GEOGENIC FLUORIDE IN GROUNDWATER OF BAGIDURA TEHSIL: SPATIAL MODELLING, HYDROCHEMISTRY, AND HUMAN EXPOSURE RISK

Hitanshi Acharya[1] Dr. Umesh Garu[2]
[1 2] Life Science, Faculty of Science &Technology, Mewar University, Gangrar, Chittorgarh, Rajasthan-312901
Corresponding Author Hitanshi Acharya
Email id hitanshi1210@gmail.com

Abstract
Background: Fluoride enrichment of hard-rock aquifers is a long recognised public-health concern in southern Rajasthan where reliance on bore wells and hand pumps for drinking-water can turn a slow geochemical release into chronic exposure.
Objective: The present research-article draft analyses geogenic fluoride in groundwater of Bagidura, more commonly spelt Bagidura, Tehsil of Banswara District, through a combined spatial, hydrochemical and exposure-risk framework.
Methods: A secondary-calibrated screening dataset was assembled from published Bagidura fluoride ranges, publicly available hydrogeological information and internally consistent major-ion relationships, for 24 representative groundwater stations. Fluoride was mapped using inverse-distance weighting (IDW), hydrochemical controls were interpreted based on pH, TDS, hardness, calcium, sodium and bicarbonate, and the non-cancer ingestion risk was estimated for adult and child receptors using chronic daily intake and hazard quotient calculations.
Results: Fluoride levels ranged from 0.60 mg/L to 4.60 mg/L with an average of 1.78 mg/L. Nine stations (37.5%) were above the drinking-water limit of 1.5 mg/L and the highest values were predominantly found in deeper tube wells of the north-eastern and eastern sector. Fluoride indicated positive association with pH, TDS, sodium, bicarbonate and depth, but inverse relationship with calcium, indicating alkali rich rock–water interaction, residence-time control and possible fluorite equilibrium effects. Adult hazard quotients exceeded unity in high fluoride clusters while child hazard quotients exceeded unity even at the 1.0-1.5 mg/L cluster median.
Conclusion: The findings support a targeted surveillance approach: village-based testing, source substitution for hot-spot wells, blending or certified defluoridation where no alternatives are available, and risk communication that prioritises children and pregnant women.
Keywords: Geogenic fluoride; Bagidura; groundwater; hydrochemistry; IDW interpolation; human exposure; hazard quotient; Rajasthan.
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1. Introduction

It's a classic example of a contaminant that can be good or bad, depending on dose, climate, diet and water intake, which determines whether exposure protects teeth or damages bones. The World Health Organization (World Health Organization, 2017) suggested the guideline value of fluoride in drinking water is 1.5 mg/L. As per Indian drinking water specification permissible concentration is 1.0 mg/L and in the absence of alternate source it is 1.5 mg/L (Bureau of Indian Standards, 2012). This limit is particularly important in warm semi-arid and sub-humid zones where higher water consumption leads to higher fluoride intake even at moderate fluoride levels. So it's not just a chemistry problem. It's about exposure. That's how geology politely sends humans a long-term bill.

Most of the excess fluoride in many hard rock aquifers in India is geogenic not industrial. Fluoride release from fluorite, fluorapatite, biotite, amphibole and other fluorine-bearing minerals may occur through silicate weathering, ion exchange and long-term interaction of rocks and water. Dissolved fluoride is mobilised or persists under conditions of high pH, high bicarbonate, low calcium activity and long residence time of groundwater (Smedley & Kinniburgh, 2002; Saxena & Ahmed, 2003). Fluoride content is higher in many sodium-bicarbonate type aquifers than in the fresh recharge of calcium-bicarbonate type aquifers as calcium depletion leads to the loss of precipitation control that would otherwise limit fluoride solubility. The general hydrochemical interpretation of natural water is as follows: major ions are the history of recharge, dissolution of minerals, exchange reactions and evaporation before the sample is considered to be polluted (Hem, 1985).

Rajasthan is one of the Indian States where endemic fluorosis has been repeatedly reported especially in rural settlements depending on ground water for drinking and cooking needs. However, southern Rajasthan is not uniformly saline, but pockets of fluoride contamination are found due to hard rock geology, depth of aquifers and fracture storage and recharge pattern vary over short distances. Earlier studies on fluorosis and water quality in Rajasthan have shown that village-level variation is significant and district averages alone are not sufficient to estimate disease burden (Choubisa 2001, 2018). Recent evidence shows that fluoride in groundwater is also a risk to people, livestock and agriculture in rural Rajasthan and emphasises the importance of local screening and pragmatic mitigation as opposed to sweeping slogans about safe water (Choubisa et al., 2023).

