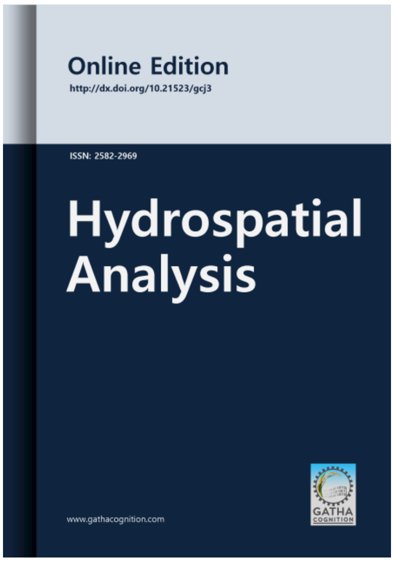

Hydrospatial Analysis

Editor-in-Chief: **Professor Pramodkumar Hire**
EISSN: 2582-2969
DOI: https://doi.org/10.21523/gcj3

Techniques and indices for groundwater quality assessment: A Comprehensive Review

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To cite this article

Aware, S. M., Zolekar, R. B. and Kasar, S. N, 2024. Techniques and indices for groundwater quality assessment: A Comprehensive Review. *Hydrospatial Analysis*, 9(1), 20-42.

DOI: https://doi.org/10.21523/gcj3.2025090103

Hydrospatial Analysis
Homepage: www.gathacognition.com/journal/gcj3
http://dx.doi.org/10.21523/gcj3

Review Article

Techniques and Indices for Groundwater Quality Assessment: A Comprehensive Review

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Abstract

Groundwater quality assessment is crucial for providing safe drinking water and supportive sustainable irrigation, especially in areas facing water scarcity and contamination risks. This review analyses 45 studies that used different techniques to evaluate groundwater quality in varied hydrogeological settings. The main objectives are to: 1) identify common assessment methods 2) examine their applications for drinking and irrigation purposes, and 3) highlight gaps and future directions.

The findings show that most studies focus on physiochemical parameters such as pH, Electrical Conductivity (EC), Total Dissolved Solids (TDS), Total Hardness (TH), and major ions like Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, Cl^{-}, HCO_3^{-}, SO_4^{2-}, NO_3^{-}, and F^{-}, as they strongly influence the water usability. The water quality index (WQI) is the most widely applied method, used in about 93% of studies, because it combines multiple parameters into a single value for drinking suitability. Hydrochemical classification methods like Piper Diagram (84%) and Gibbs Diagram (62%) are also common for identifying water types and geochemical process. For irrigation, indices such as Sodium Adsorption Ratio (SAR) (60 %), Residual Sodium Carbonate (RSC), Magnesium Hazard (MH) (27%), Permeability Index (PI) (31%), Kelly's Ratio (KR) (24%), and graphical tools like the Wilcox Diagram (40%) are frequently used. Advance statistical methods, including Principal Components Analysis (PCA) and cluster analysis, along with GIS and Remote Sensing are increasingly applied for spatial mapping and source identification.

The synthesis indicates that while traditional hydrochemical and index-based methods dominate groundwater quality evaluation, significant research gaps persist in the integration of emerging contaminants, real-time monitoring, and machine learning-based prediction models. Future studies should adopt hybrid frameworks combining chemical, biological, and spatial datasets to improve groundwater quality forecasting and resource management. The findings of this review provide a consolidated reference for developing standardized, data-driven approaches for groundwater quality assessment and sustainable utilization.

Article History

Received: 08 September 2025
Revised: 12 October 2025
Accepted: 15 October 2025
Publication: 22 November 2025

Keywords

Water Quality Index,
Groundwater Quality,
Irrigation Suitability,
Hydro Chemical Assessment,
Principal Components Analysis.

Editor(s)

P. Hire
Vijay Bhagat

1 INTRODUCTION

Groundwater, a vital and renewable natural resource, serves as one of the most reliable alternatives to surface water for various domestic, agricultural, and industrial purposes. It resides beneath the earth's surface, having infiltrated through porous soils and fractures in rocks, accumulating in aquifers over time. Its availability is closely linked with rainfall patterns and the recharge from surface water bodies such as rivers, lakes, and reservoirs. Particularly in regions facing an erratic supply of surface water, groundwater becomes an

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https://doi.org/10.21523/gcj3.2025090103

indispensable source for sustaining life and development. However, the overexploitation of this resource and increasing anthropogenic activities have led to a significant deterioration in its quality, raising serious concerns about its suitability for drinking and irrigation purposes.

The quality of groundwater is influenced by numerous physical, chemical, and biological parameters, along with geogenic and anthropogenic factors such as lithology, slope, land use, land cover, and agricultural practices. Unregulated use of fertilizers and pesticides, improper waste disposal, and the discharge of industrial effluents have exacerbated contamination levels, making groundwater unsafe for consumption in many parts of the world. Notably, the NITI Aayog (2018) report highlighted India's worsening water crisis, warning that nearly 600 million people face high to extreme water stress, with 70% of the country's freshwater contaminated. The report also revealed that about two lakh people die annually due to inadequate access to safe drinking water, emphasizing the urgency of evaluating groundwater quality across the nation.

At the global level, groundwater is extensively used in rural and agrarian regions for the cultivation of high-value crops. However, intensified agricultural activities have resulted in the indiscriminate application of agro-chemicals, leading to groundwater contamination and, consequently, deteriorating human health and agricultural sustainability. Groundwater pollution not only affects water quality but also undermines economic development, social well-being, and environmental balance. According to WHO and FAO (2008), approximately 80% of diseases in developing regions stem from the consumption of polluted water.

Given the mounting pressures on this essential resource, scientific assessment of groundwater quality has become imperative. Several studies worldwide have employed various hydrogeochemical techniques, water quality indices, and spatial mapping tools to assess groundwater quality. For drinking water evaluation, the Water Quality Index (WQI) is widely used as it integrates multiple physico-chemical parameters into a single value representing the overall quality of water (Adimalla *et al*., 2020; Chung *et al*., 2014). For irrigation assessment, indices such as the Sodium Adsorption Ratio (SAR), Soluble Sodium Percentage (SSP), Residual Sodium Carbonate (RSC), Kelly's Ratio (KR), and Magnesium Adsorption Ratio (MAR) are commonly used to determine the suitability of water for crop cultivation (Islam *et al*., 2017; Adimalla *et al*., 2018; Chung *et al*., 2014; Houatmia *et al*., 2016; Singh *et al*., 2020; Kaur *et al*., 2017; Ayed *et al*., 2017; Vasanthavigar *et al*., 2010; Li *et al*., 2016).

Advanced statistical methods such as mean, standard deviation, correlation analysis, and Principal Component Analysis (PCA) provide deeper insights into the underlying factors influencing groundwater chemistry (Sako *et al*., 2016; Subba Rao *et al*., 2020; Ayed *et al*., 2017). Additionally, Geographic Information Systems (GIS) and geospatial techniques enable the spatial visualization and interpolation of groundwater quality parameters, helping to delineate contaminated zones and guide resource management strategies (Shaikh and Birajdar 2024). Comparison of analyzed data with standards prescribed by the Bureau of Indian Standards (BIS) and the World Health Organization (WHO) further aids in determining permissible, desirable, and non-permissible limits for safe groundwater usage (BIS, 2003; WHO, 1997).

Despite extensive research conducted across the globe, comprehensive and spatially detailed analysis of groundwater quality remains limited in many high-stress agricultural regions. This review paper aims to fill this gap by analyzing groundwater quality for both drinking and irrigation purposes at the global level and by identifying various methods and techniques used in groundwater studies. The study also emphasizes the importance of sustainable groundwater management, regular monitoring, and community-level awareness to prevent further degradation of this essential resource.

In summary, the present review not only synthesizes current methodologies used in groundwater quality assessment but also contextualizes their relevance in addressing pressing environmental and public health challenges. It offers a comprehensive overview of tools and techniques ranging from traditional water quality indices to modern GIS-based spatial analysis and statistical modelling. The goal is to provide scientific evidence that can guide policymakers, water resource managers, and stakeholders towards sustainable groundwater utilization and better planning for rural and urban water security.

1.1 Groundwater Quality Assessment

Several studies have contributed significantly for understanding the groundwater recharge, hydrogeochemical processes, and quality dynamics across various regions of India, there remains a pressing need for integrated and region-specific groundwater quality assessment. Previous research, such as that of Sajil Kumar *et al*. (2022), has focused on recharge estimation and water balance, while Rajmohan and Elango (2004, 2005) examined nutrient enrichment and hydrogeochemical evolution under agricultural influence. Similarly, studies by Gowrisankar *et al*. (2017) and Magesh et al. (2017) demonstrate the effectiveness of managed aquifer recharge and the use of multivariate statistical approaches for understanding groundwater contamination and associated health risks. However, most existing works are localized or process-specific and lack a holistic integration of physical, chemical, and spatial analysis for comprehensive groundwater quality evaluation. In regions dominated by basaltic formations, such as those studied by Pawar (2008) and Wagh *et al*. (2016), hydrochemical variability is highly influenced by lithology, irrigation practices, and anthropogenic pressures, necessitating a systematic assessment of water quality through advanced indices, graphical, and statistical techniques. Therefore, there is a critical need to undertake a detailed groundwater quality assessment that integrates hydrogeochemical characterization, statistical interpretation, and water quality indices to evaluate suitability for drinking and irrigation purposes and to support sustainable groundwater resource management.

