Integrated Assessment of Groundwater Quality for Drinking and Irrigation Using WQI, NPI, and Irrigation Indices in a Semi-Arid Coastal Region, Gujarat, India

Dr. Daxa Ghevariya[1*], Tanvi Mahla[1]

1. Assistant Professor, Chemistry Department, Atmanand Saraswati Science College, Surat, Gujarat, India

daxaghevariya@gmail.com *

ABSTRACT

This study evaluates the seasonal variation and suitability of groundwater for drinking and irrigation across Ghogha, Bhavnagar, and Talaja talukas in Bhavnagar district, western India. A total of 72 samples collected during pre and post-monsoon seasons were analysed for major physicochemical parameters, Water Quality Index (WQI), Nemerow's Pollution Index (NPI), and irrigation indices. The analysis indicates pronounced spatial and seasonal variability, with total dissolved solids, hardness, and chloride exceeding permissible limits at several locations in both seasons. WQI results show that most samples fall into poor to unsuitable categories for drinking, with deterioration after the monsoon in several wells due to mobilization of salts. NPI highlights multi-parameter pollution from TDS, nitrate, and major ions. Irrigation suitability indices classify most water as suitable to marginally suitable, though coastal wells exhibit sodium and salinity hazards. The study emphasizes the need for sustained groundwater monitoring, regulated fertiliser use, artificial recharge, and controlled pumping to maintain long-term water quality and ensure sustainable domestic and agricultural use in the region.

KEYWORDS: *Groundwater quality; Water Quality Index; Nemerow's Pollution Index; Irrigation suitability; Seasonal variation*

1. INTRODUCTION

Groundwater serves as a primary source of freshwater for drinking and irrigation in many semi-arid regions. Its chemistry is shaped by natural processes such as mineral dissolution, ion exchange, and aquifer lithology, and by human activities including agriculture, waste disposal, and urban expansion [1,2]. These influences produce complex patterns in water composition that vary across space and time. Standard approaches that report individual chemical parameters do not always provide clear guidance on overall water quality or suitability for specific uses.

Index-based methods offer a way to integrate multiple water quality measurements into a single framework that supports interpretation and decision making. The Water Quality Index (WQI) is widely used to assess groundwater quality by combining concentrations of various parameters into a single score that reflects overall suitability for drinking purposes [3,4]. WQI frameworks assign weights to each parameter based on its health relevance and regulatory limits, which makes the index sensitive to changes in critical contaminants [5,6]. Several studies have shown the value of WQI in classifying groundwater quality, identifying areas with deteriorating conditions, and supporting water resource management [7,8,9].

In addition to drinking water concerns, groundwater chemistry affects agricultural productivity. Elevated sodium relative to calcium and magnesium can lead to soil structure problems that reduce water infiltration and crop yield [10,11]. Indices such as the Sodium Adsorption Ratio (SAR), Residual Sodium Carbonate (RSC), and Sodium Percentage (Na%) quantify specific aspects of groundwater chemistry relevant to irrigation. These indices, along with an irrigation water quality index (IWQI), provide practical criteria for assessing the potential impact of groundwater on soil properties and crop performance [12,13,14,15]. Research in diverse regions has demonstrated that combining multiple irrigation indices yields a more complete picture of water suitability for agricultural use [16,17].

Groundwater quality is dynamic and often exhibits marked seasonal changes. In monsoon influenced regions, post rainfall recharge can dilute dissolved ions and shift water chemistry, while dry season conditions may concentrate solutes through evaporation [18,19]. Comparative studies conducted before and after monsoon seasons reveal patterns in salinity, hardness, nutrient load, and ionic ratios that are not evident from single season surveys [20,21,22]. Assessing seasonal variation alongside index based classification improves understanding of aquifer response to recharge and helps identify persistent water quality issues.

