

Revealing Hidden Groundwater - Water Quality Nexus Relationships Using Multivariate Controls: Evidence from Vadodara, Western India

M Ushashree

Independent Researcher

Email: manneushashree[at]gmail.com

Abstract: Groundwater level fluctuations are frequently used as a standalone indicator of groundwater stress, yet their ability to explain water quality variability remains limited. This study evaluates groundwater-water quality nexus relationships in Vadodara district, western India, by integrating groundwater level change with key hydrogeochemical parameters. Using annual datasets (2014-2021) for nitrate (NO_3^-), fluoride (F^-), and electrical conductivity (EC), both bivariate and multivariate regression models were developed. Uncontrolled models show negligible explanatory power of groundwater level change alone for nitrate ($R^2 = 0.04$) and fluoride ($R^2 = 0.04$). However, controlled nexus model incorporating EC and fluoride explain up to 98.5% of nitrate variability and 77.7% of fluoride variability. Results reveal strong hydrogeochemical mediation of groundwater quality and demonstrate that fluoride behaves as a geogenically controlled parameter rather than a direct function of groundwater stress. The findings highlight the limitations of single-variable groundwater indicators and emphasize the necessity of nexus-based, multivariate approaches for groundwater quality assessment and management.

Keywords: groundwater fluctuation; water quality nexus; nitrate; fluoride; electrical conductivity; water pollution; India

1. Introduction

Groundwater forms the backbone of water security in semi-arid regions of India, supporting domestic supply, agriculture and industry. Increasing abstraction, coupled with climatic variability, has resulted in widespread groundwater depletion and deterioration of groundwater quality (Gleeson et al., 2012; Famiglietti, 2014). While groundwater level change is commonly used as indicator of aquifer stress, its ability to explain concurrent changes in groundwater quality remains limited and context dependent.

Groundwater quality parameters respond not only to hydrological fluctuations but also to hydrogeochemical processes and anthropogenic pressures operating at different spatial and temporal scales (Edmunds & Smedley, 2013). Nitrate contamination is primarily linked to agricultural intensification, fertilizer application, and sewage infiltration, whereas fluoride enrichment is dominantly geogenic, controlled by mineral dissolution, residence time, and salinity conditions (Spalding & Exner, 1993; Smedley & Kinniburgh, 2002).

Recent studies emphasize the need for integrated groundwater-water quality nexus approaches that move beyond single-variable indicators to capture interdependencies (Hiscock et al., 2011). However, such analyses are still limited in many Indian districts due to fragmented datasets and inconsistent monitoring. As a rapid first assessment, this study integrates groundwater level fluctuations with key water quality parameters to evaluate nexus relationships in Vadodara district, western India. The objective is to assess whether groundwater level change alone can explain nitrate and fluoride variability, or whether multivariate hydrogeochemical controls provide a more robust explanation.

2. Methodology

2.1 Data sources

Groundwater level data were obtained from the Central Ground Water Board (CGWB) monitoring network, which provides annual groundwater level measurements across India. Year-on-year groundwater level change was calculated to represent groundwater stress conditions in the study area.