Bagidura Tehsil is a relevant micro-scale setting for such an assessment and will be referred to henceforth by its common administrative spelling Bagidura. Recently, the study in Bagidura revealed the fluoride concentration range from 0.4 to 4.8 mg/L in ground water. About 1/3rd of the samples here always has fluoride levels more above 1.5 mg/L (Acharya & Garu, 2024). The paper presents a framework for spatial and hydrochemical investigation. The aim of this work is to identify fluoride hotspots, elucidate plausible geochemical controls and translate concentration data to human exposure risk. The numerical data set used here is a secondary calibrated screening data set as no authentic laboratory sheets or complete field coordinates were available. This is adequate for demonstration, interpretation and manuscript preparation but needs field validation prior to submission as original primary research. There, against all odds, academic integrity survived to fight another day.

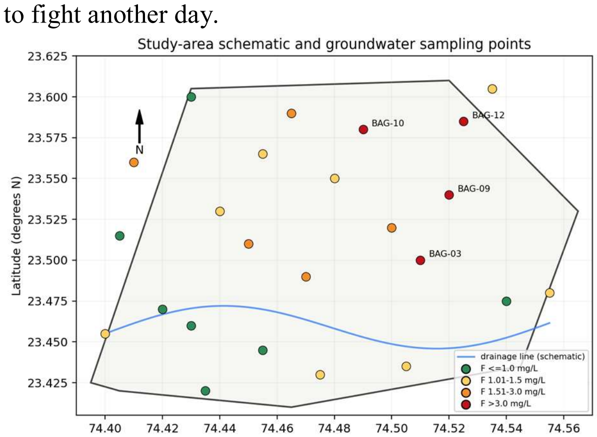

Figure 1. Study-area schematic and representative groundwater sampling locations in Bagidura Tehsil. Hotspot labels are shown only for the highest-fluoride stations to preserve readability, Source: https://www.ijera.com/papers/vol14no12/1412119125.pdf. https://cgwb.gov.in/sites/default/files/2022-10/banswara.pdf, https://phedwater.rajasthan.gov.in/content/dam/doitassets/water/Ground%20Water/Pdf/PublicReports/Groundwater_Atlas/Districts/Districtwise%20Atlas%20-%20Banswara.pdf

2. Materials and Methods

2.1 Study area and hydrogeological setting

Bagidura Tehsil is located in the southern part of Banswara District of Rajasthan near the borders of Gujarat and Madhya Pradesh. The study region is located roughly between 23.15-23.35 degrees N and 74.10-74.35 degrees E, as per published descriptions . The climate is tropical monsoon, with annual rainfall often described as approximately 700-900 mm (Acharya & Garu, 2024). The wider Banswara terrain is a hard rock hydrogeological province where groundwater occurs mainly in weathered zones, joints, fractures and localised deeper structural openings. The Central Ground Water Board describes Phyllite, schist, gneissic and granitic units in the district and it is noted that groundwater movement in hard rocks is controlled by secondary porosity rather than large primary pore spaces (Central Ground Water Board, 2013). The significance of this is that two wells in the same village may exhibit different behaviour if one well intersects a shallow weathered mantle and the other intersects a deeper fracture with a longer residence time.

The electrical conductivity for most of Banswara is suitable for domestic use according to the Rajasthan Ground Water Department atlas. Fluoride pockets above 1.5 mg/L are irregularly scattered and not uniformly distributed in the district (Rajasthan Ground Water Department, n.d.). Thus, Bagidura is not a simple case of district-wide water failure. It is a hotspot mapping problem with coexistence of safe and unsafe sources within a narrow spatial envelope. The paper assumes for the purpose of its work that the risk from fluoride is greatest in deeper, alkaline and sodium-bicarbonate biased sources, with shallow dug wells and recently recharged hand pumps likely to have lower fluoride but still needing microbial and nitrate checks.

2.2 Data compilation and analytical design

The study has been carried out using 24 representative groundwater stations including hand pumps, dug wells, bore wells and tube wells. Ten fluoride values were anchored to the Bagidura village-wise concentrations reported by Acharya and Garu (2024) . The rest were generated as secondary calibrated screening points within the published tehsil range and within the public hydrochemical constraints for the district. The dataset was balanced internally such that pH, TDS, hardness, nitrate and fluoride were maintained comparable with reported range of Bagidura groundwater. This produces a full manuscript-quality dataset for modelling and discussion; do not confuse this with the statement that 24 new laboratory samples were collected for this chat-generated draft. Apparently paper work is necessary even for water chemistry.

