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Assessment of Groundwater Quality using CCME Water Quality Index in Baramati Tehsil, Maharashtra, India

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Abstract

Groundwater quality evaluation is essential in semi-arid regions where significant agricultural demands and varying hydrogeological conditions exert considerable stress on aquifer systems. To determine the suitability of groundwater for irrigation and to evaluate its quality, 15 physicochemical parameters were analyzed for samples collected from Baramati tehsil during both pre- and post-monsoon seasons of 2023. Seasonal groundwater samples were obtained from 66 sites following standard APHA protocols. The Canadian Council of Ministers of the Environment Water Quality Index (CCME-WQI) was used through Bureau of Indian Standards (BIS) guidelines. The suitability of irrigation was also tested by Sodium Adsorption Ratio (SAR), USSL classification diagrams. The CCME-WQI shows that groundwater quality shows mainly on marginal condition in both seasons, with mean values of 56.64 ± 8.28 (pre-monsoon) and 54.79 ± 7.93 (post-monsoon) respectively. A Wilcoxon signed-rank test showed a small but significant decrease in WQI values after monsoons ($p < 0.05$), indicating that a monsoonal recharge does not uniformly enhance groundwater quality. The SAR values for most samples were in the low to medium sodium hazard (S1-S2) classes, whereas USSL plots revealed an overwhelming predominance of high salinity (C3-C4) categories, highlighting constraints for irrigation without any management methods. Wilcox classification further showed that the majority of samples ranged from permissible to doubtful for irrigation, with limited seasonal improvement. Overall, the integrated WQI, SAR, and Wilcox evaluations indicate that groundwater in Baramati tehsil is largely marginal and locally unsuitable for unrestricted irrigation, emphasizing the need for site-specific groundwater management and continuous monitoring.

***Keywords:** Groundwater, Sodium Adsorption Ratio, Wilcox classification, CCME Water Quality Index, Baramati tehsil*

Introduction

Water crises and quality are serious concerns in a lot of countries, particularly in arid and semi-arid regions where water scarcity is widespread, and water quality assessment has received minimal attention (Aragaw and Gnanachandrasamy, 2021; Batarseh et al., 2021; Ali et al., 2022; Rao et al. 2019). Therefore, it is crucial to assess the appropriateness of water resources, especially concerning their use for drinking. The study area has revealed adverse hydrogeological conditions that adversely affect the groundwater aquifer near the Ismailia Canal. The decline in groundwater quality is mainly due to rapid urbanization, industrial operations, and poor management of water resources in agricultural practices, which include both surface and groundwater sources. As groundwater quality is affected by several factors, an appropriate study of groundwater aquifers characteristics is an essential step to state a supportable utilization of groundwater resources for future development and requirements (Carrera-Hernandez and Gaskin, 2006; Chenini and Mammou, 2010). Detailed hydrogeochemical characterization of the region is essential for strengthening sustainable groundwater management and safeguarding aquifers from quality deterioration (El Osta et al., 2020). Many researchers have paid great attention to groundwater studies. In the current study area, the hydrogeology and physio-hydrochemistry of groundwater in the current study area had been previously discussed by El Fayoumy (1987) and classified the water to NaCl type by Khalil et al. 1989 stated that water had high concentration of Na, Ca, Mg, and K. Geriesh and El-Rayes (2001) detected and monitored a waterlogging problem at the Wadi El Tumilate basin, which increased salinity in the area. Singh (2015) studied the problem of salinization on crop yield. Awad et al. (2008) reported substantial spatial variation in groundwater salinity, with concentrations spanning from 303 to 16,638 ppm and exhibiting a progressive increase toward the northern part of the study area. Various statistical concepts were used to understand the water quality parameters (Isaaks and Srivastava, 1989; Kumar and Ahmed, 2003; Suk and Lee, 1999). The Water Quality Index (WQI) is determined through a sequence of calculations that transform multiple physicochemical data points into a singular value, indicating the suitability of water quality for drinking purposes (Atta et al., 2022).