Groundwater is the best alternative to surface water and a renewable resource. It is stored water that has percolated into the earth through rock cracks, soils, and beneath the surface. Groundwater levels vary with rainfall and water bodies like rivers, lakes, dams, etc., which penetrate down through cracks in rocks and soil. Groundwater is a gift from nature, but due to human unethical behavior and its unplanted practice, groundwater levels and quality have been decreasing. Physical, chemical, and biological characteristics, as well as land use and land cover, determine groundwater quality and its suitability for various purposes. Most studies use the Water Quality Index (WQI) for groundwater quality assessment for drinking purposes. SAR, SSP, KR, MAR, RSC, etc., indices are used for irrigation assessment. Statistical techniques like mean, standard deviation, principal component analysis, and correlation analysis have been used for groundwater assessment. For spatial analysis, geospatial techniques have been used for mapping. After laboratory analysis, results have been compared to standard ranges suggested by the Bureau of Indian Standards (BIS) and the World Health Organization (WHO). These standards suggest maximum permissible limits, desirable limits, and non-permissible limits for groundwater use for drinking purposes. For irrigation purposes, indices indicate safe water, moderately safe water, moderately unsafe water, and unsafe water, as per World Health Organization guidelines.

2 EMPIRICAL STUDIES ON GROUNDWATER QUALITY EVALUATION

2.1 Graphical Techniques for Hydrogeochemical Interpretation

Graphical techniques play a crucial role in groundwater quality assessment as they visually represent complex hydrochemical data and help in identifying dominant geochemical processes, water types, and suitability for drinking or irrigation (Aher *et al*., 2022). Among these, the Piper trilinear diagram (Piper, 1994) is the most extensively applied graphical tool for groundwater facies classification. It was effectively used by Baghvand *et al*. (2010), Vasanthavigar *et al*. (2010), Narsimha and Sudarshan, 2017, Adimalla *et al*. (2018, 2019, 2020), and others to interpret the hydrochemical composition and mixing trends in groundwater. For instance, Adimalla *et al*. (2018) and Kaur *et al*. (2017) employed Piper plots to distinguish major water types and identify the dominant cation-anion associations controlling groundwater evolution, while Tiwari *et al*. (2014, 2017) and Zolekar *et al*. (2020) used it to classify aquifer facies and evaluate regional variations in water chemistry. The major advantage of this diagram is its ability to visually represent geochemical facies and mixing processes, simplifying the interpretation of hydrochemical evolution (Aly *et al*., 2015; Li *et al*., 2016). However, its limitations include the lack of spatial representation and reduced interpretability when large datasets overlap, leading researchers to combine it with other graphical and statistical methods (Sako *et al*., 2016; Ayed *et al*., 2017).

To complement the Piper plot, other diagrams provide specialized insights. The Schoeller diagram (Schoeller, 1956), applied by Baghvand *et al*. (2010) and Khan *et al*. (2018), allows comparison of ionic concentrations on a semi-logarithmic scale, which helps detect relative dominance or depletion of ions but lacks facies classification capability. The Durov diagram utilized by Aly *et al*. (2015) and Singh *et al*., (2020), effectively differentiates groundwater evolution processes such as ion exchange and salinity mixing through defined chemical fields. Likewise, the Wilcox diagram (Wilcox, 1955) and the USSL diagram (USSL, 1954) have been extensively employed by Nagarajuna *et al*. (2014), Prashanth *et al*. (2012), and Singh *et al*., (2020) to assess irrigation suitability by plotting sodium and salinity hazards. These diagrams provide rapid classification of irrigation water into quality zones, but they oversimplify the chemistry by ignoring secondary ions and trace elements (Madhav *et al*., 2018; Chaudhary *et al*., 2018).

The Gibbs diagram (Gibbs, 1970) is another powerful interpretive tool used by Rajmohan and Elango (2004), Adimalla *et al*. (2018, 2019, 2020), Nagarajuna *et al*. (2014), and Zolekar *et al*. (2020) to identify dominant mechanisms such as rock–water interaction, precipitation, and evaporation controlling groundwater chemistry. Its simplicity in linking TDS and ionic ratios to hydrogeochemical processes is advantageous, yet it fails to account for anthropogenic influences and trace contaminants (Kaur *et al*., 2017; Tiwari *et al*., 2017). The Chadha diagram (Chadha, 1999), as used by Adimalla *et al*. (2018, 2020) and Subba Rao *et al*. (2020), refines Piper's approach by providing a clearer quadrant-based classification of hydrochemical facies, enhancing interpretability but still remains limited to major ions.

Supplementary graphical tools such as pie charts (Kaur *et al*., 2017), dendrograms (Baghvand *et al*., 2010; Ayed *et al*., 2017), boxplots (Vasanthavigar *et al*., 2010; Narsimha and Sudarshan, 2017; Adimalla *et al*., 2019), and scatter plots (Adimalla *et al*., 2018; Khan *et al*., 2018) have also been integrated for comparative and statistical visualization (Figure 1). These methods enhance data clarity by highlighting trends, outliers, and group similarities among water samples.

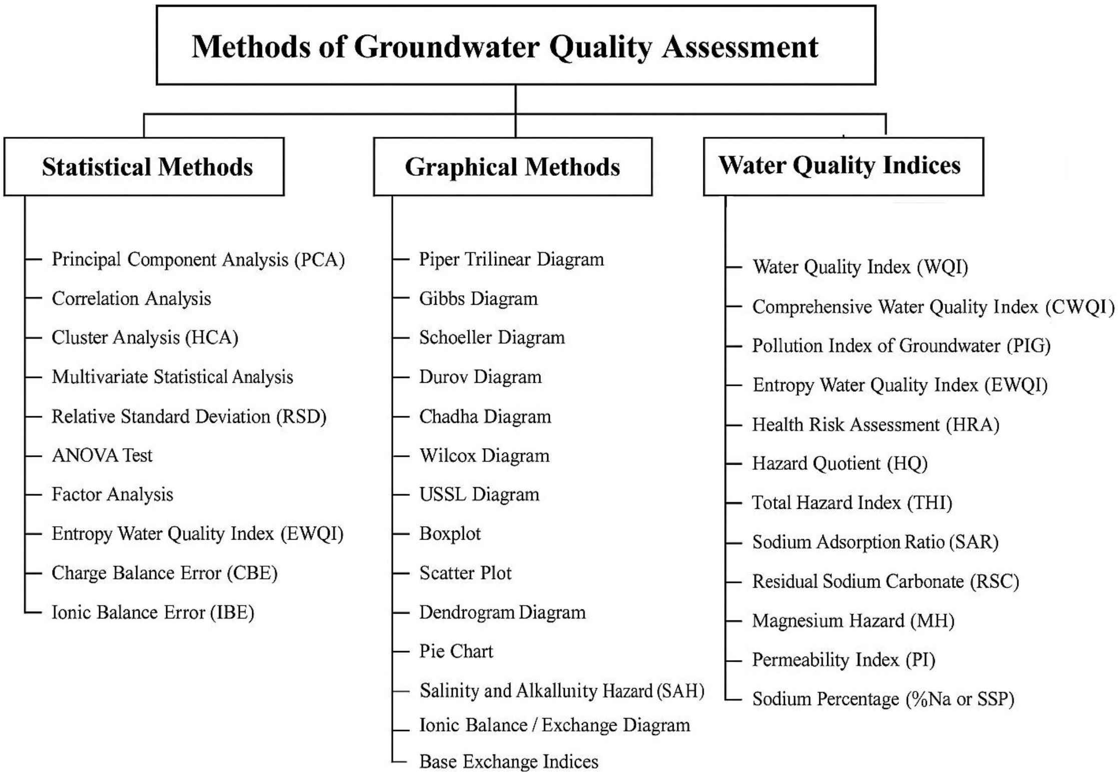

Figure 1. Methods for the groundwater quality assessment

The overall implication from these studies is that graphical techniques not only simplify hydrochemical interpretation but also help in delineating groundwater processes and assessing water suitability across diverse hydrogeological settings (Chatterjee *et al.*, 2009; Aly *et al.*, 2015; Li *et al.*, 2016). Despite their interpretive strength, these tools rely heavily on qualitative assessment and cannot represent temporal or spatial variability without integration with GIS and multivariate analysis (Zhang *et al.*, 2018; Zolekar *et al.*, 2020). Therefore, future research should focus on developing integrated visualization frameworks that combine traditional diagrams with geospatial and multivariate statistical approaches, enabling dynamic, data-rich groundwater assessments (Adimalla *et al.*, 2020; Tiwari *et al.*, 2017). Such integration would improve the precision and predictive capability of hydrogeochemical interpretations and support sustainable groundwater management.

