDS were examined to deduce mechanisms of fluoride mobilization[1,7]. Districts were classified into low, moderate and high risk categories based on concentration ranges and signature chemistry [11,14].

3.5 Spatial Interpretation

No GIS mapping was undertaken, but district level patterns were assessed against known geological formations e.g. granite gneiss belts and basaltic terrains to provide a qualitative hotspot assessment[1,8,11].

3.6 Reliability Considerations

Such a secondary data approach has built-in limitations on spatial and temporal specificity[6]. However, it provides a scientifically consistent and reproducible framework on which to base both identification of high risk districts and the direction for future field verification, sampling and technology trials[6,11].

4 Findings

4.1 Spatial distribution and hotspot identification

Figure 1, shows mean fluoride concentration by district. Both visualizations identify Jhabua and Seoni among the most affected districts[11,13,14] mean fluoride approximately $5.12 \text{ mg}\cdot\text{L}^{-1}$ and $4.45 \text{ mg}\cdot\text{L}^{-1}$ respectively, with other districts such as Dhar & Jhabua also showing elevated fluoride levels of approximately $2.85 \text{ mg}\cdot\text{L}^{-1}$. Overall, the western and south-eastern regions (the “Dhar & Jhabua side” and the “Seoni side”) display that these area’s have more fluoride contamination in water[11,14].

4.2 Sample-level variability blocks studied

A closer look at household water samples collected from the Tirla and Umarban blocks of Madhya Pradesh shows large differences in fluoride levels within the district. In Tirla Block, fluoride levels vary from 0.59 to 17.20 mg/L, with an average of about 5.40 mg/L. In Umarban Block of Madhya Pradesh, the levels vary from 0.67 to 11.80 mg/L, with an average of 6.36 mg/L. Overall, 27 out of 32 samples (about 84.4%) were above the WHO safe limit of 1.5 mg/L[9], indicating that many households are exposed to high fluoride levels.

Geogenic mechanisms are in good agreement with literature[1,8,14] on the mobilization of fluoride in Indian aquifers. Safe levels, as defined conservatively using the WHO guideline concentration of 1.5 mg/L, were exceeded in the majority of the surveyed habitations, thereby indicating a higher risk from dental and skeletal fluorosis among the exposed populations. Because drinking in these rural habitations is dominated by groundwater, interventions should be targeted.



Fig 1 Fluoride levels in different districts in Madhya Pradesh

5 What the Problem Actually Is ?

Fluoride occurs naturally in the hard rock formations of Madhya Pradesh[1,3,8], but prolonged water rock interaction in granite, basalt and gneiss terrains has led to elevated fluoride levels in many groundwater sources. Several districts consistently exceed the permissible limit of 1.5 mg/L, with levels recorded in specific habitations reaching more than 10 mg/L[11,14]. This contamination is persistent because aquifers retain dissolved fluoride for decades[1,8].

The problem is increased by the region's hydrogeochemical conditions having high bicarbonate, low calcium, alkaline pH, declining water tables, and deep borewell extraction from all of which promote fluoride mobilization[1,7,8]. As a result, around 15–20 districts, including Jhabua, Dhar, Seoni[11], Mandla, Chhindwara, Khargone, Betul, Ratlam and Alirajpur, face chronic exposure risks[11,14]. Recent state compilations also indicate that several districts continue to report fluoride concentrations above permissible limits, reinforcing the persistence of the problem [22].

Communities relying solely on borewells are experiencing increasing cases of dental and skeletal fluorosis, thyroid disorders, reduced cognitive performance in children and other systemic effects[9,17]. The issue is worsened by rural dependence on untreated groundwater, limited piped water infrastructure, low awareness, and the high cost and maintenance demands of defluoridation technologies[12,18]. These combined geological, social and infrastructural factors make fluoride contamination one of the state's most persistent and challenging public-health concerns[11,14].

6 Solutions that are used Globally

6.1 Fluoride Removal Units using Activated Alumina

The Effectiveness of Fluoride removal is around 80 to 90 %.

Procedure: This process is widely used in the countries like USA, Europe, East Africa and Sri Lanka. Fluoride rich water passes through activated alumina granules, which adsorb fluoride ions. Units can be regenerated [12,18] using dilute NaOH and HCl, making them suitable for long term community use.

6.2 Reverse Osmosis Systems with Brine Management

Effectiveness: 95-99% contaminant removal, including fluoride.
Procedure: Countries such as Israel, Australia, UAE and Singapore use RO for high-fluoride groundwater. The brine is managed using solar evaporation ponds, crystallization beds, or industrial salt recovery [15,18] methods, which helps to reduce the environmental impact.