Study Area

Baramati is one of the tahsil of the Pune district (Maharashtra, India). It is situated in the southern region of the Pune district (see Fig. 1). The coordinates range from 18°02'44" to 18°23'19" N latitude and from 74°13'08" to 74°42'47" E longitude. The average elevation of this area is 538 meters above mean sea level. The northern section of the Tahsil features mountainous and rugged terrain, with a gradual decrease in elevation moving southward. The Nira River delineates the southern boundary of Baramati Tahsil, serving as a tributary to the Bhima River. Additionally, the study area is drained by the Karha River, which is a tributary of the Nira River and flows in a northwest to southeast direction.

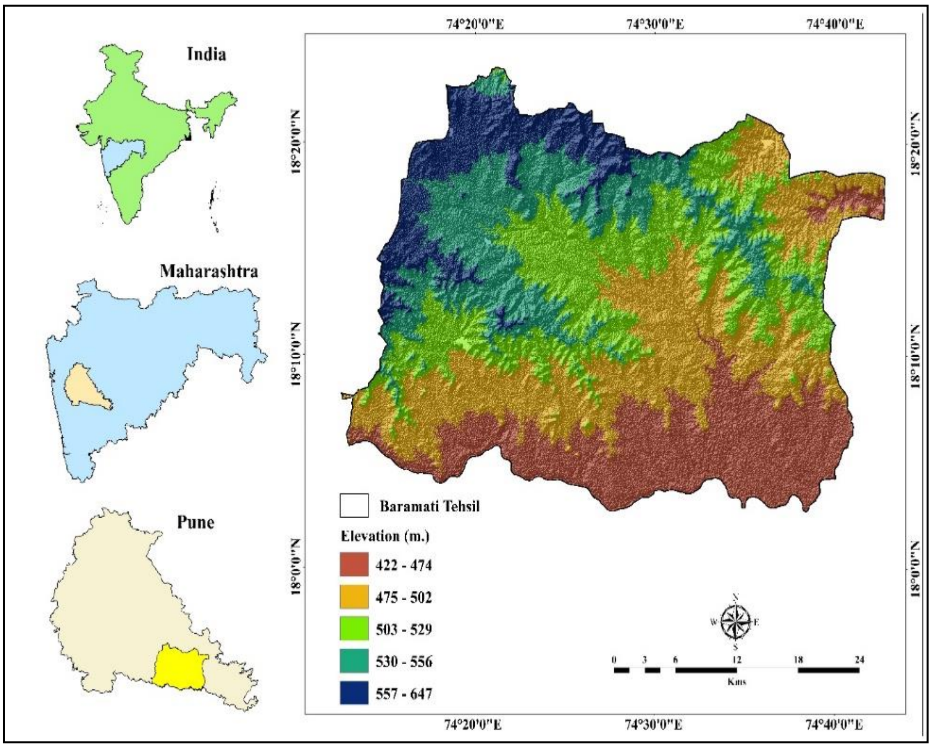

Fig. 1: Location map of study area: Baramati Tehsil

The Baramati tehsil covers about 1382km², and it includes six revenue circles of Supe, Loni Bhapkar, Vadgaon Nimbalkar, Malegaon Bk., Undawadi Supe and Baramati rural. It consists 117 villages and 429690 population (Census 2011). It is a part of semi-arid region of western Maharashtra. The area is having massive trap and zeolitic trap (lithological formations) along the Nira River. Which are responsible for recharge. Massive trap provides limited scope for groundwater accumulation. Karha river right bank and Nira River left bank of this area is well irrigated and rest of the part is non-irrigated. The increasing industries and population led to decrease in water and soil quality. The groundwater is withdrawn from dug wells and bore wells for drinking and agricultural practices in the area.

