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Decadal Changes in Groundwater Quality of an Urbanizing Semi Arid Aquifer in Vadodara Western India

Dr. Himani Pandey
School of Sciences, ITM SLS Baroda University, Vadodara, Gujarat
Email: dean.sohss@itmbu.ac.in

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***Abstract*—**Groundwater is the principal source of water for domestic, agricultural, and industrial use in rapidly urbanising regions of India; however, increasing groundwater abstraction and anthropogenic pressures threaten its long-term quality and sustainability. This study presents a decadal assessment of groundwater quality in Vadodara, Gujarat, India, by comparing historical baseline data collected during 2014–2017 with regional groundwater monitoring records available up to 2026. Six strategically selected monitoring stations representing residential, commercial, and industrial areas were investigated using standard analytical procedures recommended by the American Public Health Association (APHA). The assessment focused on key physicochemical parameters, including pH, electrical conductivity (EC), total dissolved solids (TDS), fluoride (F−), chemical oxygen demand (COD), and hardness. The results revealed a significant deterioration in groundwater quality over the study period. Fluoride concentrations increased substantially at several monitoring locations, reaching 6.90 mg/L at Sama (GW1) and 5.10 mg/L at Baroda Dairy (GW4) in the 2026 comparison dataset, greatly exceeding the Bureau of Indian Standards (BIS) permissible limit for drinking water. Organic contamination also intensified, with COD increasing from 2.0 mg/L to 45.50 mg/L at Gajravadi (GW3), indicating increasing anthropogenic influence. Elevated TDS (2100 mg/L) and electrical conductivity at Baroda Dairy, together with severe groundwater hardness at Gotri, further demonstrate progressive aquifer mineralisation and declining suitability of groundwater for domestic consumption. These long-term trends are associated with intensive groundwater abstraction, rapid urban expansion, and inadequate wastewater management. The findings demonstrate the combined influence of geogenic processes and anthropogenic activities on groundwater quality deterioration in Vadodara and emphasise the urgent need for integrated groundwater management. Sustainable interventions, including Managed Aquifer Recharge (MAR), improved municipal sewage infrastructure, regular groundwater quality monitoring, and community-scale defluoridation programmes, are recommended to safeguard groundwater resources and protect public health in rapidly urbanising semi-arid regions.

Keywords—Groundwater quality; Urban aquifer; Semi-arid region; Fluoride contamination; Hydrogeochemistry; Urbanisation; Groundwater monitoring; Vadodara; Western India.

I. INTRODUCTION

Groundwater is one of the world's most valuable freshwater resources and provides a dependable source of water for domestic, agricultural, and industrial activities. In India, groundwater supports a substantial proportion of drinking water supply and irrigation, particularly in rapidly urbanising regions where increasing population, industrial development, and expanding urban infrastructure have intensified pressure on available water resources. Continued groundwater abstraction, coupled with inadequate wastewater management and land-use change, has contributed to declining groundwater quality and raised concerns regarding the long-term sustainability of urban aquifer systems.

The quality of groundwater is governed by a combination of natural hydrogeochemical processes and anthropogenic influences. Natural factors include lithology, mineral weathering, groundwater residence time, and rock–water interactions, whereas human activities such as industrial effluent discharge, sewage infiltration, agricultural runoff, and indiscriminate groundwater extraction can accelerate groundwater contamination. Long-term over-exploitation of aquifers often enhances mineral dissolution and promotes the mobilisation of naturally occurring constituents such as fluoride while simultaneously increasing the vulnerability of aquifers to contamination from surface-derived pollutants.

Vadodara, located in western India, has experienced rapid urbanisation and industrial growth over the past two decades. The city hosts diverse industrial estates, expanding residential developments, and commercial establishments that have substantially increased groundwater demand. The underlying aquifer system comprises Quaternary alluvial deposits overlying the Deccan Trap basaltic formations, where groundwater quality is influenced by both geological conditions and increasing anthropogenic pressures. Consequently, continuous monitoring of groundwater quality has become essential for assessing long-term environmental changes and supporting sustainable water resource management.

Although several studies have reported groundwater quality in Gujarat and other parts of India, most investigations have been based on short-term monitoring programmes or seasonal assessments. Comparatively few studies have examined groundwater quality changes over a decadal timescale by integrating historical baseline observations with recent monitoring data. Such long-term assessments are important for identifying progressive hydrogeochemical changes, evaluating the cumulative effects of urbanisation, and supporting evidence-based groundwater management policies.

The present study addresses this knowledge gap by comparing groundwater quality data collected during 2014–2017 with regional groundwater monitoring records available up to 2026. Six representative monitoring stations distributed across residential, commercial, and industrial areas of Vadodara were evaluated using standard physicochemical parameters, including pH, electrical conductivity, total dissolved solids, fluoride, chemical oxygen demand, and hardness. Particular emphasis was placed on identifying long-term changes in groundwater chemistry and assessing their implications for drinking water quality and aquifer sustainability.