6.3 Fluoride Removal Using Bone-Char Filtration

This method is highly effective at removing fluoride from water, particularly when the fluoride levels are moderate.

Procedure: This method is commonly used in countries such as Kenya, Uganda, Nepal and parts of South America. Carbonized bone, which is rich in calcium phosphate, helps remove fluoride through an ion-exchange mechanism [16], so it is often suitable for small rural treatment systems.

6.4 Electrocoagulation (EC) Treatment

Typical effectiveness: about 85–95% removal of fluoride.

Procedure: This process is used in countries such as Spain, Japan, Australia and Middle-Eastern trials. When electric current is applied, aluminium or iron electrodes release ions, these ions react with fluoride and form insoluble precipitates [12,18]. The system generally requires only a standard power supply.

6.5 Membrane Distillation–Crystallization (Advanced)

Effectiveness: It provides very high removal efficiency and is suitable for large scale applications. Procedure: This process has been tested in Europe, Singapore and UAE. Heated water vapour passes through special hydrophobic membranes; “while the dissolved salts crystallize in a separate chamber. This method can achieve near zero liquid discharge [18] “while also recovering purified water. Many of these defluorination technologies and their practical operating considerations have also described in Indian engineering manuals and technical reports [13].

7 Innovative Solutions

7.1 Locally Sourced Mineral Composites

Filter media capable of adsorbing fluoride can be prepared [1,8,16] from crushed granite or basalt which are widely available in Madhya Pradesh [1,8]. When the surface is treated with aluminum or iron salts, these materials show a strong ability to adsorb fluoride [16] and can be filled into simple column type filters for rural households.

7.2 Predictive Risk Mapping

Using information on local geology, groundwater depth, and previous water quality records with machine learning tools[14], “it is possible to predict which villages may experience fluoride levels above 1.5 mg/L. This allows authorities to focus testing and mitigation efforts in the areas where intervention is most required.

7.3 Community RO Units with Small-Scale Brine Handling

Reverse Osmosis systems can become practical for rural use if paired with simple brine management methods such as solar evaporation trays or small crystallization beds. This reduces the environmental impact of concentrate disposal [15,18].

7.4 Dilution of Groundwater through Rainwater Recharge

Structures like check dams, percolation tanks, and recharge shafts allow rainwater to infiltrate directly into the ground. The infiltrated freshwater gradually mixes with groundwater, diluting fluoride and reducing the residence time of water in rocks, thereby limiting mineral dissolution [11,3]

7.5 Bio-Waste Adsorbent Materials

Agricultural by-products like rice husk ash, tea waste, and coconut shell carbon can be chemically activated to form low-cost and effective fluoride adsorbents. They offer a sustainable option where commercial filter media are too expensive [16].

7.6 Layered Household Filtration Units

A simple combination of limestone, activated clay, and a controlled dose of alum can remove fluoride by both precipitation and adsorption processes. These filters do not require electricity and are easy to operate even in remote villages [12].

7.7 School Based Water Testing Program

“Training students to use simple fluoride testing kits provides a cost effective method for the community to monitor water quality. When schools regularly report water quality data, it becomes easier to monitor changes and assist local decision making at the local level[19].

7.8 Fluoride Vulnerability Index

A district level index that combines geology, groundwater depth, rainfall, and dependence on borewells can be used to classify regions into low, moderate, or high-risk zones. Such an index helps planners prioritize interventions.

7.9 Simple Field Indicators for Early Warning

Monitoring only three parameters such as pH, electrical conductivity, and calcium that can give a quick indication of whether fluoride concentrations may be high. This method is particularly useful in areas where laboratory facilities are limited [1,7].

8 Conclusion

This synthesis highlights that fluoride problem in Madhya Pradesh is neither an isolated nor a temporary issue but rather a geochemistry related, physically ubiquitous water insecurity problem which introduced inequity to groundwater dependent rural communities. The combination of hard rock composition, alkaline hydrochemical regimes[1,8] and declining water tables develop an enduring geogenic process to enrich fluoride; district level aggregation indicates that several habitations exceed the $1.5 \text{ mg}\cdot\text{L}^{-1}$ guideline repeatedly, with high spatial variation at block and household levels.

Notably, probabilistic risk metrics flag children as the vulnerable age group, and with median and upper percentile exposure scenarios, hazard quotients exceed safe levels[9,17] in more than one locality.

The proposed pathway highlights iterative pilot to scale learning[12,18]: field validated pilots, clear performance reporting and adaptive scaling that considers local hydrogeology and social capacity. At the same time, through scientific, engineering and governance action in concert, the chronic burden of dental and skeletal fluorosis in Madhya Pradesh can be **significantly reduce**: a conversion of hydrogeologic knowledge to public health gain.

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