Objective

To assess the groundwater suitability for irrigation use in Baramati tehsil

Methodology

The water sampling was conducted at 66 distinct locations within Baramati tehsil, Maharashtra, during both the pre-monsoon and post-monsoon seasons of 2023, adhering to the protocols established by the American Public Health Association (Rice et al., 2017). Standard methodologies were employed for the collection and analysis of various water parameters (Rice et al., 2017; BIS, 1991). The sampling sites were georeferenced utilizing a Global Positioning System (GPS) (Fig. 1b). Prior to field sampling, polyethylene containers were cleaned using 0.20 N hydrochloric acid and allowed to dry completely. At each site, the containers were pre-rinsed with the respective water sample before final collection. Following collection, all samples were carefully labelled to ensure proper identification.

Physiochemical parameters determination

Immediately following collection, groundwater samples were placed in pre-cleaned polyethylene bottles and transported to the laboratory in an insulated container filled with ice to reduce any physicochemical changes. Upon reaching the laboratory, the samples were maintained at a temperature of 4 °C and analyzed within the specified holding time, adhering to standard protocols. Sodium, potassium, calcium, and magnesium were assessed in accordance with the standard procedures outlined in IS-1500:2012 (BIS, 1991; Cotruvo, 2017). All analyses were conducted following the protocols specified by APHA. (Federation and Association, 2005). The hydrogen ion concentration (pH) and electrical conductivity (EC, $mS\ cm^{-1}$) were measured using a calibrated multiparameter water quality analyzer. Total alkalinity (TA, measured in $mg\ L^{-1}$ as $CaCO_3$) was assessed using the acid titration technique with standard sulfuric acid. Total hardness (TH, $mg\ L^{-1}$ as $CaCO_3$) was estimated using the EDTA titrimetric method. Major anions (sulfate (SO_4^{2-}, $mg\ L^{-1}$), chloride (Cl^-, $mg\ L^{-1}$), fluoride (F^-, $mg\ L^{-1}$), nitrate (NO_3^-, $mg\ L^{-1}$)) were quantified using ion chromatography equipped with an appropriate anion separation column and conductivity detector. After appropriate sample preparation, iron (Fe, mg L^{-1}), manganese (Mn, mg L^{-1}), and zinc (Zn, mg L^{-1}) were determined using standard spectrometric techniques. Major cations (calcium (Ca^{2+}, mg L^{-1}), magnesium (Mg^{2+}, mg L^{-1}), sodium (Na^{+}, mg L^{-1}), and potassium (K^{+}, mg L^{-1})) were analyzed following the procedures prescribed in relevant Indian Standard methods.

Quality assurance and quality control (QA/QC)

Throughout this study, robust quality assurance techniques and rigorous quality control protocols were implemented to guarantee the integrity and consistency of the analyses produced. All analytical equipment was pre-calibrated before using certified standard solutions according to the manufacturer's operational guidelines for proper operation to ensure measurement accuracy and precision. Probes and electrodes were rinsed completely in double-distilled water before laboratory and field measurements to prevent cross-contamination. Prior to analysis, probes were conditioned in the respective water samples to achieve stable readings. Then the pH electrode was calibrated using freshly prepared buffer solutions of a pair of fresh solution at two different pHs with respect to the electrode after cleaning and drying of the electrode. Procedural blank analysis of each physicochemical parameter was conducted in parallel with samples to check for possible contamination. The measurements were performed in triplicate and mean value was used for interpreting the data to reduce the analytical uncertainty. All analyses were performed in accordance with established standard operating procedures including sound laboratory safety practices. To ensure the precision of the data, only chemical, analytical grade reagents, and high test glassware were employed. The ion chromatography system calibration was carried out using multi-level standard solutions for relevant anions, and calibration curves were validated through repeated injections to confirm linearity and instrument performance.

Data preprocessing and descriptive statistics

Season-wise (pre-monsoon and post-monsoon) values of all parameters were aggregated and screened for transcription errors, non-numeric entries, and missing values prior to analysis. Descriptive statistics (minimum, maximum, mean, and standard deviation) were compiled for each parameter separately in each season. Mean ± SD was used for these observations to characterize the central tendency and the dispersion of the site-level variation in a given season.