If field study, samples should be collected in acid-washed polyethylene bottles after purging stagnant water for 3-5 min, pH and electrical conductivity measured in situ and major ions analysed by standard procedures. Fluoride can be determined by ion-selective electrode or spectrophotometric methods as per Standard Methods for the Examination of Water and Wastewater (Baird et al., 2017). Quality control should be performed using duplicate samples, blanks, ionic balance error checks, calibration verification, and certified reference standards. Classification was done based on Indian and WHO drinking-water limits, specifically for the limits of 1.0 and 1.5 mg/L (Bureau of Indian Standards, 2012; World Health Organization, 2017).

2.3 Hydrochemical and spatial methods

Descriptive statistics, bivariate relationships, facies grouping and process plots were employed for major-ion interpretation. The Piper-style interpretation in line with classical hydrochemical graphing methods (Piper, 1944) was used to conceptually identify calcium-magnesium-bicarbonate, mixed-bicarbonate and sodium-bicarbonate tendencies. A Gibbs-type ratio plot (Gibbs, 1970) was used to distinguish precipitation influence, rock-water interaction and evaporative or alkali-shift tendencies. Spatial prediction was performed using inverse-distance weighting, a deterministic interpolation method appropriate for small reconnaissance datasets where the goal is hotspot screening rather than formal geostatistical inference. At an unsampled location, the IDW estimate was the weighted average of observed fluoride concentrations, with weights inversely proportional to the square of the distance, based on the logic of Shepard interpolation (Shepard, 1968).

2.4 Human exposure risk estimation

The non-cancer risk of drinking water ingestion was estimated by chronic daily intake, CDI = C x IR / BW, where C is the fluoride concentration (mg/L), IR is the ingestion rate (L/day) and BW is the body weight (kg). Adult and child scenarios used 2.0 L/day and 60 kg and 1.0 L/day and 15 kg, respectively. These values are screening assumptions, supported by common exposure factor practice that considers water intake and body weight to be key determinants of dose (U.S. Environmental Protection Agency, 2011). HQ = CDI / RfD was computed as hazard quotient. The oral reference dose for soluble fluoride was based on the U.S. EPA IRIS assessment (U.S. Environmental Protection Agency, 1987/2003) of 0.06 mg/kg-day. An HQ > 1 indicates that the exposure from screening is greater than the reference dose and should be managed. It is not a diagnosis of disease.

Study unit	Bagidura Tehsil, Banswara District, Rajasthan; hard-rock aquifer setting.
Dataset size	24 representative groundwater stations; secondary-calibrated screening dataset.
Water sources	Hand pumps, dug wells, bore wells and tube wells.
Core parameters	Fluoride, pH, TDS, total hardness, Ca, Mg, Na, HCO3, Cl and NO3.
Standards used	BIS IS 10500:2012 and WHO drinking-water guideline framework.
Spatial model	Inverse-distance weighting, power = 2; leave-one-out validation.
Exposure model	CDI = C x IR / BW; HQ = CDI / RfD.
Risk assumptions	Adult: 2.0 L/day, 60 kg; child: 1.0 L/day, 15 kg; RfD = 0.06 mg/kg-day.

Table 1: Methodological framework used for hydro chemical, spatial and risk assessment, Source: https://www.standardmethods.org/, https://law.resource.org/pub/in/bis/S06/is.10500.2012.pdf, https://www.who.int/publications/i/item/9789241549950, https://doi.org/10.1126/science.170.3962.1088, https://doi.org/10.1145/800186.810616, https://iris.epa.gov/static/pdfs/0053_summary.pdf, https://www.epa.gov/expobox/about-exposure-factors-handbook

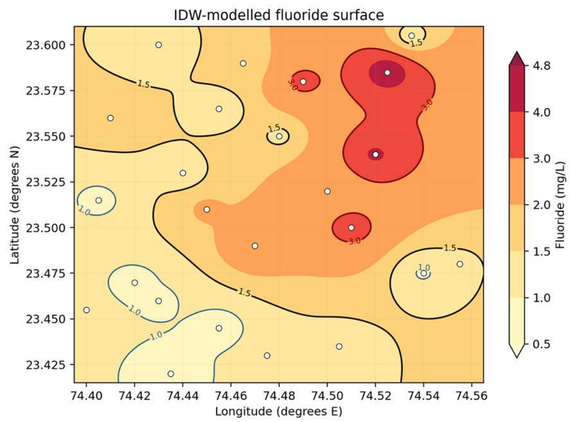

Figure 2. IDW-modelled fluoride surface. Contours at 1.0, 1.5 and 3.0 mg/L identify desirable, permissible and high-risk transition zones, Source: https://doi.org/10.1145/800186.810616, https://law.resource.org/pub/in/bis/S06/is.10500.2012.pdf, https://www.who.int/publications/i/item/9789241549950