2.2 Statistical and Multivariate Techniques in Groundwater Quality Evaluation

Principal Component Analysis (PCA) is a key multivariate statistical tool used to evaluate groundwater quality by identifying the major hydrogeochemical processes and pollution sources affecting water chemistry (Adimalla *et al.*, 2020; Subba Rao *et al.*, 2018; Ayed *et al.*, 2017). It simplifies large hydrochemical datasets into a few independent components, allowing researchers to distinguish between natural processes such as rock-water interaction, mineral dissolution, and ion exchange, and anthropogenic influences like agricultural runoff, sewage disposal, and industrial activities (Sako *et al.*, 2016). The application of PCA helps reveal interrelationships among variables and classify groundwater according to geochemical controls, while integration with GIS and entropy water quality index techniques enhances spatial interpretation and management of vulnerable zones (Subba Rao *et al.*, 2020). Its main advantage lies in reducing data complexity and improving interpretability without major loss of information (Ayed *et al.*, 2017). However, the reliability of PCA depends on data quality, sampling adequacy, and variable selection, as it identifies statistical correlations but not direct causation (Adimalla *et al.*, 2020). Despite these limitations, PCA provides valuable insights for groundwater monitoring and management. Future studies should integrate PCA with tracer, isotopic, and health risk analyses to strengthen causal understanding and guide sustainable groundwater protection (Sako *et al.*, 2016; Subba Rao *et al.*, 2018). Cluster and Hierarchical Cluster Analysis (HCA), as used by Baghvand *et al.* (2010), Ayed *et al.* (2017), and Egbueri (2019), effectively grouped groundwater samples with similar chemical characteristics, delineating spatial and quality-based classes. Although useful for pattern recognition, these methods are sensitive to distance measures and may overlook nonlinear relationships. Singh *et al.* (2015) analyzed correlations among hydrochemical parameters to identify their interrelationships, using a correlation matrix to reveal key geochemical associations in groundwater. Correlation analysis, applied by Narsimha and Sudarshan, (2017), Tiwari *et al.* (2014), Chetan and Surindra (2017), and

Singh *et al*. (2012), revealed associations among ions, indicating geochemical processes such as mineral dissolution and ion exchange. Bivariate and scatter plot analyses, applied by Subba Rao *et al*. (2018), Adimalla *et al*. (2018), and Khan *et al*. (2018), visually identified ion relationships and hydrochemical mechanisms, while Relative Standard Deviation (RSD) and basic statistics by Tiwari *et al*. (2014, 2017) aided in assessing variability and reliability. Overall, these statistical techniques enhance groundwater assessment by uncovering hidden patterns and quantifying process contributions. Their main advantage lies in integrating quantitative precision with hydrochemical interpretation, though they rely on assumptions of normality and linearity. The findings of Adimalla *et al*. (2020) and Subba Rao *et al*. (2020) emphasize that combining multivariate statistics with GIS and temporal data analysis can overcome these limitations. Future research should focus on integrating statistical models with geospatial and machine learning approaches to improve groundwater quality prediction and sustainable management.

2.3 Water Quality Index Approaches for Drinking and Domestic Purposes

Water Quality Index (WQI) is one of the most widely used and effective approaches for evaluating groundwater suitability for drinking and domestic purposes across various hydrogeological settings. It provides a single representative value derived from multiple physico-chemical parameters, offering a comprehensive assessment of overall water quality (Aly *et al*., 2015; Zolekar *et al*., 2020; Adimalla *et al*., 2018). The WQI approach has been applied in diverse environments, from urban regions in Korea (Chung *et al*., 2014) to semi-arid areas of India (Adimalla and Qian, 2019) to classify water quality into categories such as excellent, good, poor, or unsuitable for consumption. This classification allows water authorities to make informed decisions about domestic water use, infrastructure development, and pollution control strategies.

The major advantage of WQI lies in its ability to simplify complex hydrochemical data into a single, easily interpretable value, which is particularly beneficial for non-technical audiences and policymakers. According to Aly *et al*. (2015), the WQI method offers an efficient and concise framework to evaluate water quality for drinking purposes, allowing effective communication of results to the public. Similarly, Zolekar *et al*. (2020) highlighted the use of GIS-based WQI in mapping spatial variations of groundwater quality in Nashik District, India, demonstrating its usefulness in regional groundwater management and planning. Houatmia *et al*. (2016) also emphasized that the combination of WQI with hydrogeochemical techniques provides a clear understanding of groundwater quality and its spatial heterogeneity.

The flexibility of WQI is another key advantage. It can incorporate a wide range of parameters such as pH, EC, TDS, hardness, nitrate, fluoride, and major cations and anions, providing an integrated view of groundwater chemistry. Studies by Adimalla *et al*. (2018) and Chung *et al*. (2014) demonstrated that WQI efficiently identifies zones of contamination, helping prioritize areas where remedial measures are urgently required. Furthermore, the index can be combined with spatial, statistical, or health risk assessment models to strengthen groundwater quality monitoring and policy formulation.

Despite its practical benefits, WQI has several limitations. Its reliability largely depends on the selection of parameters and their assigned weightages, which may vary by region or standard, leading to inconsistencies in interpretation (Aly *et al*., 2015; Adimalla and Qian, 2019). Moreover, the WQI value offers only a numerical representation of quality, lacking diagnostic information about pollutant sources or the specific hydrogeochemical processes responsible for contamination (Zhang *et al*., 2018; Houatmia *et al*., 2016). It does not adequately capture the temporal dynamics of groundwater or interactions among multiple contaminants. Adimalla (2019) further noted that WQI alone cannot assess health hazards from fluoride or nitrate without complementary human health risk modeling. Similarly, Zolekar *et al*. (2020) cautioned that although WQI effectively summarizes quality status, it should be supplemented by detailed geochemical and statistical analyses to fully understand groundwater contamination mechanisms.

The WQI serves as a powerful, integrative, and communicative tool for assessing groundwater quality for drinking and domestic purposes. It is highly useful for quick decision-making and public awareness but should be applied alongside hydrogeochemical and spatial analyses for a comprehensive understanding of groundwater dynamics (Aly *et al*., 2015; Zolekar *et al*., 2020; Adimalla *et al*., 2018; Houatmia *et al*., 2016; Zhang *et al*., 2018).

2.4 Water Quality Indices for Irrigation Suitability Assessment

The Water Quality Indices (WQIs) formulated for irrigation purposes are essential for assessing the suitability of groundwater for agricultural use by interpreting its chemical composition and interaction with soil and crops. Indices such as Sodium Adsorption Ratio (SAR), Residual Sodium Carbonate (RSC), Sodium Percentage (% Na), Magnesium Hazard (MH), Permeability Index (PI), and Kelly's Ratio (KR) have been applied in several hydrogeochemical investigations to evaluate irrigation water quality in varied hydrogeological environments (Adimalla and Venkatayogi, 2018; Singh *et al*., 2020; Jafari *et al*., 2018; Madhav *et al*., 2018). These indices provide a quantitative means to assess ionic concentration effects on soil permeability, salinity development, and crop growth potential. The major advantage of using irrigation-based WQIs is their ability to convert complex hydrochemical datasets into interpretable classifications that are practical for agricultural and environmental management. Parameters such as SAR, MH, and PI are frequently used to identify sodicity hazards, magnesium influence, and permeability characteristics of irrigation water (Adimalla and Venkatayogi, 2018; Khan and Jhariya, 2018). However, the limitations of irrigation-related WQIs are evident in their dependence on specific hydrogeological conditions and standardized assumptions. Many indices are sensitive to local variations in soil type, aquifer lithology, and climatic factors, which may influence their reliability across regions (Kaur *et al*., 2017; Liu *et al*., 2016). Furthermore, these indices tend to generalize water quality without accounting for the cumulative impact of anthropogenic activities such as fertilizer use, wastewater infiltration, and industrial effluents (Adimalla and Venkatayogi, 2018; Liu *et al*., 2016). Since most indices are designed for typical geochemical conditions, they may not accurately reflect site-specific processes like ion exchange or mineral dissolution, which strongly affect groundwater chemistry.

From a critical perspective, relying on a single irrigation index may lead to oversimplified evaluations of complex groundwater systems. As emphasized by Adimalla and Venkatayogi (2018), the combined use of indices such as SAR, %Na, RSC, MH, and KR yields a more comprehensive and balanced interpretation of groundwater quality. Jafari *et al*. (2018) further reinforced that the integration of multiple indices enhances the reliability of assessments by capturing the multidimensional nature of groundwater chemistry under semi-arid agricultural conditions. Irrigation WQIs such as SAR, RSC, %Na, MH, PI, and KR remain indispensable tools for evaluating groundwater suitability for agriculture. Their strength lies in simplicity and interpretability, but their limitations necessitate critical application and integration for accurate and sustainable irrigation water management (Singh *et al*., 2020; Khan and Jhariya, 2018; Jafari *et al*., 2018; Kaur *et al*., 2017).