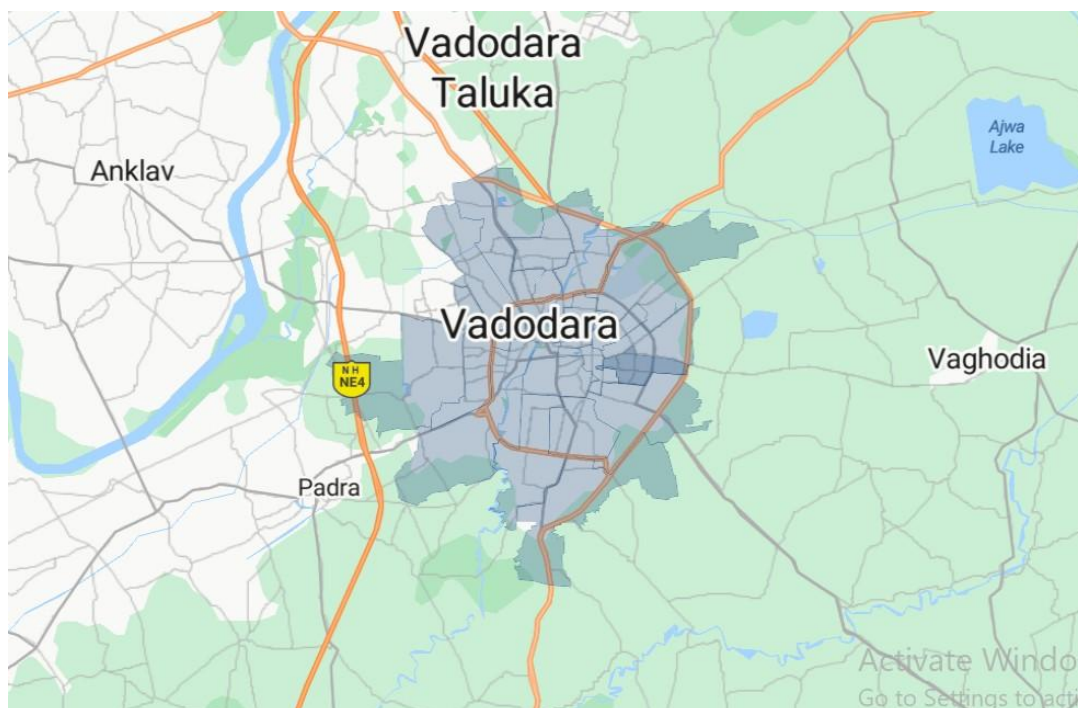


Figure 1: Map of Study area

Groundwater quality data for nitrate (NO_3^-), fluoride (F^-), and electrical conductivity (EC) were downloaded from the National Water Information Centre (NWIC) portal, Government of India. NWIC provides standardized, quality-controlled water quality datasets compiled from monitoring agencies. Only years with overlapping groundwater level and water quality records were retained for analysis, resulting in a consistent annual dataset for the period 2014-2021.

2.2 Data Processing and Analysis

All data processing, statistical analysis, and visualization were carried out using Python (3.14 version). Python-based scientific libraries were used for data cleaning, regression analysis, and graphical representation.

Groundwater level change was treated as the primary hydrological stress indicator. Electrical conductivity was included as a proxy for salinity and mineralization intensity, which strongly influence geochemical mobilization processes, particularly fluoride.

Two categories of regression models were developed:

- 1) Uncontrolled(bivariate) models, assessing groundwater level change as the sole predictor of nitrate and fluoride concentrations. (*Uncontrolled(bivariate) models were used as baseline assessments to evaluate whether groundwater level change alone can explain observed water quality variability*)
- 2) Controlled (multivariate) nexus models, incorporating groundwater level change together with EC and fluoride (for nitrate models) and EC (fluoride models).

Model performance was evaluated using regression coefficients and the coefficient of determination (R^2).

3. Results

3.1 Overview of Groundwater Level Change and Water Quality

Annual groundwater level change and corresponding groundwater quality parameters for the period 2014-2021 are summarized in Table 1. Both groundwater recovery and decline were observed during the study period, indicating fluctuating stress conditions. Water-quality parameters exhibit marked inter-annual variability, particularly nitrate concentrations, while fluoride and electrical conductivity remain consistently elevated in several years.

Table 1: Annual groundwater level change and water quality parameters in Vadodara (2014–2021)

Year	Groundwater level change (m)	Nitrate (NO_3^- , mg/L)	Fluoride (F^- , mg/L)	Electrical conductivity ($\mu\text{S}/\text{cm}$)
2014	0.28	12	0.9	2915
2015	0.38	5	1.34	3387
2016	-0.24	8	1.4	2703
2017	-0.10	7	1.4	2988
2019	-0.16	55	0.82	870
2020	-0.23	1.7	1.5	3301
2021	0.52	11.7	1.24	3236

3.2 Groundwater stress-nitrate relationships

The relationship between groundwater level change and nitrate concentration is illustrated in Figure 1. Groundwater level change shows no consistent correspondence with nitrate concentration across the study period. While groundwater decline is observed in multiple years, nitrate concentrations vary widely, including a pronounced spike in 2019.

