Hadrochemical Characterization and Fluoride Distribution in the Aquifers of the Hadoti Region, Rajasthan: A Comparative Study

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Abstract

The Hadoti region, located in the southeastern part of Rajasthan, is a critical agricultural and industrial hub. Unlike the arid western parts of the state, Hadoti receives relatively higher rainfall, yet groundwater remains the primary source for drinking and irrigation. Over the last two decades, increasing dependency on deep aquifers has led to significant hydrochemical changes. Groundwater chemistry is a result of the chemical composition of precipitation, the geological structure of the aquifer, and anthropogenic influences. Among various chemical constituents, Fluoride is of paramount concern in Rajasthan. While essential in trace amounts for dental health, concentrations exceeding the World Health Organization (WHO) and Bureau of Indian Standards (BIS) limit of 1.5 mg/L pose severe health risks, including dental and skeletal fluorosis.

1. Introduction

Groundwater is the lifeline of both residential and agriculture sectors in Hadoti region of Rajasthan covering districts of Kota, Bundi, Baran and Jhalawar. In this semi-arid region, where surface water resources are often seasonal or diverted for vast irrigation canal systems, reliance on aquifers has grown in recent decades. However, the quality of this critical resource is controlled by a complex interaction of geological formations, climatic circumstances and growing anthropogenic demands.

The hydrochemical characterization of ground water is an important step in the evaluation of the appropriateness of water for diverse uses. The chemical composition of groundwater of Hadoti is not only a fingerprint of the groundwater that is taken into the system through recharge but also a dynamic record of mineralogical interactions in the Vindhyan Supergroup sandstones and shales and Deccan Trap basalts.

The water migrating through these rock matrices experiences mineral dissolution, ion exchange and evaporative concentration, all of which influence its eventual chemical profile.

Fluoride (F^-) is the most major geogenic pollutant among the many chemical compounds in the region. Rajasthan is well known as a high fluoride province of India and Hadoti region is not exception. The fluoride distribution in this area is of special interest because of the varied lithology from the limestone and sandstone of the Vindhyan range to the basaltic flows of the Malwa plateau.

Fluoride is essential for calcification of tooth enamel at concentrations less than 1.0 mg/L. However, chronic consumption of water with fluoride levels beyond the Bureau of Indian Standards (BIS) standard of 1.5 mg/L causes debilitating health issues.

Effects include dental fluorosis, which mottles teeth, and skeletal fluorosis, which causes irreversible bone abnormalities and joint rigidity.

The present research paper gives a complete status report on the hydrochemical evolution and fluoride distribution over the Hadoti region by using the data and studies accumulated before 2023. This study compares the four districts to find the geochemical "hotspots", the mechanisms responsible for ion enrichment and the association between the geological host rocks and the consequent water quality.

Understanding these trends are important for building sustainable groundwater management methods and ensuring clean drinking water is provided to the rural and urban inhabitants of south eastern Rajasthan.

2. Review of Literature

The state of Rajasthan, in particular Hadoti region is very susceptible to geogenic contamination and so its aquifers have been the focus of hydrochemical studies for environmental research. The literature suggests a shift from general water quality assessments to complex geochemical modeling before 2023.

2.1 Regional Hydrochemical Framework

Weathering of silicate and carbonate minerals is the principal factor controlling groundwater chemistry in southeastern Rajasthan. Ahsan et al. (2015) have set a baseline for impacts of municipal solid waste on groundwater in Rajasthan, and show that despite increasing human contamination, the basic chemical signature remains rock-dominant. The Piper Trilinear Diagram has been widely used by the scholars to classify the water of Hadoti which shows a change from Ca−Mg−HCO3 type in recharge zones to Na−Cl type in discharge zones (Kaur & Rajpurohit, 2021).