2.5 Laboratory Analysis

In the 53 studies reviewed, groundwater samples were analyzed for parameters such as pH, total hardness (TH), total dissolved solids (TDS), magnesium (Mg^{2+}), sodium (Na^+), calcium (Ca^{2+}), chloride (Cl^-), bicarbonate (HCO_3^-), nitrate (NO_3^-), sulfate (SO_4^{2-}), fluoride (F^-), and potassium (K^+) (Table 1). In the published water quality research, standards recommended by the American Public Health Association (APHA, 1995) were used to identify hydrochemical parameters. It was also observed in these studies that a pH meter was used to measure pH. The acid titration method was employed to determine the concentration of bicarbonate (HCO_3^-) in groundwater. The concentration of dissolved silica was determined using a UV-VIS spectrophotometer based on the molybdosilicate method. Anion concentrations specifically F^-, Cl^-, SO_4^{2-}, and NO_3^--were analyzed using an ion chromatograph. Cation concentrations, including Ca^{2+}, Mg^{2+}, Na^+, and K^+, were measured using a flame atomic absorption spectrophotometer (Table 1).

3 METHODOLOGICAL INSIGHTS INTO GWQI STUDIES: A LITERATURE SYNTHESIS

A comprehensive review of 45 research papers reveals the frequency and purpose of various groundwater quality assessment techniques used by researchers (Table 2). Among these techniques, the Water Quality Index (WQI) was the most widely applied, as 42 research papers (93%) used this method to aggregate many complex water quality parameters into a single understandable index. This approach simplifies the interpretation and communication of the overall quality of water bodies, particularly for drinking water purposes.

Table 1. Instrumental, titrimetric and calculation methods

Parameters	Analytical Method	Unit	References
pH	Portable meter	--	APHA, 1995
Total dissolved solids (TDS)	Calculation	mg/L	APHA, 1995
Fluoride (F^-)	Ion chromatograph	mg/L	APHA, 1995
Chloride (Cl^-)	Ion chromatograph	mg/L	APHA, 1995
Nitrate (NO_3^-)	Ion chromatograph	mg/L	APHA, 1995
Sulphate (SO_4^{2-})	Ion chromatograph	mg/L	APHA, 1995
Bicarbonate (HCO_3^-)	Aid titration technique	mg/L	APHA, 1995
Calcium (Ca^{2+})	Flame atomic absorption spectrophotometer	mg/L	APHA, 1995
Magnesium (Mg^{2+})	Flame atomic absorption spectrophotometer	mg/L	APHA, 1995
Sodium (Na^+)	Flame atomic absorption spectrophotometer	mg/L	APHA, 1995
Potassium (K^+)	Flame atomic absorption spectrophotometer	mg/L	APHA, 1995
Total hardness (TH)	EDTA titrimetric	mg/L	APHA, 1995

Table 2. Comparative Analysis of Groundwater Quality Evaluation Methods

Name of the Author	Parameters/Criterions	Data	Sampling	Analytical methods in laboratory	Methodology /Techniques	Objectives	Purposes	Study area
Chatterjee *et al.*, 2009	pH, EC, TDS, TH, Na^+, Ca^{2+}, Mg^{2+}, K^+, Cl^-, HCO_3^-, SO_4^{2-}, CO_3^{2-}, NO_3^-, and F^-	Primary Data Field Survey	79 Samples- out of them 26 surface water, 41 subsurface water and 12 mine waters	--	GIS, WQI	To make a ground water quality assessment using GIS	Drinking and Irrigation	Dhanbad district, Jharkhand, India,
Baghvand *et al.*, 2010	pH, EC, TDS, Major Cations (Na^+, K^+, Ca^{2+}, Mg^{2+}) and Major Anions (CO_3^{2-}, HCO_3^-, SO_4^{2-}, Cl^-)	Primary Data Field Survey	20 Boreholes considered for sampling	Digital pH and EC meter, Flame Photometry, Flame atomic absorption Spectrometer, HACH DR/2000	Piper trilinear diagram, Schoeller diagram, Wilcox diagram, Dendrogram diagram, Cluster analysis	To analyse the hadrochemical characterizations of groundwater for the suitability analysis	Groundwater suitability analysis	Iran Central Desert
Vasanthavigar *et. al.*, 2010	Na^+, Mg^{2+}, Ca^{2+}, K^+, HCO_3^-, Cl^-, SO_4^{2-}, PO_4^{3-}, H_4SiO_4, F^-, pH, EC, and TDS	Primary Data Field Survey	148 (bore holes) groundwater samples	Digital spectrophotometer, Flame photometer, Titrimetric method	SAR, RSC, SSP, WQI, Piper trilinear diagram, Box plots	To evaluate water quality index for groundwater quality assessment	Health risks assessment	Thirumanimuttar sub-basin, Tamilnadu, India
Prashant *et al.*, 2012	pH, EC, TDS, TH, HCO_3^-, Ca^{2+}, Mg^{2+}, Na^+, K^+, Cl^-, SO_4^{2-}, NO_3^-, F^-	Primary Data Field Survey	22 shallow open dug wells samples		Piper trilinear diagram, Wilcox diagram, PI, SAR, MH	To evaluate the spatial extent of groundwater quality and its suitability for drinking and agricultural uses in the costal stretch	Drinking and Agriculture	Alappuzha District, Kerala, India

Singh *et al.*, 2012	pH, EC, TDS, TH, Na^+, Ca^{2+}, Mg^{2+}, K^+, Cl^-, HCO_3^-, SO_4^{2-}, CO_3^{2-}, NO_3^-, and F^-	Primary Data Field Survey	15 groundwater samples were collected in August 2010 from shallow and deep bore hand-pumps	EDTA titrimetric method, UV–Visible spectrophotometer model, Sampling and analytical procedure	Correlation analysis, Base-exchange indices, Meteoric genesis indices, Piper trilinear diagram, Salinity index, Chlorinity index, Sodicity index	To evaluate the groundwater quality for drinking, domestic and irrigation purposes	Drinking Domestic and Irrigation	Lutfullapur Nawada, Loni, District Ghaziabad, Uttar Pradesh, India
Nagarjuna *et al.*, 2014	pH, EC, TH, TDS, TA, NCH, SAR, SP, RSC	Primary Data Field Survey	40 Samples	pH/EC/TDS Meter Indices of exchange	SAR, RSC, Indices of exchange magnesium ratio, KR, Saturation index, Gibbs diagram Piper trilinear diagram, Wilcox diagram, Permeability Index (PI)	Assessment of ground water quality for irrigation	Irrigation	Bandalamottu lead mining area Guntur District, Andhra Pradesh South India
Chung *et al.*, 2014	$Na^+ > Ca^{2+} > Mg^{2+} > K^+$; $Cl^- > HCO_3^- > SO_4^{2-} > NO_3^- > F^-$; and $Ca(HCO_3)_2$, $CaCl_2$, NaCl	Primary Data Field Survey	40 - wells Samples	Ion chromatography (IC, Water 431), Standard analytical methods, WATEQ4F geochemical model	WQI, Wilcox diagram, Gibbs diagram, Piper trilinear diagram, PI, SAR, RSC, Index of Base Exchange, Chloro-alkaline indices (CAI-I and CAI-II), Saturation index (WATEQ4F)	To assess the present quality of groundwater and determine the suitability of groundwater use for various purposes	Drinking and Domestic	Busan City, Korea
Tiwari and Singh, 2014	pH, EC, TDS, TH, Na^+, Ca^{2+}, Mg^{2+}, K^+, Cl^-, HCO_3^-, SO_4^{2-}, CO_3^{2-}, NO_3^-, and F^-	Primary Data Field Survey	55 groundwater samples	UV-VIS spectrophotometer	Piper trilinear diagram, Relative standard deviation, SI, Mineral Equilibrium, SAR, KR, Wilcox diagram, USSL diagram	To identify the factors controlling groundwater composition and assess its suitability for domestic and irrigation uses	Domestic and irrigation	Pratapgarh District, Uttar Pradesh
Aly *et al.*, 2015	EC, pH, Ca^{2+}, Mg^{2+}, Na^+, K^+, Cl^-, SO_4^{2-}, NO_3^-	Primary Data Field Survey	28 groundwater samples collected from tube wells	Phenoldisulfonic acid method, Turbidity method	WQI Piper trilinear diagram, Gibbs diagram, Schoeller diagram, Durov's diagram, SAR, KR, IBE	To assess groundwater quality for drinking and evaluate its hydro chemical characteristics	Drinking	Hafar Albatin, Saudi Arabia