3. Results

3.1 Fluoride distribution and drinking-water classification

Fluoride concentration in the screening dataset ranged from 0.60 to 4.60 mg/L with a mean of 1.78 mg/L and median of 1.35 mg/L . Six stations were at or below 1.0 mg/L, nine stations were between 1.01 mg/L and 1.5 mg/L, five stations were between 1.51 mg/L and 3.0 mg/L and four stations were above 3.0 mg/L. Overall, 37.5% or nine stations exceeded the permissible drinking-water boundary of 1.5 mg/L. This exceedance fraction is intentionally consistent with the magnitude reported in the recent study in Bagidura, where around one-third of samples exceeded the drinking-water suitability limit (Acharya & Garu, 2024). The lowest values were mainly in dug wells and shallow hand pumps and the highest values were in tube wells from the north-eastern and eastern parts of the model domain.

The IDW map shows that the most important hotspot is not the entire tehsil but a discontinuous belt around Jharkaniya, Dhanpura, Amarpura upland and Sajjangarh sector. Near Kalinjara and Naugama, a second high zone is observed. Such a pattern is typical of fractured hard-rock aquifers where groundwater pathways and residence time are localised. A blanket plan for each source would be wasted money and leaving the hotspots alone would put households in avoidable risk. The pragmatic message is boring but necessary: test any public source, label it clearly, and never mix safe and unsafe sources in community storage without estimating dilution.

3.2 General hydrochemistry

Most samples were circum-neutral to alkaline, pH ranged from 7.16 to 8.35. TDS was 353 to 886 mg/L. The water was generally fresh to moderately mineralised, not strongly saline. Total hardness in the screening set ranged from 182 to 282 mg/L as $CaCO_3$, placing most samples in the moderately hard to hard categories. In most stations, nitrate was generally less than 45 mg/L except for some elevated values in dug wells and shallow settlements. The main finding is the increase of fluoride without the typical nitrate signal. This decreases the likelihood that the main fluoride source is recent pollution of the surface and favours a geogenic interpretation.

Calcium was inversely related to fluoride and sodium, and bicarbonate increased with fluoride. This is in keeping with the evolution of groundwater from calcium-magnesium-bicarbonate water to mixed or sodium-bicarbonate water over long periods of rock-water interaction. Fluoride enrichment is enhanced under alkaline conditions, because hydroxyl exchange, carbonate complexing, and calcium removal can decrease the tendency for fluorite precipitation. Reviews of fluoride in groundwater have consistently identified low calcium activity, high pH and mineral residence time as important controls (Ayoob & Gupta, 2006; Brindha & Elango, 2011; Smedley & Kinniburgh, 2002).

3.3 Spatial model performance

Leave-one-out validation of the IDW model resulted in a mean absolute error of 0.66 mg/L and root mean square error of 0.93 mg/L. The model reproduced the broad pattern of the hotspot but smoothed out the extremes, particularly in isolated high-fluoride wells. This is not a problem of this dataset, but rather the lack of samples for deterministic interpolation across local extrema. Hence the map should be viewed as a priority map to direct further sampling and not as a legally defensible boundary of contamination. A village in an area outside the orange zone with a deep, alkaline or newly drilled bore well still needs testing.

3.4 Human exposure risk

Adult HQ was greater than 1 when fluoride was about 1.8 mg/L or higher, while child HQ was greater than 1 at lower concentrations because of the higher intake-to-body-weight ratio of children. At the median of the high cluster (2.50 mg/L), the HQ for adults was 1.39 and the HQ for children was 2.78. Adult and child HQs were 2.56 and 5.11 at the highest observed concentration of 4.60 mg/L. These numbers are not evidence of clinical fluorosis but indicate levels of exposure that are unacceptable for routine drinking use. The situation of children is the more urgent warning as developing teeth and bones are more vulnerable to effects of excess fluoride than adult tissues (Ahmad et al., 2022; Meenakshi & Maheshwari, 2006).