Hydro-chemical diagrams such as Piper, Gibbs, and Durov plots are useful tools to visualize water types and interpret the dominant processes controlling groundwater chemistry [23,24,25,26]. These diagrams distinguish recharge dominated water from evolved water and highlight transitions associated with evaporation, ion exchange, or anthropogenic influence [27,28]. Integrating hydrochemical visualization with index based assessment strengthens conclusions about groundwater behavior and its implications for human and agricultural use.

Despite extensive work in groundwater quality assessment, many areas with growing demand for water resources remain under studied, particularly in semi-arid districts where both domestic supply and irrigation depend on groundwater. Incorporating weighted WQI, drinking water quality classification, and irrigation specific indices into a unified assessment can reveal critical insights not captured by traditional analysis alone. This study applies these methods to groundwater samples collected from three talukas during pre and post-monsoon seasons. The goal is to classify water quality for drinking and agricultural use, document spatial and seasonal variation, and support evidence based management of groundwater resources.

2. STUDY AREA

Groundwater is the primary source of drinking and irrigation water in the study area due to limited and seasonal surface water availability. The study was carried out in **Bhavnagar district** of Gujarat, India, with groundwater samples collected from **Ghogha**, **Bhavnagar**, and **Talaja talukas**. These talukas represent a mix of inland and coastal settings that influence groundwater chemistry and seasonal recharge. Bhavnagar district lies along the western coast of India and forms part of the dry to semi-arid climatic belt of the region [29,30].

The district experiences a **semi-arid climate**, with a clear distinction between the **pre-monsoon** and **post-monsoon** seasons. Rainfall is controlled by the southwest monsoon and generally occurs between June and September. This seasonal pattern produces marked variation in groundwater recharge and water table fluctuations, similar to trends reported for other semi-arid regions of western India [31,32]. Summer temperatures remain high, while winter temperatures are moderate, which affects evaporation and groundwater storage.

Topographically, the area consists of flat to gently undulating terrain. Coastal regions of Ghogha and parts of Bhavnagar taluka lie close to the Gulf of Khambhat, where saline ingress and evaporative concentration can influence groundwater composition [33]. Talaja taluka lies farther inland and contains alluvial and sedimentary formations that support shallow and intermediate aquifers. The geology of Bhavnagar district is dominated by **Quaternary alluvium, coastal deposits, and older sedimentary units**, which exert strong control on groundwater chemistry through mineral dissolution and water rock interaction processes [34,35].

Groundwater occurs in **unconfined to semi-confined aquifers**, with depth to water table varying seasonally. Similar to other districts of Saurashtra, agricultural demand is the dominant factor influencing groundwater abstraction [36]. Cropping patterns include cereals, cotton, pulses, and fodder crops, all of which rely on groundwater during dry periods. In addition to agriculture, urban growth in Bhavnagar taluka and small industries add to the overall pressure on water resources. These combined natural and human influences contribute to spatial and seasonal variation in groundwater quality, making the region suitable for a comparative assessment of pre-monsoon and post-monsoon conditions.

3. MATERIALS AND METHODS

3.1 Sampling Strategy

Groundwater samples were collected from open wells and bore wells located across Ghogha, Bhavnagar, and Talaja talukas during the pre-monsoon (May) and post-monsoon (October) seasons. The wells were selected to represent coastal, inland, and peri urban settings so that spatial and seasonal variation could be properly evaluated. Each well was purged before sampling to remove stagnant water and to ensure collection of representative aquifer water. All samples were collected following standard groundwater sampling procedures recommended by APHA [37]. Samples were stored in clean polyethylene bottles, sealed immediately after collection, and transported to the laboratory under cooled conditions to minimize any alteration.