Batabyal and Chakraborty, 2015	pH, TDS, TH, HCO_3^-, Cl^-, SO_4^{2-}, NO_3^-, F^-, Ca^{2+}, Mg^{2+}, Fe^{2+}/Fe^{3+}, Mn^{2+}, Zn^{2+}	Primary Data Field Survey	28 tube wells	-	WQI, Correlation coefficient matrix, triangulation with linear interpolation method	To assess groundwater quality for drinking	Drinking purposes	Kanksa-Panagarh area, Bardhaman District of West Bengal.
Sako *et al.*, 2016	pH, EC, COD, TDS, TH, HCO_3^-, Ca^{2+}, Mg^{2+}, Na^+, K^+, Cl^-, SO_4^{2-}, NO_3^-, F^-, NO_2^-, NH_4^+, PO_4^{3-}, Al, As^T, Cu, Mn^T, Ni^T, Cr, Pb, Zn, Na^+/Cl^-, Na^+/Ca^{2+}, TC^c	Primary Data Field Survey	6 dug wells and 7 boarewells samples	ICP-OES-Inductively, coupled plasma- optical emission spectroscopy, ICP-MS-Inductively, coupled-mass spectroscopy, Colometric method (APHA5220D)	Multivariate Statistic techniques, Piper trilinear diagram, PCA, Boxplots diagram	To assess the groundwater suitability for human consumption	Drinking	Bombore gold mineralized zone, Central Burkina Faso
Houatmia *et al.*, 2016	pH, $CaCO_3$, Ca^{2+}, Mg^{2+}, K^+, Na^+, HCO_3^-, Cl^-, SO_4^{2-}, NO_3^-	Primary Data Field Survey	39 water sample collected from Wells	Colorimetric method, Nephelometric methods, Volumetric method	WQI, KR, PI, SAR, RSC, MH, Wilcox diagram, Piper trilinear diagram, Saturation index (PHREECQ)	To assess the groundwater geochemistry and evaluate its suitability for drinking and irrigation purposes	Drinking and Irrigation	North- eastern, Tunisia
Li *et al.*, 2016	pH, EC, TDS, TH, Na^+, Ca^{2+}, Mg^{2+}, K^+, Cl^-, HCO_3^-, SO_4^{2-}, CO_3^{2-}, NO_3^-, and F^-	Primary Data Field Survey	31 groundwater samples - wells and hand pumping	Flame atomic absorption spectrophotometry, EDTA titration, Ion chromatography Traditional titrimetric method, spectrophotometry	HRA, Gibbs diagram, SAR, RSC, SSP, USSL diagram, Wilcox diagram, Piper diagram	To assess overall groundwater quality for irrigation and drinking water intake and dermal contact for different age group	Drinking and Irrigation	Northwest China

Islam *et al.*, 2017	Temperature, pH, EC, TDS, Na^+, K^+, Ca^{2+}, Mg^{2+}, Cl^-, SO_4^{2-}, NO_3^-, HCO_3^-, Br^-, and trace elements such as As, Pb, Li, Rb, Ba, Be, Co, Mn, Ti, Cd, and Se.	Field Survey Primary data	18 groundwater samples collected from tube wells	pH meter, Portable meter, Portable EC meter, TDS meter, Gallenkamp Flame Analyzer	Soluble sodium percentage (SSP), Sodium absorption ratio-(SAR), Magnesium absorption ratio (MAR), Residual sodium carbonate (RSC), Kelley's ratio (KR), Wilcox diagram, USSL diagram	To assess the hydro chemical characteristics and water quality, and evaluate their impact on human health	Health risk assessment	Patuakhali District Southern Coastal Region of Bangladesh
Narsimha and Sudarshan, 2017	pH, EC, TDS, TH, CO_3^{2-}, NO_3^-, F^-, Ca^{2+}, Mg^{2+}, Na^+, K^+	Primary Data Field Survey	104 groundwater samples	Flame photometry, Titrimetrically using standard EDTA Method, UV-Visible Spectro photometer, Fuoride ion-selec- tive electrode	Piper trilinear diagram, Correlation analysis, Gibbs diagram	To understand fluoride distribution in groundwater, its relationship with major ions, and identify high-fluoride zones	Human health risk assessment	Siddipet, Telangana State, India
Adimalla and Venkatayogi, 2017	pH, EC, TH, TDS, Ca^{2+}, Mg^{2+}, Na^+, K^+, Cl^-, SO_4^{2-}, NO_3^-	Primary Data Field Survey	194 groundwater Samples	pH/EC/TDS Meter, Titration method, Flame Photometer, Fluoride Ion-selective electrode, UV-Visible spectrophotometer	Gibbs diagram, Piper trilinear diagram	Mechanism of Fluoride enrichment in groundwater of hard rock aquifers	Fluoride concentration s	Medak, Telangana State, South India
Kaur *et al.*, 2017	Na^+, Ca^{2+}, Mg^{2+}, K^+, HCO_3^-, SO_4^{2-}, Cl^-, pH, EC, TDS, Temperature	Primary Data Field Survey	24 (well) groundwater samples	Water quality analyzer (ELICO), Standard methods Acid titration method, Argentometric method, SPADNS calorimetric method, Turbidimetric method, Stannous chloride method, UV–visible spectrophotometer Flame Atomic Absorption Spectrophotometer	ELICO- Water quality analyser (PE 138.), American Public Health Association, Pie - Diagram, Piper trilinear diagram, Gibb's diagram, SAR, Sodium percentage (SP), Magnesium ratio (MR), Corrosivity ratio (CR), Wilcox diagram, SI	To assess the groundwater quality for drinking and irrigation purposes	Drinking and Irrigation	Malwa region southwestern part of Punjab, India

Ayed *et al*., 2017	Na^+, Ca^{2+}, Mg^{2+}, K^+, HCO_3^-, SO_4^{2-}, Cl^-, pH, EC, TDS, Temperature	Primary Data Field Survey	47(wells) groundwater samples	Calibrated pH meters, Conductivity meter, Titration method, Ionic equilibrium, Diagram" and "Excel 2016" Shapiro–Wilk test	Multivariate statistical analysis, Hierarchical cluster analysis (HCA), PCA, Piper trilinear diagram, Dendrogram diagram, PI, SI, SAR, SP, Magnesium Percent	To assess the water quality and to determine the main hydro-chemical process which affect groundwater	Planning and Management	The Maitime Djeffara shallow aquifer (Southeastern Tunisia)
Khan and Jhariya, 2017	pH, EC, TDS, TH, Na^+, Ca^{2+}, Mg^{2+}, K^+, Cl^-, HCO_3^-, SO_4^{2-}, CO_3^{2-}, NO_3^-, and F^-	Primary Data Field Survey	34 groundwater samples	--	Standard methods, GIS, WQI	To assess the groundwater quality for drinking purpose	Drinking	Raipur City, Chhattisgarh
Tiwari *et al*., 2017a	pH, EC, TDS, TH, Na^+, Ca^{2+}, Mg^{2+}, K^+, Cl^-, HCO_3^-, SO_4^{2-}, CO_3^{2-}, NO_3^-, and F^-	Primary Data Field Survey	55 groundwater samples - shallow (dug wells) and deep aquifers (tube well/hand pumps)	Portable conductivity, pH meter, Acid titration method, UV–VIS spectrophotometer, Ion chromatograph, Flame atomic absorption spectrophotometer	WQI, GIS Piper trilinear diagram, Gibbs diagram, Statistical analysis, Inverse distance weighted (IDW)	To assess the groundwater quality for its suitability to drinking	Drinking	Pratapgarh district, in India
Tiwari *et al*., 2017b	pH, EC, TDS, F^-, Cl^-, HCO_3^-, SO_4^{2-}, NO_3^-, Ca^{2+}, Mg^{2+}, Na^+, K^+, TH, SAR, RSC, PI, MH, KI, and Silica	Primary Data Field Survey	25 Surface sample collected from river, ponds and canals	Portable Conductivity, pH Meter, Acid titration method, Molybdosilicate methods, Ion chromatograph (Dionex DX-120), Flame atomic absorption spectrophotometer	WQI, Piper trilinear diagram, Gibbs diagram, Correlation coefficient matrix, Interpolation techniques	To evaluate the water quality of surface water	Utilization and planning	Pratapgarh district, Uttar Pradesh
Zhang *et al*., 2018	pH, TH, TDS, Na^+, K^+, Ca^{2+}, Mg^{2+}, CO_3^{2-}, HCO_3^-, Cl^-, SO_4^{2-}, NO_3–N, NO_2–N, NH_4–N	Primary data Field Survey	47 groundwater samples collected from pumping wells	Portable pH mete, EDTA titrimetric method, Routine titrimetric methods, Fame atomic absorption spectrometry	CBE, Comprehensive Water Quality Index Method (CWQI), Piper trilinear diagram, Gibbs diagram	To evaluate groundwater quality for human health risks assessment	Health risks assessment	Jinghui Canal, Irrigation area of the loess region, Northwest China