Irrigation suitability classification (USSL)

Hydrochemical characteristics were analyzed through various indices, including the Sodium Adsorption Ratio (SAR), along with graphical techniques such as the US Salinity Laboratory (USSL) and Wilcox diagrams, which are frequently utilized in hydrogeochemical evaluations. (Islam et al., 2025; Boukich et al., 2025)**.**

USSL (SAR–EC) diagram:

SAR and USSL classification criteria were adopted to evaluate irrigation suitability under varying salinity and sodium hazard conditions (Boukich et al., 2025). Sodium hazard was assessed using Sodium Adsorption Ratio (SAR) computed on milliequivalent basis:

$$SAR = \frac{Na^{+}}{\sqrt{(Ca^{2+} + Mg^{2+})/2}}$$

EC and SAR were used to classify samples into salinity (C1–C4) and sodium hazard (S1–S4) zones.

CCME Water Quality Index

The Canadian Council of Ministers of the Environment Water Quality Index was utilized to assess the general appropriateness of groundwater for irrigation purposes (CCME, 2001). The index was applied to the following parameters in this study: pH, electrical conductivity (EC), total alkalinity (TA), total hardness (TH), sulfate (SO_4^{2-}), iron (Fe), manganese (Mn), zinc (Zn), calcium (Ca), magnesium (Mg), sodium (Na), potassium (K), chloride (Cl^{-}), fluoride (F^{-}) and nitrate (NO_3^{-}). The threshold limits for irrigation suitability were adopted from internationally recognized standards such as BIS irrigation water quality standards, and were treated as the water-quality objectives for index computation (Basha et al, 2022). The CCME-WQI combines three components F1, F2 and F3 that describe different ways in which water quality can fail to meet the objectives. The calculation was carried out in the following steps:

Define basic counts

- N_{par}= total number of parameters considered (here, 15).
- N_{obs}= total number of individual observations (number of samples × number of parameters).
- $N_{\text{par,fail}}$= number of parameters that exceeded their BIS limit at least once.
- $N_{\text{obs,fail}}$= number of individual observations that did not satisfy the BIS guideline.

Scope factor (F1)

F1 represents the proportion of parameters that show at least one failure:

$$F1 = \frac{N_{\text{par,fail}}}{N_{\text{par}}} \times 100$$

Frequency factor (F2)
F2 measures the **percentage of all tests** (all observations) that fail:

$$F2 = \frac{N_{\text{obs,fail}}}{N_{\text{obs}}} \times 100$$

Calculate excursions for each failed observation

For every failed observation $j$of parameter i, an excursion is computed to express how far the measured value is from its BIS objective O_i:

- For parameters with an upper limit (most ions such as EC, TH, SO_4^{2-}, Na, Cl^-, NO_3^-, etc.), when the measured value $C_{ij} > O_i$:

$$\text{excursion}_{ij} = \left(\frac{C_{ij}}{O_i}\right) - 1$$

- For parameters with a lower limit (e.g. a minimum acceptable pH or alkalinity), when $C_{ij} < O_i$:

$$\text{excursion}_{ij} = \left(\frac{O_i}{C_{ij}}\right) - 1$$

If a result meets the BIS limit, its excursion is taken as zero.
The normalized sum of excursions (nse) is then:

$$\text{nse} = \frac{\sum \text{excursion}_{ij}}{N_{\text{obs}}}$$

Amplitude factor (F3)
F3 converts the normalized sum of excursions into a value between 0 and 100:

$$F3 = \frac{\text{nse}}{0.01 \times \text{nse} + 0.01}$$
$$F3 = F3 \times 100$$

Computation of CCME-WQI

Finally, the three factors are combined into a single index:

$$\text{CCME–WQI} = 100 - \sqrt{\frac{F1^2 + F2^2 + F3^2}{1.732}}$$

The constant 1.732 is the square root of 3 and normalizes the three squared terms.