3.2 Physicochemical Analysis

Field measurements of pH, electrical conductivity, and total dissolved solids were performed at each well using calibrated portable meters. Laboratory analysis included major cations (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}) and major anions (HCO_3^-, Cl^-, SO_4^{2-}, NO_3^-). Calcium, magnesium, and bicarbonate were determined by titrimetric methods. Chloride was measured through silver nitrate titration. Sodium and potassium were analysed using flame photometry. Sulfate and nitrate were measured by spectrophotometric techniques. All procedures followed APHA guidelines [38], and BIS drinking water standards were used as a benchmark for comparison [39].

3.3 Irrigation Suitability Indices

To assess the suitability of well water for irrigation, several established indices were calculated. These include sodium adsorption ratio, percent sodium, residual sodium carbonate, Kelly ratio, magnesium hazard, permeability index, and total hardness. Each index reflects the influence of sodium, calcium, magnesium, and carbonate chemistry on soil permeability and crop tolerance. Calculations followed established formulations used in groundwater quality studies [40,41,42].

3.4 Water Quality Index

The groundwater was classified for drinking suitability using the weighted arithmetic water quality index approach. Each parameter was assigned a weight based on its relative significance in human health and water quality standards. Subindices were calculated and combined to obtain the final index value. The procedure followed methods adopted in earlier WQI studies [43,44].

3.5 Data Processing and Statistical Methods

All results were checked for ionic balance to ensure that charge errors were within acceptable limits. Descriptive statistics were used to evaluate spatial and seasonal variation in well water chemistry. Correlation analysis was performed to identify relationships between major ions. Hydrogeochemical interpretation was supported by Piper and Gibbs diagrams to identify groundwater facies and to evaluate the influence of evaporation and rock water interaction, as applied in previous studies [45,46].

3.6 Nemerow's Pollution Index (NPI)

Nemerow's Pollution Index was calculated using the combined maximum and average pollution index values of individual parameters relative to drinking water standards, following established methodology.

4. Results and Discussion

Groundwater quality in Ghogha, Bhavnagar, and Talaja talukas displays clear spatial and seasonal variation shaped by lithology, evaporation, agricultural practices, and marine influence. These processes are typical of semi-arid coastal regions of western India and have been widely documented in groundwater studies [47,48,49].

4.1 Physicochemical Characteristics of Groundwater

Seasonal summary statistics (Table 1) show that total dissolved solids, hardness, and chloride concentrations vary substantially across both seasons. Elevated TDS values (pre: 320–9900 mg/L; post: 300–13100 mg/L) indicate strong evaporative concentration and salinity influence, which are common in arid and coastal aquifers [50,51]. High hardness values correspond to carbonate mineral dissolution and prolonged water–rock interaction, also reported in similar geological settings [52].

Chloride values reaching more than 4000 mg/L in Ghogha and coastal Bhavnagar confirm marine influence and evaporative enrichment, processes documented in groundwater along the Gulf of Khambhat and other Indian coastal belts [53,54]. Nitrate values up to 189 mg/L point to agricultural leaching, a known issue in regions with intensive fertiliser use and shallow groundwater levels [55,56].

The near neutral pH values (mean ≈ 7.4) indicate buffering by carbonate minerals, consistent with findings from other alluvial and hard rock aquifers in western India [57].

Table 1. Seasonal summary statistics of groundwater parameters

Parameter	Pre-monsoon Min	Pre-monsoon Max	Pre-monsoon Mean	Post-monsoon Min	Post-monsoon Max	Post-monsoon Mean
pH	6.03	8.57	7.46	6.32	8.20	7.47
TDS (mg/L)	320	9900	2193	300	13100	2279
Total Hardness (mg/L)	72	3640	792	116	4400	770
Calcium (mg/L)	16	504	128	4	604	110
Magnesium (mg/L)	2	465	97	4	671	119
Chloride (mg/L)	28	4112	706	23	4282	656
Sulfate (mg/L)	37	562	225	20	612	158
Nitrate (mg/L)	0	189	53	1	162	56
Bicarbonate (mg/L)	98	690	294	36	666	300

Sodium (mg/L)	56	926	224	10	1035	190
Potassium (mg/L)	0	16	2	0	18	3

4.2 Water Quality Index (WQI) for Drinking

WQI results (Table 2) show that groundwater quality is predominantly in the poor to unsuitable category. During pre-monsoon, 33 percent of samples fall in the poor category, and 11 percent are unsuitable. After monsoon, unsuitable samples increase to 29 percent, which suggests mobilization of salts or insufficient dilution by recharge, a phenomenon reported in coastal aquifers with high salinity storage [58,59].