Adimalla, 2018	TDS, TH, Ca^{2+}, Na^{+}, Mg^{2+}, Cl^{-}, K^{+}, NO_3^{-}, SO_4^{2-}, and F^{-}	Primary Data Field Survey	194 Groundwater samples	Interpolation technique, Inverse distance-weighted	SAR, RSC, Magnesium hazard (MH), PI, Piper trilinear diagram, Gibbs diagram, USSL diagram	To assess groundwater quality, health risks, monitoring efficiency, and vulnerability for informed policy-making	Health risks assessment	Semi-Arid Region of South India
Adimalla *et al*., 2018	pH, TDS, TH, HCO_3^{-}, Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, Cl^{-}, SO_4^{2-}, NO_3^{-}, F^{-}	Primary Data Field Survey	105 Groundwater samples	pH/EC/TDS Meter	WQI Piper trilinear diagram, Gibbs diagram, SAR, RSC, MH, KR, Wilcox diagram, USSL diagram, Chloro-alkaline indices (CAI-I and CAI-II)	To evaluation of groundwater quality for Drinking and irrigation purpose	Drinking and Irrigation	Central Part of Telangana
Adimalla *et al*., 2018b	pH, EC, TDS, TH, HCO_3^{-}, Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, Cl^{-}, SO_4^{2-}, NO_3^{-}, F^{-}, (TZ^{+}), and (TZ^{-})	Primary Data Field Survey	35 groundwater samples	pH/EC/TDS meter, EDTA titrimetric Method, Flame photometric, UV visible spectrophotometer, Standard methods	GIS (Kriging method), Ionic balance error, Gibbs diagram, Piper trilinear diagram, Scatters plots	To understand the correlation between fluoride and other chemical indices, hydro geochemistry of fluoride occurrence and its distribution	Fluoride enrichments	Peddavagu in Central Telangana (PCT)
Khan and Jhariya, 2018	pH, EC, TDS, TH, HCO_3^{-}, Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, Cl^{-}, SO_4^{2-}, NO_3^{-}, F^{-}	Primary Data Field Survey	100 groundwater samples	Titration, Flame photometer, UV-VIS spectroscopy, Atomic absorption spectroscopy (AAS)	Gibbs diagram, Piper trilinear diagram, Scatter diagram, Schoeller diagram, SAR, PI, USSL diagram	To assess groundwater quality for drinking and irrigation Purpose	Drinking and Irrigation	Raipur City, Chhattisgarh
Adimalla *et al*., 2018b	pH, EC, TDS, TH, Na^{+}, Ca^{2+}, Mg^{2+}, K^{+}, Cl^{-}, HCO_3^{-}, SO_4^{2-}, CO_3^{2-}, NO_3^{-}, and F^{-}	Primary Data Field Survey	34 groundwater samples-borewells	pH meter, Ethylenediaminetetraacetic acid (EDTA), Flame photometric, Titration method, ISE meter	HHRA, Hazard quotient (HQ), Total hazard index, IBE	Evaluation of groundwater contamination for fluoride and nitrate	Contamination- fluoride and nitrate	semi-arid region of Nirmal Province, South India

Adimalla and Venkatayogi, 2018	Na^+, Ca^{2+}, K^+, Mg^{2+}, Cl^-, HCO_3^-, SO_4^{2-}, CO_3^{2-}, NO_3^-, F^-	Primary Data Field Survey	34 groundwater samples (bore well/hand pumps)	EDTA titration, Flame Photometer, Fluoride ion-selective electrode	Standard methods, Piper trilinear diagram, Gibbs diagram, Box plot	To assess fluoride concentration in groundwater for study area	Fluoride concentration	Basara, Adilabad District, Telangana State, India
Subba Rao *et al.*, 2018	pH, EC, TDS, TH, Na^+, Ca^{2+}, Mg^{2+}, K^+, Cl^-, HCO_3^-, SO_4^{2-}, CO_3^{2-}, NO_3^-, and F^-	Primary Data Field Survey	30 (dug wells) groundwater samples	Portable meters, EDTA titration Method, Flame photometer, Volumetric method, UV-spectrophotometer, Titration method	Pollution index of groundwater, Bivariate and Piper trilinear diagram, ANOVA test, IBE	To evaluate the quality of groundwater for drinking water quality limits, and unhide the sources responsible for variation of quality of groundwater	Drinking	Rural part of Telangana State, India
Madhav *et al.*, 2018	pH, EC, TDS, TH, Na^+, Ca^{2+}, Mg^{2+}, K^+, Cl^-, HCO_3^-, SO_4^{2-}, CO_3^{2-}, NO_3^-, and F^-	Primary Data Field Survey	20 groundwater samples	pH and conductivity meters,	WQI, Piper trilinear diagram, Gibbs diagram, Wilcox diagram, PI, KR, USSL diagram	Geochemical assessment of groundwater suitability for drinking and irrigation purpose	Drinking and Irrigation	Rural areas of Sant Ravidas Nagar (Bhadohi), Uttar Pradesh
Jafari *et al.*, 2018	pH, EC, TDS, TH, Na^+, Ca^{2+}, Mg^{2+}, K^+, Cl^-, HCO_3^-, SO_4^{2-}, CO_3^{2-}, NO_3^-, and F^-	Primary Data Field Survey	30 groundwater samples	Ion meter model, UV–Vis spectrophotometer, flame photometer model, EDTA titrimetric method	RSC, PI, KR, MH, SP, SAR, SSP	Groundwater quality assessment for drinking and agriculture purposes	Drinking and agriculture	Abhar city, Iran
Chaudhary and Satheeshkuma, 2018	pH, EC, TDS, TH, Na^+, Ca^{2+}, Mg^{2+}, K^+, Cl^-, HCO_3^-, SO_4^{2-}, CO_3^{2-}, NO_3^-, and F^-	Primary Data Field Survey	300 groundwater samples collected from hand pumps	Spectrophotometric techniques	RSC, PI, KR, Piper trilinear diagram, Wilcox diagram, USSL diagram, Gibb’s diagram, MH, SP, SAR, SSP, Potential salinity	To assess the groundwater quality for drinking and agriculture purposes	Drinking and agriculture	Arid areas of Rajasthan, India

Adimalla *et al*., 2019	EC, pH, Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, Cl^{-}, SO_4^{2-}, NO_3^{-}	Primary Data Field Survey	107 Groundwater samples	pH/EC/TDS, Meter, Flame photometer meter, UV-visible spectrophotometer, Orion 4-star meter, pH/ISE meter	WQI, Piper trilinear diagram, Gibbs diagram, Boxplots diagram	To evaluate groundwater quality and assess non-carcinogenic risks from fluoride-rich water consumption	Health risks assessment and fluoride consumption	Shasler Vagu (SV) Watershed of Nalgonda, India
Adimalla and Qian, 2019	pH, EC, COD, TDS, TH, HCO_3^{-}, Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, Cl^{-}, SO_4^{2-}, NO_3^{-}, F^{-}, NO_2^{-}, NH_4^{+}	Primary Data Field Survey	61 groundwater Samples collected from hand pumps and bore wells	Portable pH/EC/TDS meter, Titration method, UV–visible Spectrophotometer, Flame photometer	IBE, WQI, HRA	To assess the non-carcinogenic health risks associated with groundwater quality for drinking purposes	Health risks assessment	Nanganur region, Telangana State, South India
Adimalla, 2019	pH, TDS, SO_4^{2-}, Cl^{-}, NO_3^{-}, F^{-}, Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, EC, TH, HCO_3^{-}, SAR	Primary Data Field Survey	194 groundwater samples were collected: 160 granitic, 24 basaltic, and 10 lateritic aquifers	pH/EC/TDS meter, EDTA., AgNO3 titration, Fame photometer,	WQI, KR, SAR, RSC	To assess groundwater quality for drinking and agricultural purposes and evaluate the health risks assessment	Drinking and Agriculture	Semiarid region of south India
Egbueri, 2019	Na^{+}, Ca^{2+}, K^{+}, Mg^{2+}, SO_4^{2-}, Cl^{-}, NO_3^{-}, HCO_3^{-}, and Ca^{2+}	Primary Data Field Survey	20 groundwater samples -out of them 3 hand-dug wells and 17 from boreholes	pH meter, Standard testing methods, Titration method, Flame photometer, Atomic Absorption Spectrophotometer (AAS)	PIG, Ecological risk index, Hierarchical cluster analysis, Piper trilinear diagram, Pollution index	To examine the drinking water quality of the groundwater	Drinking	Ojoto suburban in southeast Nigeria