The specific objectives of this study were to assess decadal changes in groundwater quality; compare historical baseline observations with groundwater monitoring data up to 2026; evaluate the influence of geogenic and anthropogenic factors; and recommend sustainable groundwater management strategies. The findings provide valuable insights

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into the long-term evolution of groundwater quality in a rapidly urbanising semi-arid environment and support groundwater protection and sustainable aquifer management.

II. MATERIALS AND METHODS

A. Study Area

The study was conducted in Vadodara City, Gujarat, India, located at approximately 22.30° N latitude and 73.19° E longitude in western India. The city experiences a tropical semi-arid climate characterised by hot summers, a southwest monsoon season, and mild winters. The area is underlain by Quaternary alluvial deposits comprising sand, silt, clay, and gravel overlying Deccan Trap basaltic formations. Rapid urbanisation, industrial expansion, and increasing groundwater abstraction have imposed considerable stress on the aquifer system, making Vadodara an appropriate case study for long-term groundwater quality assessment.

B. Groundwater Monitoring Network

Six representative monitoring stations (GW1–GW6) were selected across residential, commercial, mixed-use, and industrial areas to represent the spatial variability of groundwater quality. Monitoring locations were maintained consistently and cross-referenced using QGIS for long-term comparison.

Station	Location	Land-use Category	Water Source
GW1	Sama	Residential Area	Borewell
GW2	Old City (Kothi Govt. Press)	Dense Residential Area	Hand Pump
GW3	Gajravadi (Vachali Pol)	Residential–Commercial	Hand Pump
GW4	Baroda Dairy	Commercial–Industrial	Borewell
GW5	Gotri	Residential / Gardening Zone	Deep Borewell
GW6	Gorwa (Dalitwadi Karodiya Road)	Industrial–Commercial	Hand Pump

TABLE I. GROUNDWATER MONITORING STATIONS

C. Analytical Methods

Groundwater quality was assessed using standard analytical procedures. The principal methods and techniques are summarised in Table II.

Parameter	Analytical Method	Instrument/Technique	Reference
pH	Electrometric method	Digital pH meter	APHA (2023)
Electrical Conductivity (EC)	Conductivity method	Digital conductivity meter	APHA (2023)
Total Dissolved Solids (TDS)	Gravimetric method	Drying oven and analytical balance	APHA (2023)
Total Suspended Solids (TSS)	Gravimetric method	Filtration and drying	APHA (2023)
Total Hardness	EDTA titrimetric method	Volumetric titration	APHA (2023)
Calcium (Ca^{2+})	EDTA titrimetric method	Volumetric titration	APHA (2023)
Magnesium (Mg^{2+})	Calculated from total hardness and calcium hardness	Volumetric method	APHA (2023)
Total Alkalinity	Acid–base titration	Standard acid titration	APHA (2023)
Chloride	Argentom	Silver nitrate	APHA

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(Cl^-)	etric (Mohr) method	titration	(2023)
Chemical Oxygen Demand (COD)	Open reflux dichromate method	Reflux digestion and titration	APHA (2023)
Fluoride (F^-)	As reported in laboratory methodology	Laboratory analytical procedure	APHA (2023)

TABLE II. ANALYTICAL METHODS USED FOR GROUNDWATER QUALITY ANALYSIS

D. Sample Collection and Preservation

Groundwater samples were collected during the pre-monsoon periods of 2014–2015 and 2016–2017. Wells were purged for approximately 10 minutes before sampling. Grab samples were collected in clean pre-rinsed HDPE bottles. Samples for physicochemical analyses were preserved at approximately 4 °C and transported to the laboratory. COD and nitrate samples were acidified to pH <2 using concentrated H_2SO_4 following APHA recommendations.

E. Laboratory Analysis

All analyses followed APHA Standard Methods (22nd Edition). pH and electrical conductivity were measured using calibrated digital meters. TDS and TSS were determined gravimetrically. Total hardness, calcium, and magnesium were analysed by EDTA titration. Alkalinity was determined by acid–base titration, chloride by argentometric titration, and COD by the open reflux dichromate method.

F. Quality Assurance and Quality Control

Analytical instruments were calibrated before analysis using standard solutions. Analytical-grade reagents were used throughout the study. Standard laboratory procedures were followed to ensure consistency and reliability of analytical results.

G. Data Processing and Comparative Assessment

Baseline groundwater data (2014–2017) were compiled and compared with regional groundwater monitoring datasets available up to 2026. Comparative assessment focused on pH, EC, TDS, fluoride, COD, and hardness. Spatial consistency among monitoring locations was maintained using QGIS.

III. RESULTS AND DISCUSSION

A. General Hydrogeochemical Characteristics

The groundwater quality assessment across the six monitoring stations revealed pronounced temporal changes between the 2014–2015 and 2016–2017 baseline surveys, with comparison against regional monitoring records up to 2026 indicating continued deterioration of selected physicochemical parameters. The most notable changes were observed for fluoride, total dissolved solids (TDS), electrical conductivity (EC), chemical oxygen demand (COD), and hardness, demonstrating the combined influence of urbanisation and hydrogeochemical processes. The greatest deterioration occurred at Baroda Dairy (GW4), Gajravadi (GW3), Gotri (GW5), and Sama (GW1).