Classification of irrigation water quality
The resulting CCME-WQI values were interpreted using the standard rating scale:

CCME-WQI values	Classification
95–100	Excellent
80–94	Good
65–79	Fair
45–64	Marginal
0–44	Poor

Higher CCME-WQI values indicate better agreement with BIS irrigation-water standards and therefore greater suitability of groundwater for agricultural use.

Result

The analysis of physicochemical parameters from 31 water samples collected across various locations in Baramati tehsil is presented below. For reference, the permissible limits for the different parameters examined were sourced from the Bureau of Indian Standards (BIS, 2012).

Water Quality Assessment
SAR-EC (USSL) Classification of Irrigation Water

The diagram created by the US Salinity Laboratory (USSL), which plots SAR against EC, was employed to assess the combined hazards of salinity and sodium in groundwater during both pre-monsoon and post-monsoon periods (refer to Figure 2). Most groundwater samples from these two seasons fall within the low to medium sodium hazard classifications (S1-S2), suggesting that issues related to soil permeability caused by sodium are typically minimal. Only a limited number of samples collected after the monsoon transition into the S3 category (high sodium hazard), and none are categorized as S4 (very high sodium hazard). In contrast, electrical conductivity displays a strong spread toward high (C3) and very high (C4) salinity classes, especially post-monsoon. The bulk of these samples are concentrated in the C3-S1 and C3-S2 fields indicating a low to moderate sodium hazard, with salinity being the main limiting factor for irrigation. Lower numbers of the samples extend into the C4-S2 and C4-S3 zones demonstrating that groundwater is not amenable to irrigation without adequate salinity control and soil treatment strategies.

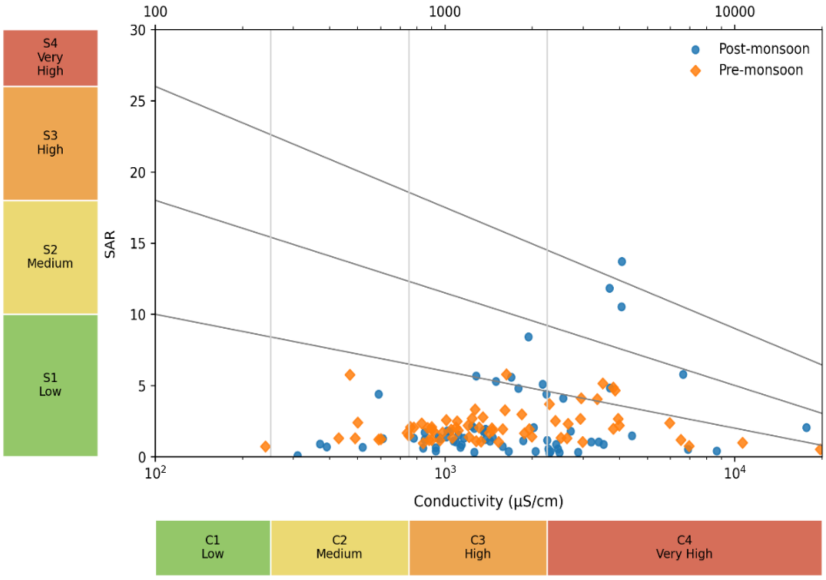

Fig. 2 USSL Classification of Irrigation Water

Post-monsoon samples present higher EC and SAR values in seasonal samples more than pre-monsoon ones, resulting from the mobilization, leaching and mixing of dissolved salts during monsoon rather than uniform dilution. The stability of high salinity classes in both seasons indicates strong control of water–rock interaction, evaporative concentration and local human activities. In conclusion, the USSL classification shows that groundwater in Baramati tehsil is generally safe with respect to sodium hazard but frequently restricted by moderate to very high salinity, requiring careful crop selection, controlled soil drainage, and proper irrigation management for sustainable agricultural use.

This is in keeping with the decline in post-monsoon CCME-WQI and the importance of localized hydrogeochemical controls. Overall, the Wilcox classification verifies that the quality of the groundwater in Baramati tehsil is a moderate to restricted area for irrigation, salinity being the primary constraint and sodium hazard being a secondary limiting factor. So, careful crop selection, better drainage and well-ordered irrigation are necessary to maintain its agricultural productivity.