Adimalla and Li, 2019	pH, EC, TDS, TH, Na^+, Ca^{2+}, Mg^{2+}, K^+, Cl^-, HCO_3^-, SO_4^{2-}, CO_3^{2-}, NO_3^-, and F^-	Primary Data Field Survey	105 groundwater	UV-visible spectrophotometer, pH/EC/TDS meter' Ethylenediaminetetraacetic acid (EDTA), Flame photometric,	Piper trilinear diagram, Gibbs diagram, Total Hazard Index, HQ, IBE, CAI	To delineate occurrence of fluoride and nitrate contamination and understand the hydro chemical processes responsible for their enrichment	contamination -fluoride and nitrate	The rock-dominant semi-arid region, Telangana State, India
Adimalla, 2019	pH, EC, TDS, TH, Na^+, Ca^{2+}, Mg^{2+}, K^+, Cl^-, HCO_3^-, SO_4^{2-}, CO_3^{2-}, NO_3^-, and F^-	Primary Data Field Survey	194 (bore/hand pumps) groundwater samples	Digital pH/EC/TDS meter, UV-visible spectrophotometer, EDTA titrimetric method, Flame photometer, Ion-selective electrode method	GIS, WQI, Pollution index, Piper trilinear diagram, Gibbs diagram, IBE	To assess the overall suitability of groundwater for drinking; and to evaluate groundwater quality comprehensively	Drinking	the hard rock terrain of South India
Adimalla *et al.*, 2020	pH, EC, TDS, Ca^{2+}, Mg^{2+}, Na^+, K^+, Cl^-, HCO_3^-, NO_3^-, SO_4^{2-}, F^-	Primary data (Field survey)	43 groundwater samples		Pollution Index (PIG), Principal component analysis (PCA)	The pollution index of groundwater and evaluation of potential human health risk	Human health risk	Hard rock terrain of south India
Adimalla *et al.*, 2020	pH, EC, TDS, Ca^{2+}, Mg^{2+}, Na^+, K^+, Cl^-, HCO_3^-, NO_3^-, SO_4^{2-}, F^-	Field Survey Primary Data	43 samples	Titrimetric methods, Flame photometer, UV - Visible spectrophotometer,	PIG, Charge balance errors (CBE), Gibbs diagram, Chadha diagram, Ion – selective electrode method (ISE), PCA	To assess groundwater quality for fluoride and nitrate, and evaluate their associated health risks for residents	Health risk assessment	The Northern part of the Nalgonda district, south of Telangana State, India
Subba Rao *et al.*, 2020	pH, TDS, Ca^{2+}, Mg^{2+}, Na^+, K^+, HCO_3^-, Cl^-, SO_4^{2-}, NO_3^-, F^-	Primary data Field survey	30 groundwater sample	Portable meters, EDTA titration method, Flame photometer, HCl volumetric method, AgNO3 titration method, Colorimetric method	Ionic Balance Error (IBE), Entropy Water Quality Index (EWQI), PCA, Chadha's diagram	Assessment of groundwater quality for drinking and domestic purposes	Drinking and domestic purposes	Wanaparthy District, Telangana State, India

Zolekar *et al.*, 2020	TDS, TH, Ca^{2+}, Na^{+}, Mg^{2+}, Cl^{-}, K^{+}, NO_3^{-}, and SO_4^{2-}	Primary Data Field Survey	61 Groundwater samples	pH/EC/TDS meter, Ionc chromatograph, Flame atomic absorption spectrophotometer, EDTA titrimetric	GIS Water Quality Index (WQI), Piper trilinear diagram, Gibbs Index	To evaluate the groundwater quality for drinking and agriculture uses	Drinking and agriculture	Nashik District in Maharashtra India
Singh *et al.*, 2020	pH, EC, TDS, TH, HCO_3^{-}, Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, Cl^{-}, SO_4^{2-}, NO_3^{-}	Primary Data Field Survey	50 groundwater samples	Potable kit, UV spectrophotometric method, Titration method, Flame photometer method	USSL- diagram, Wilcox diagram, Piper trilinear diagram, Gibbs diagram, Durov diagram, Chloralkaline Index, PI, SAR, Soluble sodium percentage (SSP), MH, Salinity and Alkalinity Hazard (SAH), Sodium Hazard (SH),	To evaluate of groundwater quality for suitability of irrigation purposes	Irrigation	Udham sigh Nagar, Uttarakhand
Adimalla *et al.*, 2020	pH, EC, TDS, TH, HCO_3^{-}, Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, Cl^{-}, SO_4^{2-}, NO_3^{-}, F^{-}	Primary Data Field Survey	105 groundwater samples	pH/EC/TDS meter, Ethylenediaminetetraacetic acid, Flame photometer, UV–visible spectrophotometer, Ion-selective electrode,	WQI, SAR, RSC, MH, KR, Kriging interpolation technique	To analyse overall groundwater quality and evaluate its suitability for drinking and irrigation purposes	Drinking and Irrigation	Central Telangana, India
Aher *et al.*, 2022	pH, EC, TDS, TH, Na^{+}, Ca^{2+}, Mg^{2+}, K^{+}, Cl^{-}, HCO_3^{-}, SO_4^{2-}, CO_3^{2-}, NO_3^{-}, and F^{-}	Primary Data Field Survey	33 groundwater sample	Spectrophotometric techniques	WQI, Piper trilinear diagram, Wilcox diagram, Correlation analysis	To investigate hydrogeochemical characteristics and groundwater quality	Drinking water and irrigation	Pravara River, Maharashtra, India

The Piper Diagram (Piper Plot) was employed in 38 research papers (84%) for hydro-chemical facies classification. Researchers used this graphical representation to visualize the chemical composition (major ions) of groundwater and classify water types, providing essential insights into the water's origin and rock-water interaction processes. Similarly, the Gibbs Diagram was used by 28 researchers (62%) to determine the mechanisms influencing groundwater chemistry, such as atmospheric precipitation, rock-water interaction, and evaporation-crystallization processes (Figure 2).

In terms of irrigation suitability assessment, the Sodium Adsorption Ratio (SAR) was adopted by 27 research papers (60%). This index helps predict the extent to which sodium in water will be adsorbed by the soil, affecting soil structure and permeability. Likewise, the Residual Sodium Carbonate (RSC) index was utilized in 19 studies (42%) to assess the potential precipitation of calcium and magnesium, which can increase the relative proportion of sodium and negatively impact soil quality. Another related technique, the Wilcox Diagram, was applied in 18 research papers (40%) to classify water for irrigation by plotting salinity (EC) against sodium hazard (SAR), reducing the risk of salinization and soil damage (Figure 2).

The Magnesium Hazard (MH) Index was used by 12 studies (27%) for evaluating irrigation water quality, particularly the negative effects of excess magnesium on soil structure. Additionally, the Irrigation Water Quality Index (WQI) appeared in 11 research papers (24%), representing an effort to create a simplified index specifically for agricultural water use, often combining parameters such as SAR, MH, and RSC.

Advanced statistical methods were also incorporated, although less frequently. The Multivariate Statistical Analysis technique was applied in 14 research papers (31%) to identify contamination sources, whether natural or anthropogenic, and to simplify complex datasets through methods like factor analysis and cluster analysis. Similarly, Principal Component Analysis (PCA) was used by 6 studies (13%) to reduce dimensionality, identifying a few principal components that explain most of the variance in groundwater quality data (Figure 2).

Other indices include the Permeability Index (PI), which was adopted by 14 studies (31%) for predicting the long-term suitability of water for irrigation by assessing its potential to reduce soil permeability. The Kelly's Ratio (KI) appeared in 11 research papers (24%) for evaluating sodium hazards by comparing sodium concentrations to those of calcium and magnesium. The Pollution Index of Groundwater (AIG) was used in 4 studies (9%) to assess groundwater contamination by combining pollutant concentrations into a single value.

Less commonly used graphical techniques include the Durov, Schoeller, and Chadha diagrams each applied in 3 research papers (7%) for detailed hydrochemical facies interpretation, comparison of major ion concentrations, and classification of groundwater types, respectively (Figure 2).

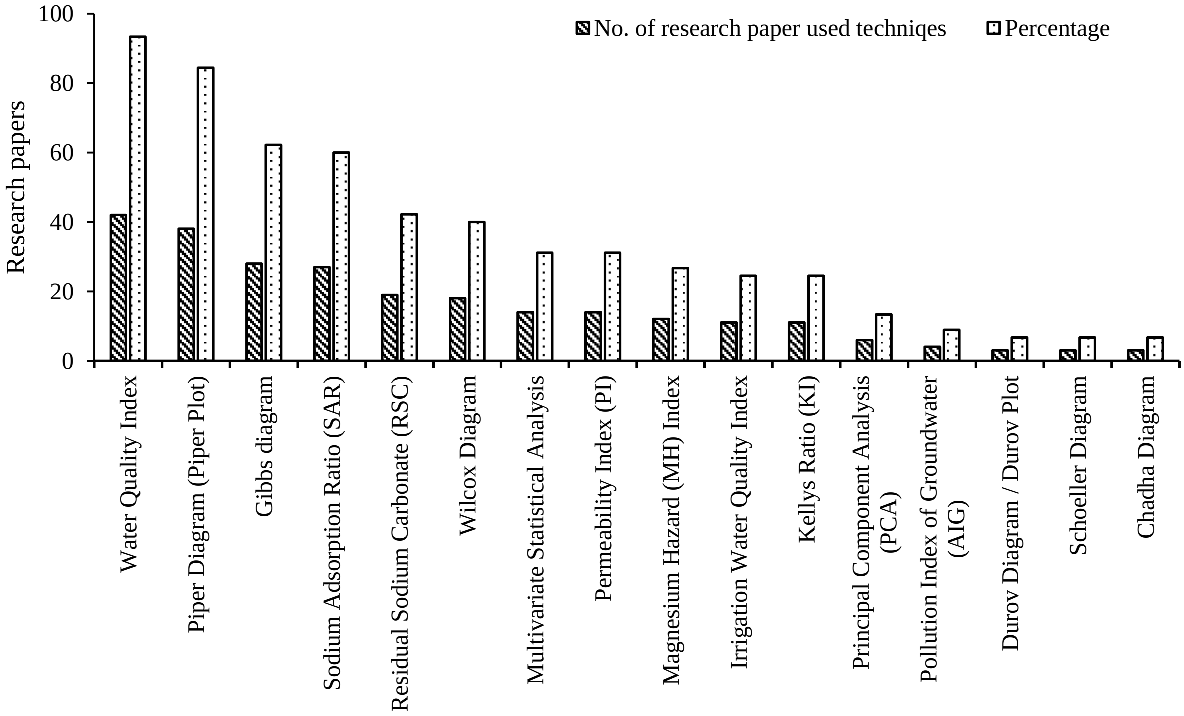

Figure 2. The usage of various techniques for water quality assessment

Overall, this review highlights those graphical techniques such as the Piper Diagram and Gibbs Diagram, along with composite indices like WQI and SAR, dominate groundwater quality assessment studies.