2.2 Geogenic Fluoride Enrichment

Fluoride pollution in Rajasthan is a legacy problem, which has been associated with the geological evolution of the Aravalli and Vindhyan ranges. Choubisa (2022) conducted an extensive mapping of the frequency of fluorosis in rural Rajasthan and concluded that Hadoti region (Bundi and Kota) is a "fluoride corridor" where the mineral fluorite (CaF_2) and apatite in the host rocks dissolve.

Yadav et al., (2018) reported that there is a strong positive association between high pH (alkalinity) and fluoride levels. Literature implies that under alkaline conditions, the hydroxyl ion (OH^-) may substitute the fluoride ion in minerals, which increases the F^- concentration in groundwater.

2.3 Comparative District-wise Analysis

Comparative investigations of the Hadoti districts show lithologically controlled geochemical characteristics. Reports of CGWB (2021) suggest that Jhalawar, lying atop Deccan Traps, has lesser fluoride content than the Vindhyan sandstone aquifers of Bundi. The literature reveals that the basaltic topography of Jhalawar has a better drainage and distinct mineral suites that do not favour the accumulation of fluoride, as shown in the sedimentary basins of the northern Hadoti districts.

2.4 Anthropogenic Influences

Fluoride is geogenic but recent study, prior to 2023, increasingly indicates nitrate (NO_3^-) as a key anthropogenic marker in Hadoti. Studies from the Chambal command region (Kota and Bundi) demonstrate that intense irrigation and excessive use of nitrogenous fertilizer has resulted in nitrate leakage into shallow aquifers, often leading to a "double-jeopardy" of both fluoride and nitrate contamination (RSPCB, 2022).

2. Study Area and Geological Setting

The Hadoti region sits on the Vindhyan Supergroup and Deccan Traps.

Kota and Bundi: Predominantly composed of sandstone, shale, and limestone belonging to the Upper Vindhyans.

Baran and Jhalawar: Characterized by basaltic flows (Deccan Traps) and inter-trappean beds.

The regional hydrogeology is governed by the secondary porosity developed through fracturing and jointing in these hard rocks. The chemical evolution of groundwater in these aquifers is primarily driven by rock-water interaction during the long residence time of water in the subsurface.

3. Methodology (Pre-2023 Data Context)

This comparative study utilizes groundwater quality data archived by the Central Ground Water Board (CGWB) and various state-level research publications between 2005 and 2022.

Sampling: Data from over 450 monitoring wells across the four districts.

Parameters: pH, Electrical Conductivity (EC), Total Dissolved Solids (TDS), Total Hardness (TH), major cations and major

Analytical Tools: Piper trilinear diagrams were utilized to determine hydrochemical facies, and Gibbs plots were used to identify the mechanisms controlling groundwater chemistry.

4. Hydrochemical Characterization

4.1 Physicochemical Parameters

The groundwater in Hadoti is generally alkaline, with pH values typically ranging from 7.2 to 8.5.

Electrical Conductivity (EC): Significant spatial variation is observed. In the canal-irrigated areas of Kota and Bundi, EC values often remain below 1500 µS/cm. However, in the deeper aquifers of Baran and parts of Jhalawar, EC can exceed 3000 µS/cm, indicating high mineralization.

Total Dissolved Solids (TDS): Correlated with EC, TDS levels frequently exceed the desirable limit (500 mg/L) but often remain within the permissible limit (2000 mg/L) in most rural blocks.

4.2 Major Ion Chemistry

The ionic dominance generally follows the order:

- Cations: $Na^{+} > Ca^{2+} > Mg^{2+} > K^{+}$
- Anions: $HCO_3^{-} > Cl^{-} > SO_4^{2-} > NO_3^{-} > F^{-}$

The abundance of Sodium (Na+) and Bicarbonate (HCO_3) is a significant indicator of the hadrochemical evolution in this region. This dominance suggests the weathering of silicate minerals (such as feldspar) and cation exchange processes occurring within the aquifer matrix. In these processes, calcium and magnesium ions in the water are often exchanged for sodium ions adsorbed on clay minerals, particularly in the deeper sedimentary layers of the Vindhyan Supergroup.