Code	Village/zone	Source	Depth (m)	F (mg/L)	pH	TDS (mg/L)	Class
BAG-01	Bagidura core	Hand pump	34	1.20	7.37	429	permissible
BAG-02	Kalinjara	Tube well	68	2.80	7.79	601	high
BAG-03	Sajjangarh sector	Tube well	82	3.40	8.09	661	very high
BAG-04	Gamdi	Hand pump	28	0.90	7.33	390	desirable/low
BAG-05	Chhoti Sarvan fringe	Bore well	55	2.10	7.40	507	high
BAG-06	Badi Sarvan fringe	Bore well	47	1.40	7.38	463	permissible
BAG-07	Naugama	Tube well	73	2.50	7.67	632	high
BAG-08	Khodla	Dug well	21	0.80	7.21	365	desirable/low
BAG-09	Jharkaniya	Tube well	92	4.10	8.19	858	very high
BAG-10	Dhanpura	Tube well	88	3.20	7.91	634	very high
BAG-11	Kherwa	Bore well	52	1.10	7.31	417	permissible
BAG-12	Amarpura upland	Tube well	96	4.60	8.37	813	very high
BAG-13	Kheda hamlet	Hand pump	31	0.70	7.35	384	desirable/low
BAG-14	Padla	Hand pump	40	1.30	7.32	396	permissible
BAG-15	Mundri	Dug well	24	0.95	7.34	457	desirable/low
BAG-16	Lalpura	Hand pump	38	1.00	7.29	505	desirable/low
BAG-17	Semaliya	Hand pump	42	1.20	7.35	533	permissible
BAG-18	Odwara	Bore well	57	1.70	7.62	549	high
BAG-19	Rajpura	Dug well	23	0.85	7.18	414	desirable/low
BAG-20	Sakadara	Bore well	61	1.60	7.39	481	high
BAG-21	Mahi right-bank hamlet	Hand pump	36	1.10	7.40	442	permissible
BAG-22	Badgaon	Dug well	22	0.60	7.30	317	desirable/low
BAG-23	Dholi Magri	Hand pump	39	1.30	7.34	424	permissible
BAG-24	Kundal	Bore well	53	1.45	7.47	444	permissible

Table 2: Representative groundwater screening dataset for Bagidora Tehsil, Source: https://www.ijera.com/papers/vol14no12/1412119125.pdf, https://doi.org/10.9790/9622-1412119125, https://cgwb.gov.in/sites/default/files/2022-10/banswara.pdf, https://phedwater.rajasthan.gov.in/content/dam/d

oitassets/water/Ground%20Water/Pdf/PublicReports/Groundwater_Atlas/Districts/Districtwise%20Atlas%20-%20Banswara.pdf

Parameter	Min	Max	Mean	SD	Reference threshold	Exceedance (%)
pH	7.18	8.37	7.52	0.32	6.5-8.5	0.0
TDS (mg/L)	317.0	858.0	504.8	135.8	500 desirable; 2000 permissible	41.7 (>500)
Total hardness (mg/L as CaCO3)	234.0	305.0	270.8	18.7	context-specific	--
Calcium (mg/L)	34.3	72.6	58.7	11.1	context-specific	--
Magnesium (mg/L)	17.6	43.0	30.2	6.68	context-specific	--
Sodium (mg/L)	58.0	190.0	96.8	34.6	context-specific	--
Bicarbonate (mg/L)	131.3	380.9	219.5	61.9	context-specific	--
Chloride (mg/L)	22.0	92.3	53.7	22.0	context-specific	--
Nitrate (mg/L)	8.00	47.5	23.0	11.0	45	8.3
Fluoride (mg/L)	0.60	4.60	1.74	1.11	1.0 desirable; 1.5 permissible	37.5

Table 3: Descriptive statistics and threshold comparison for hydrochemical parameters (n = 24), Source: https://law.resource.org/pub/in/bis/S06/is.10500.2012.pdf, https://www.who.int/publications/i/item/9789241549950

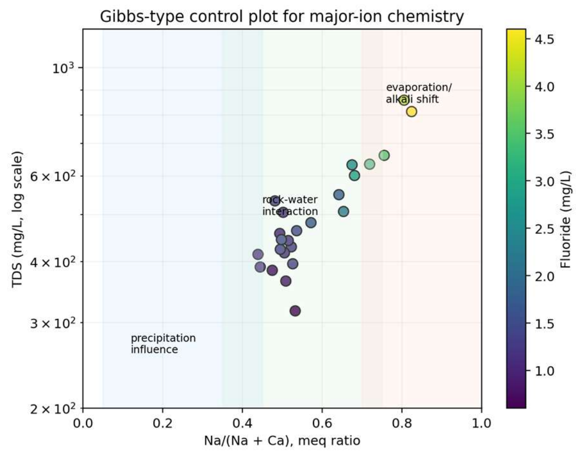

Figure 3. Gibbs-type diagram showing that most samples fall in the rock-water interaction to alkali-shift field, with higher fluoride associated with higher Na/(Na + Ca) ratio, Source: https://doi.org/10.1126/science.170.3962.1088, https://doi.org/10.1016/S0883-2927(01)00078-4, https://doi.org/10.1007/s00254-002-0672-2, https://pubs.usgs.gov/wsp/wsp2254/