These methods are favored for their ability to simplify complex chemical data, communicate findings effectively, and assess water suitability for drinking and irrigation purposes, whereas advanced statistical approaches are increasingly used for source identification and multivariate analysis of groundwater quality.

4 LIMITATIONS AND RESEARCH GAPS OBSERVED IN THESE STUDIES

1. Most of the researchers have used conventional methods like WQI, SAR, MAR, SSP, RSC, PI, KI, HR, Gibbs diagrams, Piper diagram and Wilcox diagram. These techniques, though useful for simplifying complex geochemical interactions, fail in the studying dynamic groundwater processes.
2. From a human health perspective, it is important to study pollutants like heavy metals, trace elements, pesticides, etc. but these elements have been considered very rarely.
3. Geochemical modelling, PCA, CA and FA are applied in most of the groundwater studies but simulation approaches and predictive modelling are used in very few cases.
4. Data based on long term observations and seasonal variations is not commonly used; most studies are based on short term data.
5. Groundwater quality is affected by changes in rainfall pattern, land use and agriculture activities, but the impact of these factors has been studied in few research works.
6. Chloride and Nitrate contamination appears to be studied aspect of groundwater quality, but hazardous risk assessment such as carcinogenic and non-carcinogenic risks have been given very limited attention.
7. Most of the studies appear to be based on traditional laboratory analysis, with no integration of smart sensor or real-time groundwater quality monitoring approaches.
8. In current groundwater quality studies, chemical parameters are extensively used for drinking and irrigation purposes, but physical, biological and toxicological indicators seem to be ignored.
9. Most studies do not assess cumulative risk and probabilistic analysis for multiple contaminates; instead, they mainly report the concentrations of individual contaminates.
10. For studying groundwater vulnerability, the use of advance technology such as GIS, RS and satellite data appears to be very limited.
11. In WQI, each determinant factor is assigned a different weight, and variations in index calculation methods affect the comparability of groundwater studies across different regions.

5 PERSPECTIVES ON FUTURE RESEARCH

From this literature, it is evident that the use of graphical, statistical, and GIS based methods such as WQI, Piper diagram, Gibbs analysis, Wilcox diagram, Durov diagram, SAR, MAR, SSP, RSC, PI, KI and HR, along with artificial intelligence and geochemical modelling, is becoming popular. There is emphasis on determining integrated indices of chemical parameters and using GIS for accurate analysis and spatial mapping. However, while integrating statistical techniques with modern technologies such as GIS and RS, certain limitations and challenges are observed, as mentioned in the previous section. These issues may pose challenges for groundwater quality assessment. Therefore, some major needs for future research are outlined below.

1. Selected studies, mainly focused on chemical indicators, however, future research needs to adopt an integrated approach that includes physical, biological and chemical indicators to develop a framework for a comprehensive assessment of groundwater quality.
2. Future research needs to develop models related to public health safety based on results and findings from various groundwater quality studies.
3. It is necessary to develop tools that support decision making and enable integrated groundwater quality management for water resource managers and policy makers.
4. In future studies, the uncertainty in spatial predictions of groundwater quality should be checked using cross-validation and the accuracy of different interpolation techniques should be compared to identify the best interpolation techniques.
5. Developing a universal GWQI for different purposes will be challenging for future researchers. A versatile framework should be created to allow comparisons from local to regional levels (Lumb *et al*., 2011).
6. The hybrid GWQI include fuzzy or neuro-fuzzy techniques along with physicochemical, organic matter, microbiological, major anions/cations and heavy metals (Vadiati *et al*., 2016).

6 CONCLUDING REMARKS

Parameters such as major cations, anions, pH, EC, TDS, TH were frequently used and analyzed, highlighting their universal relevance in assessing groundwater quality for both drinking and irrigation purposes. For the purpose of evaluating water chemistry and hydro chemical characterization, techniques like Piper diagram, Wilcox diagram, Gibbs Diagram and correlation analysis were widely employed. Multiple parameters were integrated into a Single assessment metric and used for WOI calculation enabling a straightforward evaluation of groundwater suitability for human use. In various studies, indices such as SAR, RSC, SSP, PI, KR were widely used to assess the potential effect of salinity and sodicity in groundwater for irrigation purposes. A comprehensive assessment was conducted by integrating GIS-based spatial analysis, interpolation techniques, and statistical methods like PCA, correlation analysis ad cluster analysis to understand the spatial distribution, hydro chemical characterization, and potential health risks of assessment. The reported studies are mainly focused on chemical parameters while physical, biological toxicological and immerging pollutants are often neglected. Future research should adopt a comprehensive approach that considers all parameters. For this integrated approach data driven as well as predictive models are needed. Long term data and real time monitoring is essential, and health risk analysis should be included. Moreover, developing approach, such as GWQI, would be useful for overall assessment of water quality.

ABBREVIATIONS

AAS: Atomic Absorption Spectrophotometer; **Al:** Aluminium; **APHA**: American Public Health Association; **As^T:** Total Arsenic; **BIS:** Bureau of Indian Standards; **Br^-:** Bromide ion; **Ca^{2+}:** Calcium ion; **CAI-I/CAI-II**: Chloro-Alkaline Indices; **CBE**: Charge Balance Error; **Cl^-**: Chloride ion; **CO_3^{2-}**: Carbonate ion; **COD**: Chemical Oxygen Demand; **Cr:** Chromium; **Cu:** Copper; **CWQI**: Comprehensive Water Quality Index; **EC**: Electrical Conductivity; **EDTA**: Ethylenediaminetetraacetic Acid; **EWQI**: Entropy Water Quality Index; **F^-**: Fluoride ion; **GIS**: Geographic Information System; **HCA**: Hierarchical Cluster Analysis; **HCO_3^-**: Bicarbonate ion; **HHRA**: Human Health Risk Assessment; **HQ**: Hazard Quotient; **HRA**: Health Risk Assessment; **IBE**: Ionic Balance Error; **IC**: Ion Chromatography; **ICP-MS**: Inductively Coupled Plasma Mass Spectrometry; **ICP-OES**: Inductively Coupled Plasma Optical Emission Spectroscopy; **ISE**: Ion-Selective Electrode; **K^+**: Potassium ion; **KR (KI)**: Kelley's Ratio; **MAR**: Magnesium Adsorption Ratio; **Mg^{2+}**: Magnesium ion; **MH**: Magnesium Hazard; **Mn^T:** Total Manganese; **Na^+**: Sodium ion; **NH_4^+:** Ammonium ion; **Ni^T:** Total Nickel; **NO_2^-**: Nitrite ion; **NO_3^-**: Nitrate ion; **Pb:** Lead; **PCA**: Principal Component Analysis; **pH**: Potential of Hydrogen; **PI**: Permeability Index; **PIG**: Pollution Index of Groundwater; **PO_4^{3-}**: Phosphate ion; **RSC**: Residual Sodium Carbonate; **SAH**: Salinity and Alkalinity Hazard; **SAR**: Sodium Adsorption Ratio; **SH**: Sodium Hazard; **SI**: Saturation Index; **SO_4^{2-}**: Sulphate ion; **SP**: Sodium Percentage; **SSP**: Soluble Sodium Percentage; **TA**: Total Alkalinity; **TC^c**: Total Carbon; **TDS**: Total Dissolved Solids; **TH**: Total Hardness; **TZ^+ / TZ^-**: Total Cations / Total Anions; **USSL**: United States Salinity Laboratory Diagram; **UV–VIS**: Ultraviolet–Visible Spectrophotometer; **WHO:** World Health Organization; **WQI**: Water Quality Index; **Zn:** Zinc.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the Principal of K. V. N. Naik Shikshan Prasarak Sanstha's Arts, Commerce, and Science College, Nashik, for encouragement and support in completing this research. A portion of this manuscript forms part of the author's Ph. D. work; therefore, sincere thanks are extended to Savitribai Phule Pune University for fostering research activities. The authors also appreciate the critical and constructive comments provided by the anonymous reviewers, which greatly improved the quality of the final manuscript. We would like to express our gratitude to the Department of Geography at K.T.H.M. College for their continued support during the research. The editorial guidance and efficient handling of the paper by Dr. Pramodkumar Hire (Editor-in-Chief) and Dr. Vijay Bhagat are also sincerely acknowledged.

CONFLICT OF INTEREST

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

DATA AVAILABILITY

No datasets were generated or analyzed during the current study.

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