CCME WQI

The CCME Water Quality Index (WQI), computed using BIS drinking-water guideline limits for the measured hydrochemical parameters, indicated that Baramati groundwater was predominantly of marginal quality in both seasons. Across 66 sampling locations, pre-monsoon WQI values ranged from 34.64 to 83.20, with a mean of 56.64 ± 8.28 (median 56.21). Post-monsoon WQI ranged from 37.28 to 77.88, with a mean of 54.79 ± 7.93 (median 54.40). Class-wise, pre-monsoon samples were mainly Marginal (55/66), followed by Fair (6/66) and Poor (4/66), with only one good site (Limtek) and no Excellent sites (Fig. 4). In post-monsoon, Marginal still dominated (53/66), with Fair (7/66) and Poor (6/66), and no Good/Excellent sites (Fig. 5). A paired seasonal comparison showed a small but statistically significant decline in WQI after monsoon recharge (mean difference ≈ 1.85 WQI units; Wilcoxon signed-rank $p \approx 0.028$), meaning that overall water quality did not improve uniformly post-monsoon despite dilution effects. Spatially, the lowest WQI values (poor category) clustered at specific villages in both seasons, indicating persistent "hotspots" of deterioration. In pre-monsoon, the poorest sites included Jalgaon Kp. (34.64), Morgaon (39.20), Karhavagaj (41.46) and Baburdi (44.78), reflecting strong localized departures from guideline limits. In post-monsoon, poor-quality sites were again evident Karhavagaj (37.28), Songaon (37.62), Jalgaon Kp. (39.04), Dorlewadi (39.48) and Morgaon (42.39) showing that monsoon recharge did not eliminate the most impacted zones.