Similar deterioration patterns after monsoon have been reported in semi-arid districts where flushing is limited and ionic loads increase due to mixing and seepage [60].

WQI deterioration is primarily controlled by TDS, chloride, hardness, and nitrate, consistent with dominant pollutant groups in many Indian groundwater studies [61,62].

Table 2. WQI classification of groundwater samples

WQI Class	Interpretation	Pre-monsoon %	Post-monsoon %
< 50	Excellent	4%	0%
50-100	Good	38%	15%
100-200	Poor	33%	34%
200-300	Very Poor	14%	22%
> 300	Unsuitable	11%	29%

4.3 Nemerow's Pollution Index (NPI)

NPI results show that Ca^{2+}, Mg^{2+}, TDS, Cl^{-}, and NO_3^{-} contribute most to pollution. Wells exceeding limits for more than six parameters show significant cumulative pollution stress. Multi-parameter exceedance is also reported in regions where natural salinity and anthropogenic inputs overlap [63,64].

Table 3. NPI classification of groundwater samples

NPI Range	Category	% of Samples
< 1	Clean	Minor proportion
1–2	Slightly polluted	Moderate proportion
2–3	Moderately polluted	Dominant
> 3	Heavily polluted	Limited but significant

Footnote: Qualitative proportions are based on station-wise NPI distribution; detailed values can be provided upon request.

4.4 Irrigation Water Suitability

SAR, RSC, Na%, and EC-based classifications (Table 3) demonstrate that groundwater is generally suitable for irrigation, although several wells in Ghogha show sodicity and salinity hazards. SAR values up to 17.63 place some samples into the medium to high sodium hazard category, which can negatively influence soil structure and crop performance [65].

RSC remained within acceptable limits for all samples (<2.5 meq/L), indicating limited carbonate hazard. Low RSC is typical for aquifers dominated by calcium and magnesium, which precipitate bicarbonate in the soil and reduce alkalinity hazard [66].

CSSRI classification shows 40 percent of wells as Good (A), while 8 percent fall under the High SAR Saline category (B3). Such distributions are common in coastal and semi-arid irrigation systems where both salinity and sodium accumulate in the soil–water system [67].

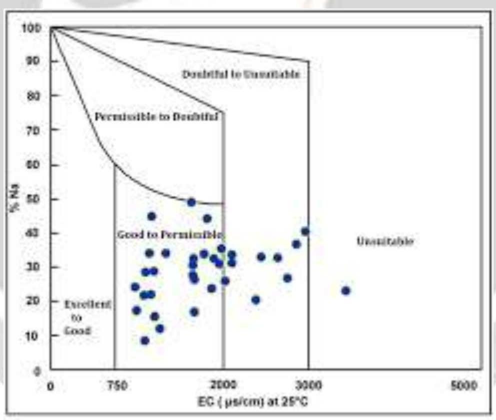

Figure 1. Wilcox diagram showing irrigation water suitability of groundwater samples based on Na% and EC.

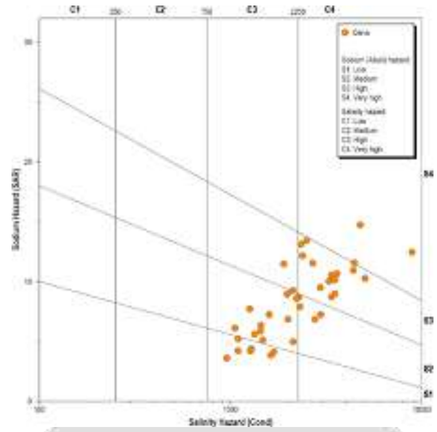

Figure 2. USSL diagram illustrating salinity and sodium hazard classification of groundwater samples.