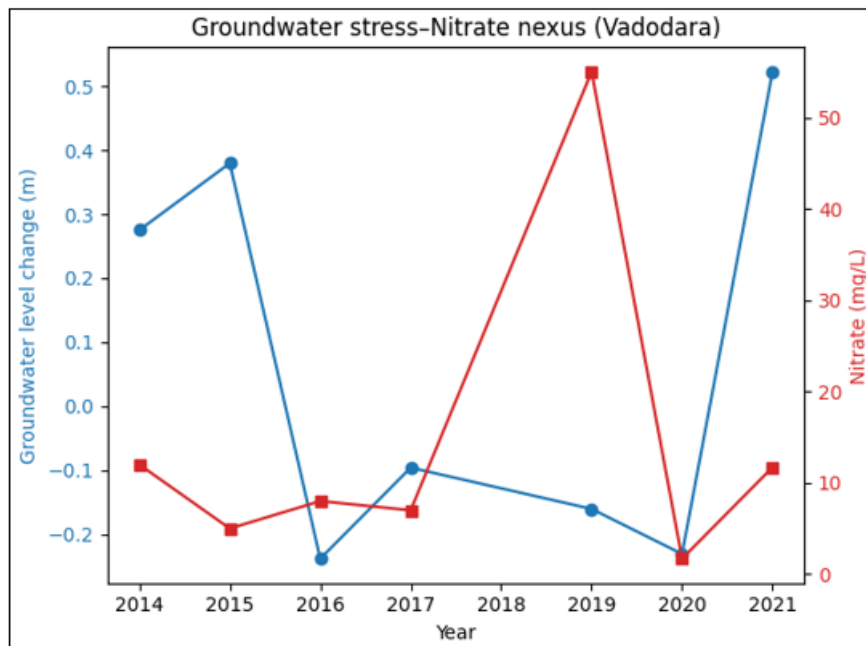


Figure 2: Groundwater stress- Nitrate nexus

The weak association is reflected in the uncontrolled regression results, where groundwater level change explains only a small proportion of nitrate variability. This suggests that nitrate concentration is largely decoupled from short-term groundwater stress and is likely influenced by external anthropogenic inputs rather than hydrological fluctuation alone.

3.3 Groundwater stress-fluoride relationships (uncontrolled)

The bivariate relationship between groundwater level change and fluoride concentration is shown in Figure 2. Fluoride concentrations remain within a relatively narrow range despite alternating periods of groundwater recovery and decline. No clear monotonic trend is observed, indicating weak sensitivity of fluoride to groundwater level change alone.

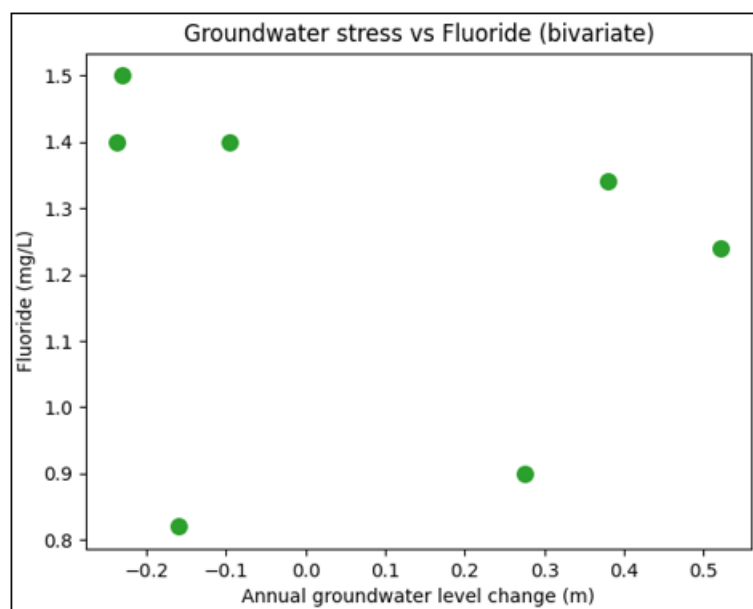


Figure 3: Groundwater stress vs fluoride (bivariate)

This pattern is consistent with the low explanatory power of the uncontrolled regression model, suggesting that groundwater stress by itself is insufficient to explain fluoride variability.

3.4 Controlled groundwater stress-fluoride nexus

When electrical conductivity (EC) is included as a controlling parameter, the groundwater stress-fluoride becomes more structured. Figure 3 shows the controlled regression fit between groundwater level change and fluoride concentration with EC held constant.