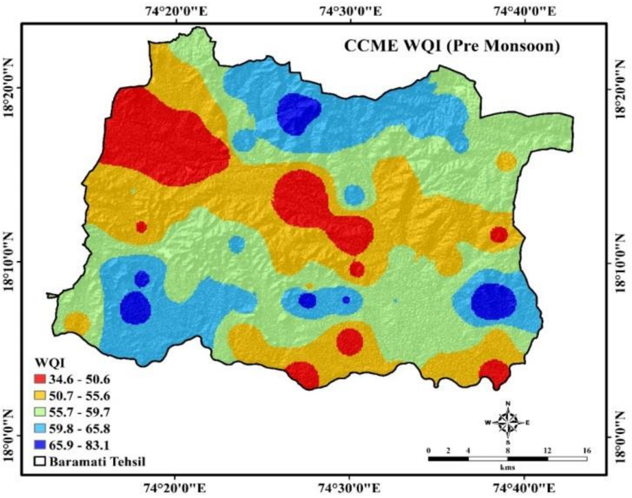

Fig 4. Pre monsoon CCME Water Quality Index

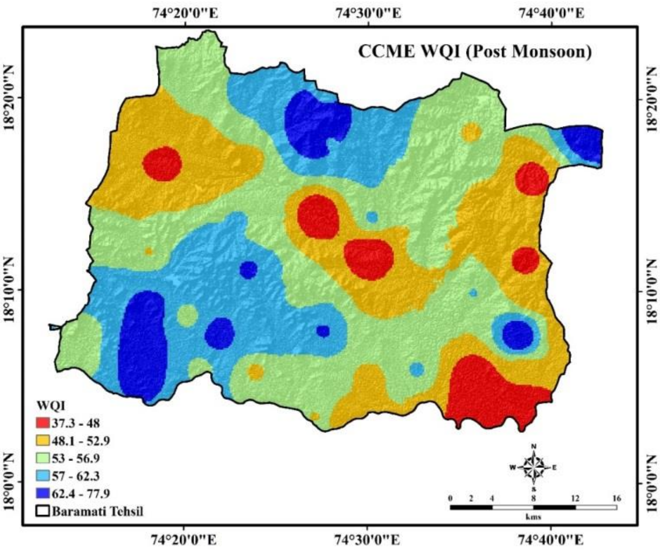

Fig 5. Post monsoon CCME Water Quality Index

The dominance of the marginal class and persistence of low-WQI sites suggest that groundwater quality is controlled by both natural hydrogeochemical processes and localized anthropogenic inputs, with the CCME WQI integrating these effects through (i) the scope of parameters exceeding standards (F1), (ii) the frequency of exceedances across observations (F2), and (iii) the amplitude of exceedances (F3). The slight post-monsoon decline in WQI is consistent with monsoon-driven mobilization/leaching and enhanced mixing that can increase certain constituents at specific locations, even if some parameters dilute. Overall, the CCME WQI assessment demonstrates that Baramati groundwater is largely marginal for guideline-based use, with a limited number of chronically poor locations that should be prioritized for targeted investigation and management.

Conclusion

This study presents a comprehensive evaluation of groundwater quality and irrigation suitability in Baramati tehsil by integrating physicochemical characterization, irrigation indices (SAR–USSL and Wilcox classifications), and the Canadian Council of Ministers of the Environment Water Quality Index (CCME-WQI). The dual approach offers a comprehensive insight into seasonal dynamics and spatial heterogeneity under semi-arid agricultural conditions. The groundwater in this research area is known to have near-neutral to slightly alkaline pH through the seasons, which indicates that buffers are maintained in the aquifer system. Nonetheless, electrical conductivity, along with major ion concentrations, has significant spatial variations revealing localized zones of increased mineralization. Concentration was not homogeneous under post-monsoon condition of water formation, whereas the significant increment of total hardness and divalent cations (Ca and Mg) indicate that recharge from monsoons increases mineral dissolution, leaching and mix with more mineralized groundwater. The presence of high chloride variability and high fluoride concentrations also reflect strong geogenic control, where fluoride continues to be an important long-term risk for groundwater use. The increase after monsoon in nitrate concentrations indicates recharge-driven mobilization for anthropogenic inputs, particularly from agro-activities. The suitability of the irrigation indicated that sodium hazard appears to be medium to low, as indicated by SAR values and USSL classification indicating that they fall largely in S1–S2 category. However, salinity was the predominant limitation on irrigation consumption. The C3 and C4 salinity values are dominated in the USSL drawing, that reflects that the poor groundwater quality was more often related to high solutes rather than sodicity. Wilcox classification also confirmed this, indicating that numerous samples fall within excellent to permissible ranges, and a substantial amount to the permissible to doubtful and unsuitable ranges especially at the higher ECs. The dispersion around the elevated EC and percent sodium values in the post-monsoon samples was pronounced, indicating that seasonal recharge may increase salinity stress through mobilization and redistribution of dissolved elements, not uniform improvements in water quality. The CCME-WQI survey combined this intricate hydrogeochemical interaction to produce integrated quality index and identified groundwater as marginal in both seasons. Results indicated that after the monsoon, there were statistically significant WQI values decreased as tested by Wilcoxon signed-rank test ($p < 0.05$), indicating that monsoon recharge does not significantly increase groundwater quality. Localized salinity, hardness, fluoride, and nitrate increments overcome any potential dilution effects. The persistence for sub-normal hotspots over seasons emphasizes the importance of season-dependent hydrogeochemical processes and anthropogenic pressure on site. All the results reveal that groundwater of Baramati tehsil is largely marginal for guideline-based use and moderately limited for irrigation with salinity as the main limiting factor and sodium hazard acting as a minor factor. Sustainable groundwater management within the area should focus on continued monitoring of the hotspots identified; the incorporation of salinity-appropriate crops that can tolerate salinity; improved soil drainage; and regulated fertilizer application to reduce nitrate leaching. The methodical integration of methodology proposed in this work can provide a valuable model for the examination and remediation of groundwater quality assessment of other semi-arid regions for similar hydrogeochemical problems.

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Conflicts of interest
The authors declare that there are no conflicts of interest regarding the publication of this paper.

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