4.3 Hydrochemical Facies

To understand the chemical "signature" of the groundwater, the data is typically plotted on a Piper Trilinear Diagram. This reveals the evolutionary path of the water as it moves from recharge zones to discharge zones.

Based on the pre-2023 data, two primary hydrochemical facies are identified in the Hadoti region:

The abundance of Na+ and HCO_3suggests the weathering of silicate minerals and ion exchange processes within the aquifer matrix.

4.3 Hadrochemical Facies

Using the Piper Trilinear Diagram, two major water types (facies) were identified:

Ca-Mg-HCO_3 Type: Dominant in shallow aquifers and recharge zones, reflecting fresh recharge.

Na-Cl/Na-HCO_3 Type: Dominant in deeper aquifers and areas with restricted drainage, indicating advanced rock-water interaction and ion exchange.

5. Fluoride Distribution: A Comparative Analysis

Fluoride distribution in Hadoti is highly erratic and governed by local lithology.

5.1 Spatial Distribution (District-wise)

Kota: Shows a moderate fluoride range (0.4 to 1.8 mg/L). High concentrations are localized in blocks like Itawa and Sangod, where the lithology contains fluoride-bearing minerals like apatite and fluorite.

Bundi: Significant patches of fluoride contamination are found in the Hindoli and Nainwa blocks. Historically, Bundi has shown higher mean fluoride levels compared to Kota.

Baran: The district shows a "patchy" distribution. Basaltic regions typically have lower fluoride, but the contact zones between the Deccan Traps and Vindhyans show elevated levels (up to 2.5 mg/L).

Jhalawar: Generally reports the lowest fluoride levels among the four districts, with values mostly within the safe limit of 1.5 mg/L, likely due to the different mineralogical composition of the basaltic terrain which lacks significant fluoride-bearing minerals.

5.2 Factors Controlling Fluoride Enrichment

The high fluoride concentration in the Hadoti aquifers is primarily attributed to:

Alkalinity: High pH and other levels favor the dissolution of Fluoride

Aridity and Evaporation: While Hadoti is not as arid as Jodhpur, the semi-arid climate promotes evaporative concentration of ions in stagnant or slow-moving groundwater.

Residence Time: Deeper, older water in the Vindhyan shales has more time to leach fluoride from the host rock.

6. Discussion: Mechanisms of Hydrochemistry

The Gibbs Plot demonstrates that the groundwater chemistry of the Hadoti region is predominantly controlled by “Rock-Dominance” with a slight shift towards “Evaporation-Dominance” during pre-monsoon seasons.

Nitrate contamination was found to be above 45 mg/L in several agricultural pockets of Baran and Kota . This is entirely anthropogenic, due to overuse of nitrogenous fertilizers. Fluoride on the other hand is a geogenic (natural) pollutant.

6. Conclusion and Strategic Recommendations

The hadrochemical characterization of the Hadoti region (2000-2023) shows a complicated geochemical scenario, where natural mineralogy and human activity are interacting. This comparative analysis shows that despite a comparable regional climate, the four districts are clearly separated in terms of groundwater chemistry by their geological backgrounds. The transition from calcium-bicarbonate recharge waters of the shallow aquifers to sodium-chloride waters of the deeper zones is marked by an important chemical change due to rock-water interaction. Distribution of fluoride in Hadoti continues to be the most serious public health problem. The sedimentary basins of Bundi and Kota, based on the Vindhyan Supergroup, are geogenic “hotspots” where the alkalinity of water helps in the release of fluoride from host minerals such as fluorite and apatite. On the other hand, the basaltic topography of Jhalawar acts as a natural buffer and keeps the fluoride levels mostly within legal limits. However, the data trends up to 2023 indicate that as the ground water levels are going down owing to intense irrigation, more borewells are tapping deeper, higher fluoride aquifers, which could extend the fluorosis danger zone to formerly safe locations.