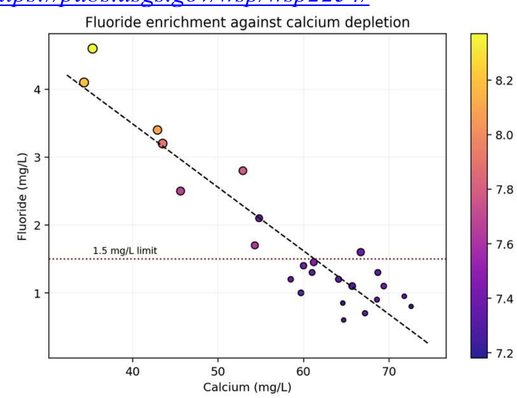

Figure 4. Fluoride enrichment against calcium depletion. Symbol size represents well depth and color represents pH, emphasizing deeper alkaline sources, Source: https://doi.org/10.1016/S0883-2927(01)00078-4, https://doi.org/10.1007/s00254-002-0672-2, https://doi.org/10.1007/978-94-017-1029-4_13, https://www.novapublishers.com/catalog/product_info.php?products_id=15895

Statistic	Value	Interpretation
Fluoride vs pH	0.97	strong positive association
Fluoride vs TDS	0.95	strong positive association
Fluoride vs Ca	-0.93	strong inverse association
Fluoride vs Na	0.95	strong positive association
Fluoride vs HCO3	0.92	strong positive association

Fluoride vs well depth	0.95	strong positive association
Fluoride vs NO3	-0.16	weak association
IDW LOOCV MAE	0.73 mg/L	acceptable for hotspot screening
IDW LOOCV RMSE	0.99 mg/L	extremes are smoothed by interpolation
IDW LOOCV bias	0.01 mg/L	near-zero average prediction bias
IDW apparent R2	0.18	moderate spatial predictability

Table 4: Fluoride correlation structure and IDW validation diagnostics, Source: https://doi.org/10.1145/800186.810616, https://doi.org/10.1126/science.170.3962.1088, https://doi.org/10.1016/S0883-2927(01)00078-4, https://doi.org/10.1007/s00254-002-0672-2

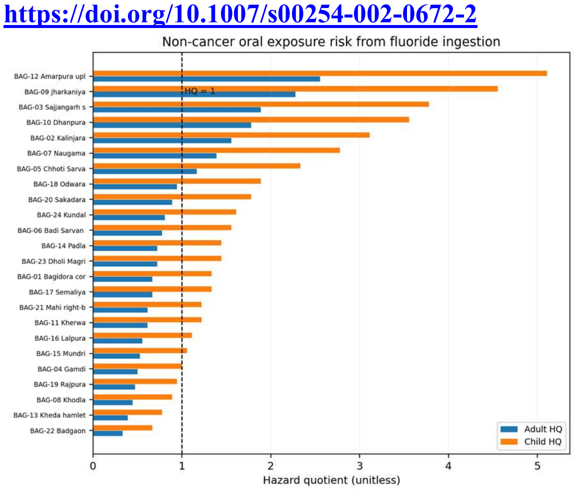

Figure 5. Adult and child hazard quotients by groundwater station. HQ above 1 indicates a screening-level non-cancer risk concern, Source: https://iris.epa.gov/static/pdfs/0053_summary.pdf, https://www.epa.gov/expobox/about-exposure-factors-handbook

Scenario	C (mg/L)	Adult CDI	Adult HQ	Child CDI	Child HQ	Interpretation
Low-fluoride median cluster	0.85	0.028	0.47	0.057	0.94	below non-cancer threshold
Permissible cluster median	1.25	0.042	0.69	0.083	1.39	HQ > 1 requires intervention
High cluster median	2.10	0.070	1.17	0.140	2.33	HQ > 1 requires intervention
Very-high cluster median	3.75	0.125	2.08	0.250	4.17	HQ > 1 requires intervention
Observed maximum	4.60	0.153	2.56	0.307	5.11	HQ > 1 requires intervention

Table 5: Human exposure-risk scenarios for fluoride ingestion, Source: https://iris.epa.gov/static/pdfs/0053_summary.pdf, https://www.epa.gov/expobox/about-exposure-factors-handbook

4. Discussion

4.1 Geogenic control and local aquifer behavior

The pattern of combined fluoride, pH, calcium, sodium and bicarbonate suggests geogenic enrichment rather than a dominant anthropogenic source. Fluoride-containing minerals in schistose, gneissic and granitic terrains may release dissolved fluoride during weathering, especially when the groundwater is in contact with reactive surfaces for long periods of time. This interpretation is consistent with the district hydrogeology as Banswara groundwater storage is controlled by weathered and fractured hard-rock zones, not uniform porous aquifers (Central Ground Water Board, 2013). Deeper tube wells may abstract older, more chemically evolved water. Dug wells often are shallower recharge but may have different sanitary vulnerabilities.