The Wilcox diagram (EC vs Na%) positions most wells within permissible to marginal classes, while a few coastal wells fall in the unsuitable zone. Similar EC–Na relationships have been reported for irrigation waters in semi-arid India and coastal Gujarat [68].

Table 4. Irrigation water quality indices

Index	Range Observed	Mean Value	Interpretation Summary
SAR	0.88–17.63	Moderate	Six wells show sodicity hazard
RSC	–78.03–2.31 meq/L	Safe	All samples suitable (<2.5 meq/L)
Na%	12–78%	Moderate	High in coastal Ghogha
KR	0.1–3.5	Moderate	Some wells >1, marginal quality
MH	10–87%	Moderate	Few exceed 50% limit
CSSRI class	—	—	40% Good, 31% B1, 21% B2, 8% B3

4.5 Integrated Interpretation

Integrating physicochemical data, WQI, NPI, irrigation indices, and hydrochemical facies reveals the following:

1. **Salinity and hardness dominate groundwater quality degradation**, consistent with trends in other arid and semi-arid regions. [69].

2. **Inland regions show bicarbonate facies typical of recharge dominated aquifers**, while coastal regions show chloride facies influenced by marine intrusion. [70].

3. **Agricultural nitrate enrichment persists**, reflecting fertiliser use and shallow aquifer systems [71].

4. **Monsoon recharge improves water quality only marginally**, and in some wells increases salinity through mobilization of stored salts. [72].

5. **Irrigation suitability is higher than drinking suitability**, although sodium hazard is a concern for specific wells in Ghogha taluka [73].

Overall, the results highlight the need for controlled groundwater abstraction, improved recharge structures, and monitoring programs to safeguard drinking and irrigation water quality.

5. CONCLUSION

This study assessed the seasonal variation, hydrochemical processes, and suitability of groundwater for drinking and irrigation across Ghogha, Bhavnagar, and Talaja talukas of Bhavnagar district. The results demonstrate that groundwater quality is shaped by a combination of geogenic and anthropogenic influences. High concentrations of dissolved solids, hardness, and chloride in both seasons indicate persistent salinity, particularly in coastal areas, and reflect evaporation and saline mixing processes documented in similar semi-arid coastal aquifers [47,53]. Inland regions show predominantly Ca–Mg–HCO_3 facies, consistent with carbonate dissolution, while Na–Cl facies dominate in Ghogha due to marine influence and long residence time.

Water Quality Index values confirm widespread drinking-water stress, with most samples falling into poor, very poor, or unsuitable categories in both seasons. An increase in unsuitable samples during the post-monsoon period indicates that recharge does not uniformly dilute salinity and may mobilize stored salts in shallow aquifers [63,72]. Nemerow's Pollution Index further shows that multiple parameters, including TDS, Cl^-, NO_3^-, Ca^{2+}, and Mg^{2+}, exceed recommended limits in several wells, revealing the combined impact of natural salinity and agricultural inputs.

Irrigation suitability is more favorable than drinking suitability. SAR, RSC, and Na% values show that most wells are suitable or marginally suitable for irrigation, although sodicity and salinity hazards remain in specific coastal wells. CSSRI classification indicates that nearly 40 percent of groundwater is good for irrigation, whereas 8 percent falls into the high-SAR saline category, requiring soil management interventions [69,71].

Overall, the results highlight the need for sustained groundwater monitoring, controlled abstraction, and management practices such as artificial recharge, crop selection based on salinity tolerance, and regulated fertilizer use. These measures are essential to preserve groundwater quality and ensure reliable water resources for both domestic supply and agricultural production in Bhavnagar district.

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