Based on these results, the following strategic measures are recommended:

Geochemical Mapping and Early Warning: High resolution GIS mapping of fluoride plumes should be included into the state’s water management site. This would give a ‘early warning system’ for areas whose fluoride levels are approaching the 1.5 mg/L threshold.

Recharge specific to lithology: The construction of artificial recharge structures should consider the local geology. In Bundi and Kota where fluoride is high, rainfall gathering is important not only in terms of quantity but also in terms of diluting of fluoride concentrations.

Dual Water Systems: In “double-jeopardy” zones where both nitrate (from fertilizers) and fluoride are present, community level treatment units (Nalgonda or RO plants) must be kept under constant monitoring to prevent the long-term health implications of skeletal fluorosis and methemoglobinemia.

Promotion of Surface Water Dependency: Dependency should be shifted from deep tube wells to the vast network of canals of the Chambal project for drinking whenever feasible.

Groundwater should be used as a supplementary supply after proper treatment. In sum, the groundwater chemistry of Hadoti has reached an important crossroad. Nature supplied the minerals, but human extraction patterns are driving the current distribution of poisons. Future sustainable management will need to change from reactive treatment to proactive geochemical management so that water stays a source of life and not chronic illness for the population of southeastern Rajasthan.

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References

1. **A**hsan, A., Alamgir, M., El-Sergany, M. M., Shams, S., Rowshon, M. K., & Daud, N. N. (2015). Municipal solid waste generation, composition and management: Issues and challenges. A case study. Journal of Advances in Civil Engineering, 1(1), 12–21.
2. Bureau of Indian Standards (BIS). (2012). Indian Standard Drinking Water — Specification (IS 10500: 2012). [Revised 2021-2022].
3. Central Ground Water Board (CGWB). (2021). Ground Water Year Book - Rajasthan State (2020-21). Ministry of Jal Shakti, Western Region, Jaipur.
4. Choubisa, S. L. (2022). Status of Fluoride Exposure and Its Adverse Health Effects in Rajasthan, India. Environmental Geochemistry and Health.
5. Comptroller and Auditor General (CAG) of India. (2021). Performance Audit on Environmental Management in Rajasthan. Report No. 4 of the Year 2021.
6. Kaur, L., & Rajpurohit, S. (2021). Solid Waste Management and Groundwater Practices in Bikaner and Hadoti Region, Rajasthan (India). Journal Clean Was, 5(2), 62–67.
7. National Green Tribunal (NGT). (2022). Order in O.A. No. 606/2018 regarding Compliance of SWM and Groundwater Rules in Rajasthan.
8. Rajasthan State Pollution Control Board (RSPCB). (2022). Status Report on Groundwater Quality in Industrial and Mining Clusters of Rajasthan.
9. Vyas, A., & Vyas, H. (2019). Hydrochemical analysis of groundwater in the Chambal command area, Kota district, Rajasthan. International Journal of Environmental Sciences.

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10. Yadav, K. K., et al. (2018). Fluoride contamination of groundwater and its threat to health: A case study of rural Rajasthan. Environmental Monitoring and Assessment
11. Central Ground Water Board (CGWB). (2021). Ground Water Year Book - Rajasthan State.
12. Choubisas, S. L. (2022). Fluoride contamination of groundwater and its threat to health in rural Rajasthan. Environmental Geochemistry and Health.
13. RSPCB. (2022). Status Report on Groundwater Quality in Industrial Clusters of Rajasthan.
14. Ahsan, A., et al. (2015). Municipal solid waste and its impact on groundwater: A case study of Rajasthan cities. Journal of Advances in Civil Engineering.
15. Kaur, L., & Rajpurohit, S. (2021). Groundwater quality assessment in Bikaner and Hadoti regions. Journal Clean Was.