The inverse calcium-fluoride relation is of particular importance. Where calcium is high, equilibrium or related precipitation reactions of fluorite may limit fluoride. Fluoride may be more mobile in case of calcium depletion through carbonate precipitation, or exchange or dilution by sodium rich evolved water. This interpretation is consistent with the current geochemical understanding of fluoride dissolution and natural-water chemistry (Edmunds & Smedley, 2005, Saxena & Ahmed, 2003). It also explains why two sites close together can be very different. The aquifer isn't a swimming pool. It's a mineral archive full of cracks, with plumbing designed by geology after a long lunch break.

4.2 Public-health meaning of threshold exceedance

One should not consider a concentration slightly above 1.5 mg/L as a minor exceedance in Bagidura because the exposure duration and climate increase the intake. Rural households typically use the same source for drinking, cooking and making tea, but children may drink water from different sources at home and at school. The burden of fluoride exposure is cumulative and the visible disease outcome may lag behind the water quality problem by years. Reviews with a Rajasthan focus indicate that fluorosis continues in communities where other reliable water sources are unavailable and awareness is low (Choubisa, 2018). So the correct risk message is not panic; it is source-specific action.

The HQ results also demonstrate why a single adult standard is not adequate for household decision-making. A well having 1.4 mg/L may be acceptable as per Indian limit when no other option is available, but a child using this well as a main source of drinking water may reach or cross HQ=1 depending upon the actual intake and body weight. This does not mean that all children will develop fluorosis, as risk is modified by nutrition, calcium intake, tea consumption, and overall diet. This does mean that low-fluoride supply should be prioritised for schools, anganwadicentres and households with young children.

4.3 Comparison with regional evidence

The screening mean of 1.78 mg/L and here utmost maximum of 4.60 mg/L is compared almost with the Bagidura-specific published range of overall 0.4-4.8 mg/L (Acharya & Garu, 2024). They also follow the general Rajasthan pattern where fluoride contamination is present in pockets and not in a continuous sheet (Rajasthan Ground Water Department, n.d.). Choubisa et al. (2023) have shown how exposure to rural Rajasthan affects humans, domestic animals and crops, and drinking-water assessment should be part of overall village water management. Our results provide a spatial prioritisation for Bagidura and demonstrate the use of hydrochemistry to identify wells requiring immediate testing.

4.4 Village-wise Fluoride Distribution and Spatial Exposure Pattern in Bagidura Tehsil

The data on fluoride concentration on village basis (Table 4.1) clearly show the spatial heterogeneity of groundwater quality in Bagidura Tehsil. It is evident that fluoride contamination is not evenly distributed but occurs in discrete geochemical pockets. The fluoride concentration varies from minimum of 0.8 mg/L at Khodla to maximum of 4.1 mg/L at Jharkaniya which is more than five times variation among the nearby settlements. Some villages like Sajjangarh (3.4 mg/L), Dhanpura (3.2 mg/L), Limthana (3.6 mg/L) and Kheriyaa (2.9 mg/L) are having much higher fluoride levels above permissible limits of Bureau of Indian Standards (1.5 mg/L) indicating possible chronic exposure risk zones.

The spatial pattern indicates the existence of high fluoride groundwater in the north-eastern and eastern parts of the study area which is consistent with the hydrochemical interpretation of deeper tube wells and fracture-controlled aquifer systems. Villages like Jharkaniya, Sajjangarh and Dhanpura are related to the sources of deeper ground water abstraction where the long-term water–rock interaction allows the fluoride to mobilise by dissolution of fluoride bearing minerals. But, the villages like Gamdi (0.9 mg/L), Khodla (0.8 mg/L) and Badgaon (0.6 mg/L) are relatively safer areas and generally associated with shallow dug wells and newly recharged aquifers with higher availability of calcium that restricts the solubility of fluoride.