B. Temporal Changes in Fluoride Concentration

Fluoride concentrations increased markedly during the monitoring period. At GW1 (Sama), fluoride increased from 0.42 mg/L during 2014–2015 to 7.82 mg/L during 2016–2017, with regional records indicating approximately 6.90 mg/L in 2026. At GW4 (Baroda Dairy), fluoride increased from 0.47 mg/L to 5.61 mg/L and remained elevated in subsequent monitoring. These concentrations substantially exceed the BIS permissible limit of 1.5 mg/L and indicate progressive fluoride enrichment within the aquifer system.

C. Evolution of Salinity and Dissolved Solids

TDS and EC showed increasing mineralisation of groundwater. GW4 recorded TDS increasing from approximately 1250 mg/L during the baseline period to about 1850 mg/L, while

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regional datasets indicated values approaching 2100 mg/L by 2026. Electrical conductivity reached approximately 2900 µS/cm, reflecting elevated dissolved ionic content and increasing salinity.

D. Organic Pollution Indicators

COD values demonstrated increasing organic contamination. At GW3 (Gajravadi), COD increased from about 2.0 mg/L during the 2014–2015 survey to 40.09 mg/L during 2016–2017, with regional monitoring indicating approximately 45.50 mg/L by 2026. Elevated COD at GW4 and GW5 further suggests the influence of sewage infiltration and urban wastewater on groundwater quality.

E. Hardness and Hydrogeochemical Evolution

Groundwater hardness increased substantially at several stations. At GW5 (Gotri), total hardness reached approximately 930 mg/L, with magnesium hardness increasing to around 750 mg/L during 2016–2017. These observations indicate intensified water–rock interaction together with concentration effects associated with groundwater abstraction.

F. Discussion

The observed deterioration reflects both geogenic and anthropogenic processes. Elevated fluoride is consistent with enhanced dissolution of fluoride-bearing minerals under prolonged groundwater exploitation, whereas increasing COD indicates deterioration associated with sewage leakage and urban wastewater infiltration. Increasing TDS and EC further demonstrate progressive mineralisation of groundwater. Comparison with regional monitoring datasets up to 2026 indicates that these trends have persisted, highlighting the need for managed aquifer recharge, improved wastewater infrastructure, and regular groundwater quality monitoring.

The groundwater quality trends observed in the present study are consistent with findings reported from other parts of Gujarat and semi-arid regions of India, where rapid urbanisation, intensive groundwater abstraction, and inadequate wastewater management have contributed to progressive groundwater quality deterioration. Elevated fluoride concentrations exceeding the permissible drinking-water limit have been widely documented in western India and are commonly attributed to prolonged groundwater residence time, enhanced water–rock interaction, and dissolution of fluoride-bearing minerals under favourable hydrogeochemical conditions (Subba Rao, 2006; Kumar et al., 2007). Similar hydrogeochemical processes are likely responsible for the increasing fluoride concentrations observed at the Sama and Baroda Dairy monitoring stations, where values remained substantially above the BIS guideline values.

Likewise, the observed increases in total dissolved solids, electrical conductivity, chemical oxygen demand, and groundwater hardness indicate the cumulative effects of aquifer mineralisation together with anthropogenic contamination associated with expanding urban development. Comparable observations have been reported by Ravikumar and Somashekar (2013), who demonstrated that increasing urban pressure significantly influences groundwater hydrochemistry and overall water quality. Foster and Chilton (2003) further emphasised that continued groundwater exploitation without adequate protection of recharge areas accelerates aquifer degradation in rapidly developing regions. The long-term deterioration identified in the Vadodara aquifer therefore reflects broader groundwater quality challenges reported across semi-arid regions of India and highlights the importance of integrated groundwater monitoring, managed aquifer recharge, and improved wastewater management to ensure sustainable utilisation of groundwater resources.

IV. CONCLUSION

This study presents a decadal assessment of groundwater quality in the urbanising aquifer system of Vadodara, Gujarat, by comparing baseline observations collected during 2014–2017 with regional groundwater monitoring

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records available up to 2026. The comparison indicates a persistent deterioration in groundwater quality, particularly with respect to fluoride, total dissolved solids (TDS), electrical conductivity (EC), chemical oxygen demand (COD), and hardness. The most pronounced changes were observed at the Sama, Baroda Dairy, Gajravadi and Gotri monitoring stations, demonstrating spatial variability in the response of the aquifer to urban development and groundwater exploitation. The elevated fluoride concentrations suggest an important geogenic contribution associated with prolonged groundwater abstraction and intensified water–rock interaction, whereas increased COD values indicate anthropogenic inputs linked to urban wastewater and sewage infiltration. Progressive increases in TDS, EC and hardness further reflect the cumulative effects of mineralisation and expanding urban pressures. Comparison with regional monitoring records up to 2026 suggests that these trends have continued rather than stabilised. Overall, the findings emphasise the need for integrated groundwater management, including regular monitoring, protection of recharge zones, improved wastewater infrastructure, managed aquifer recharge, and appropriate fluoride mitigation measures where concentrations exceed drinking-water standards. Establishing long-term groundwater quality baselines remains essential for evaluating future changes and supporting evidence-based urban water resource management.

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