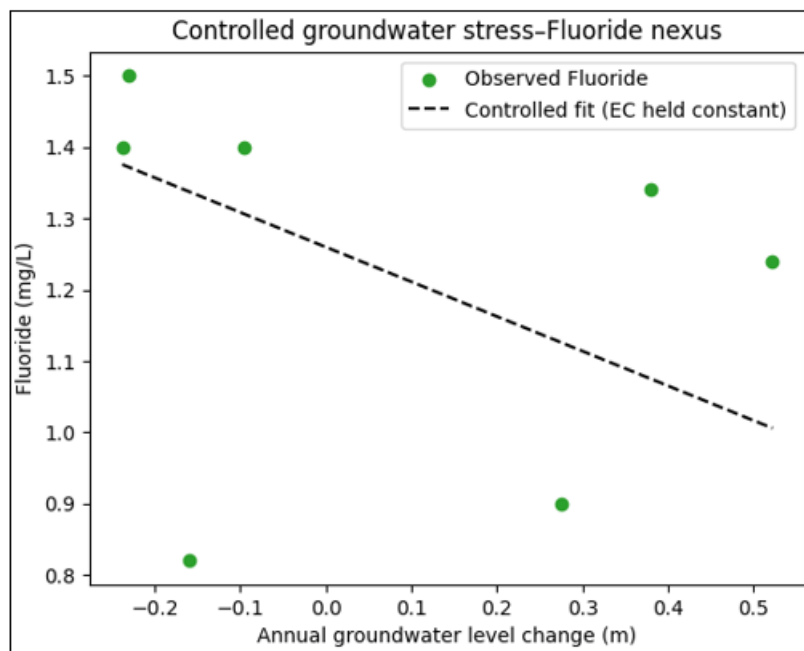


Figure 4: Controlled groundwater stress–fluoride nexus

Under controlled conditions, fluoride exhibits a clearer negative response to groundwater level change, indicating enhanced fluoride concentrations during periods of groundwater decline. This demonstrates that fluoride mobilisation is strongly mediated by hydrogeochemical conditions rather than groundwater stress alone.

3.5 Inter-annual groundwater–water quality nexus patterns

Inter-annual variation in normalized groundwater stress, nitrate, fluoride and electrical conductivity is shown in Figure 4. This figure highlights distinct behavioural differences between nitrate and fluoride. Nitrate displays sharp episodic variability, particularly in 2019, which is not mirrored by groundwater stress trends. In contrast, fluoride exhibits closer correspondence with electrical conductivity, reinforcing the role of salinity and mineralisation processes.

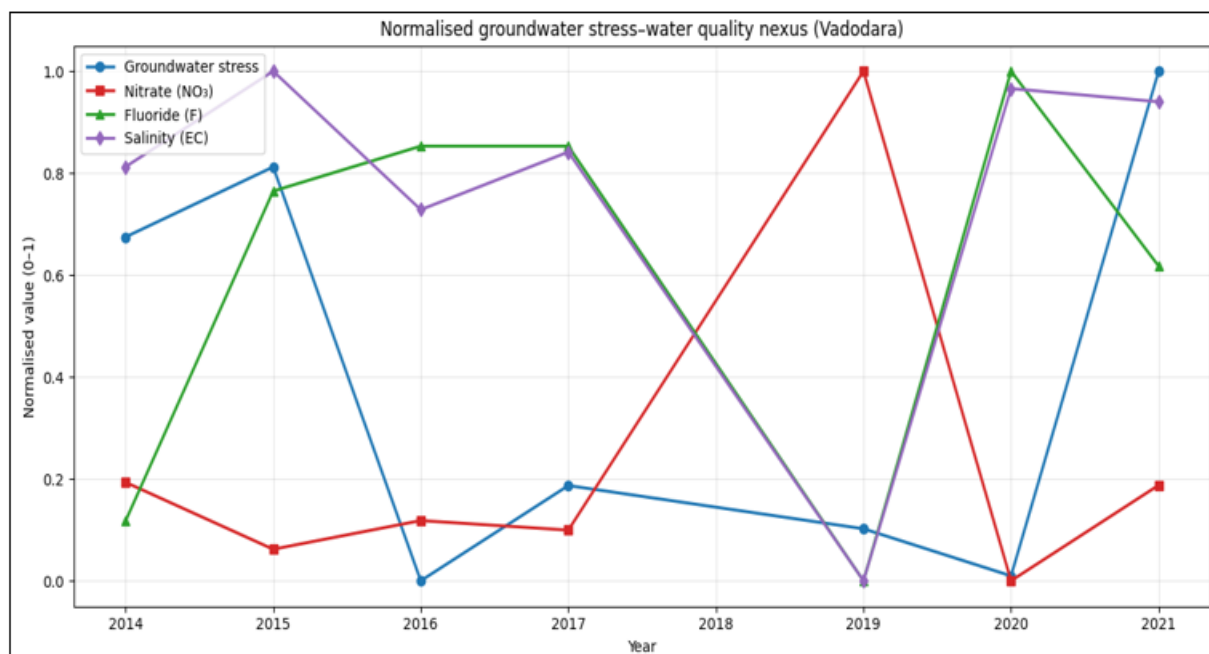


Figure 5: Normalised groundwater stress–water quality nexus (Vadodara)

3.6 Temporal groundwater stress–fluoride dynamics

The combined temporal behaviour of groundwater level change and fluoride concentration is illustrated in Figure 5. Fluoride concentrations increase during certain periods of

groundwater decline; however, similar groundwater stress conditions do not always result in comparable fluoride levels. This non-linearity further suggests that fluoride enrichment is governed by subsurface geochemical processes rather than hydrological forcing alone.