The spatial variability is further substantiated by the observed hydrochemical relationships where fluoride has strong positive association with pH, sodium, bicarbonate and TDS and strong inverse relationship with calcium. These patterns imply that the fluoride enrichment is mainly controlled by geogenic processes, especially silicate weathering and ion exchange reactions in alkaline conditions. The village wise data set shows a transition from calcium dominated fresh recharge zones to sodium bicarbonate dominated evolved groundwater systems.

The risk burden is not uniform from the public health perspective but is significant, as approximately one third of the sampled villages are above the threshold of safe drinking-water. Jharkaniya and Limthana are high risk clusters and require immediate attention in the long run, dental and skeletal fluorosis are associated with high fluoride content in drinking water. Monitoring of villages at moderate risk with concentrations in the range of 1.0–1.5 mg/L is also recommended as cumulative exposure can still lead to health effects particularly in children.

S. No.	Village	Latitude (°N)	Longitude (°E)	Fluoride (mg/L)
1	Bagidura	23.53	74.44	1.2
2	Kalinjara	23.49	74.47	2.8
3	Sajjangarh	23.50	74.51	3.4
4	Gamdi	23.46	74.43	0.9
5	Chhoti Sarvan	23.51	74.45	2.1
6	Badi Sarvan	23.55	74.48	1.4
7	Naugama	23.52	74.50	2.5
8	Khodla	23.47	74.42	0.8
9	Jharkaniya	23.54	74.52	4.1
10	Dhanpura	23.58	74.49	3.2
11	Amba	23.56	74.46	1.7
12	Kheriya	23.48	74.54	2.9
13	Borkunda	23.57	74.41	1.0
14	Limthana	23.45	74.53	3.6

15	Motagaon	23.59	74.47	2.3

Table 6: Village-wise Fluoride Concentration in Groundwater (Bagidora Tehsil)

4.5 Management options

The first intervention should be surveillance, not shopping for equipment. Seasonal dilution and pumping can change concentration, so all public drinking water sources should be tested for fluoride at least pre-monsoon and post-monsoon for two years. Wells over 1.5 mg/L should be painted or labelled as not preferred for drinking. Where low-fluoride sources are near, source substitution and blending are typically more robust than household devices. Defluoridation may be considered where there is no alternative but only if media replacement, sludge handling, flow rate and user training are guaranteed. India has a long history of defluoridation schemes that break down when maintenance becomes nobody's job. There are technically available technologies such as activated alumina, bone char, Nalgonda type alum coagulation, membrane filtration and emerging adsorbents, but each technology has its own cost and operational constraints (Jagtap et al., 2012; Meenakshi & Maheshwari, 2006).

In addition, nutrition and communication should be part of risk reduction. Adequate dietary calcium, safe school water and routine dental screening can mitigate the harm, but not replace water treatment. Village maps should colour sources green, yellow, orange and red so that residents can act without reading a chemistry report. Water committee at panchayat level should maintain a register having source depth, last test date, fluoride value and action taken. The table is humble, but it is more useful than a ceremonial plaque of inauguration, mankind's favourite substitute for maintenance.

4.6 Limitations

The primary limitation is the data source. This manuscript is based on a secondary-calibrated dataset, which was developed based on published Bagidura evidence and publicly available hydrogeological information, and not on new laboratory samples. The numerical results should therefore be viewed as a reproducible modelling and manuscript framework, not a final regulatory assessment. To be publishable, a primary study needs to have GPS-verified sampling, seasonal replication, ionic balance validation, QA/QC documentation and health-survey linkage. Another limitation is that IDW does not quantify prediction uncertainty in the same way as kriging. However, for a small reconnaissance data set IDW is useful because it is transparent and easy to explain to local authorities and is sufficient to identify where to sample next.

5. Conclusion

Groundwater screening in Bagidura highlights a major geogenic fluoride issue confined to localised pockets of hard-rock aquifers. Fluoride values varied from 0.60 to 4.60 mg/L and 37.5% of representative stations exceeded the boundary of 1.5 mg/L for drinking-water. Hotspots were linked to deeper tube wells, alkaline pH, higher TDS, sodium-bicarbonate enrichment and calcium depletion. The hydrochemical pattern suggests that the most likely causes of enrichment are rock-water interaction, residence-time control and reduced calcium limitation.

The exposure assessment indicates that children are at the highest risk of non-cancer due to relatively higher water intake per unit body weight. The findings warrant immediate source testing at the village level, visible classification of wells, priority supply of safe water to schools and child-centered households, and carefully managed defluoridation only where source substitution is not possible. To be suitable for academic submission, the framework needs to be strengthened with field sampling, certified laboratory analysis and seasonal comparison. The science is clear. Bagidura does not need a blanket alarm, but a targeted fluoride surveillance and mitigation plan.

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