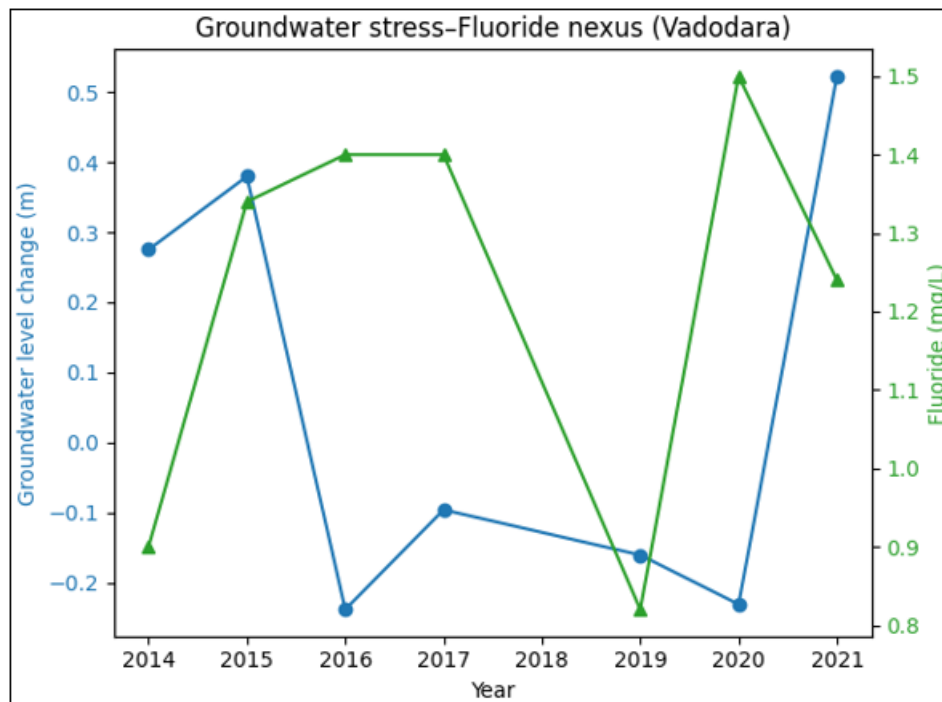


Figure 6: Groundwater stress-fluoride nexus (Vadodara)

4. Discussion

The study demonstrates that the weak performance of bivariate models highlights the limitations of relying on groundwater level change as a sole indicator of groundwater quality dynamics. Groundwater systems are influenced by processes operating over longer timescales than annual water-level fluctuations, particularly with respect to contaminant transport and geochemical mobilisation (Edmunds & Smedley, 2013). As a result, short-term groundwater stress signals may fail to capture the drivers of water quality variability.

The marked improvement in model performance when hydrogeochemical parameters are included suggests that groundwater quality is governed by coupled hydrological and geochemical processes rather than groundwater dynamics alone. For nitrate, this reflects the interaction between anthropogenic inputs and subsurface conditions (Spalding & Exner, 1993). In contrast, fluoride exhibits behaviour consistent with geogenic control, where salinity and mineral dissolution dominate over direct hydrological forcing (Smedley & Kinniburgh, 2002).

The contrasting responses of nitrate and fluoride emphasize the importance of parameter-specific interpretation in groundwater assessments. Nexus-based approaches that integrate groundwater levels with water chemistry therefore provides a more robust framework for groundwater quality assessment, particularly in semi-arid aquifer systems.

From a management perspective, these findings suggest that groundwater monitoring and mitigation strategies should incorporate hydrogeochemical indicators alongside groundwater level measurements. Such integrated approaches are particularly relevant in regions facing increasing groundwater abstraction and salinization pressures.

5. Limitations

This study represents a rapid, explanatory assessment based on annual aggregated data and a limited temporal record. The use of district-scale averages may mask local-scale heterogeneity and seasonal dynamics in groundwater quality. Additionally, the analysis does not account for land-use patterns, well depth variability, or aquifer-specific geochemical conditions. Despite these limitations, the approach is sufficient to identify dominant groundwater–water quality nexus relationships and provides a foundation for more detailed future investigations.

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Conflict of Interest

The authors declare no conflict of interest.

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Data Availability Statement

The data used in this study are available from open source government data-use platforms as mentioned in the acknowledgements section.

Author Contributions

Conceptualization: M. Ushashree

Methodology: M. Ushashree

Formal analysis: M. Ushashree

Investigation: M. Ushashree

Writing – original draft: M. Ushashree

Writing – review & editing: M. Ushashree

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