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Sustainable groundwater management through water quality index and geochemical insights in Valsad India

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Groundwater quality assessment is crucial for sustainable water resource management and public health protection. This study evaluated the Water Quality Index (WQI) of groundwater in the southern part of Gujarat focusing on the Valsad District. Groundwater in this region occurs in porous, unconsolidated formations and fracture formations, both under groundwater table conditions and confined aquifers. Various parameters including Nitrate (NO_3^-), pH, Calcium (Ca^{2+}), Electrical Conductivity (EC), Total Hardness (TH), Magnesium (Mg^{2+}), Total Dissolved Solids (TDS), Potassium (K^+), Sodium (Na^+), Sulphate (SO_4^{2-}), Chloride (Cl^-), Bicarbonate (HCO_3^-), Silicate (SiO_4^{4-}), and Fluoride (F^-) were analyzed to assess groundwater quality. Results indicate that most of the parameters fell within acceptable permissible limits for drinking water, except for Muli and Nanaponda villages with the parameters Cl^-, EC, and TDS exceeding the permissible limit. The WQI analysis revealed that 31.25% of water samples from different villages were found in the excellent category (WQI < 25). About 68.75% of samples from 16 villages were classified as good quality category (WQI ~ 25–50). Overall, the WQI ranged from 14.20 to 41.98, suggesting that groundwater in the Valsad district is suitable for drinking. The Piper diagram analysis of water samples collected from the field indicated unique geochemical compositions and good water. The diagram revealed that the Ca^{2+} was the predominant cation, followed by K^+, Na^+, and Mg^{2+}. Among the anions, the HCO_3^- showed the highest concentrations, followed by SO_4^{2-}, NO_3^-, and Cl^-. This dominance pattern demonstrated that the weathering of minerals significantly influenced the groundwater. This study recommends remediation for areas with reduced water quality to address geogenic and anthropogenic contamination.

Keywords *Drinking suitability, GIS, Valsad, WQI, Potentially toxic elements*

Abbreviations

WQI	Water Quality Index
EC	Electrical Conductivity
TH	Total Hardness
TDS	Total Dissolved Solids
LULC	Land Use and Land Cover
DWNQI	Drinking Water Nutritional Quality Index
GIS	Geographical Information Systems
WHO	World Health Organisation

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IDW   Inverse Distance Weighted

Water quality is a crucial environmental and public health concern in India, where both surface and groundwater resources face increasing pressures from anthropogenic activities[1]. The rapid pace of population growth, industrialization, and urban expansion has escalated the demand for groundwater, leading to overexploitation and a decline in both availability and quality[2]. The indiscriminate disposal of industrial, domestic, and agricultural waste has further exacerbated groundwater contamination, raising concerns over long-term sustainability. Several studies have employed multivariate statistical methods to assess the spatial and temporal variations in water quality across various river systems, including the Gomti[3], Asi[4], Xiangxi[5], and Kaduna rivers[6]. The evaluation of physicochemical and biological parameters has been widely used as a key indicator of water quality, emphasizing the necessity for continuous monitoring and assessment[7]. Comparative studies between India and Indonesia have highlighted the significance of bioindicator-based approaches to ensure water safety[8]. Furthermore, the impact of external factors, such as the COVID-19 lockdown, has been explored, revealing temporary improvements in water quality in several freshwater bodies during the restricted human activity period[9,10].

Among India's major rivers, the Ganges has been a focal point of extensive research due to its high pollution levels, leading to discussions on pollution mitigation strategies[11]. Investigations into emerging pollutants, such as pharmaceutical residues, have further emphasized the need for addressing contaminants affecting drinking water safety[12]. Similarly, studies assessing the Yamuna and Hindon rivers have provided insights into the water quality status of these significant water bodies in North India[13–14]. Additionally, research has examined the impact of the COVID-19 lockdown on drinking water accessibility in arsenic-affected regions like the Ganges River basin, highlighting challenges in maintaining sustainable water resources[15].

The WQI has been widely used as a standardized tool for evaluating and communicating water quality status in various parts of the world, including India[16]. It provides a mathematical framework for assessing multiple water quality parameters, simplifying the interpretation of complex datasets[17,18]. WQI applications in India have been instrumental in assessing water quality across diverse regions, including Tumkur Taluk (Karnataka)[19], Yercaud Taluk (Tamil Nadu)[20], Vishwamitri River (Gujarat)[21], Kot Dam (Rajasthan)[22], and Kolong River (Assam)[23]. The formulation of WQI in India is largely guided by national water quality standards established by organizations such as the Bureau of Indian Standards (BIS), ensuring compliance with regulatory benchmarks[24,25]. Long-term studies, such as the decade-long assessment of the Yamuna River (2000–2009), have demonstrated the effectiveness of WQI in monitoring changes in water quality over time[8]. Additionally, comparative studies between India and other countries, such as Indonesia, have highlighted differences in regulatory frameworks and water quality assessment methodologies, underscoring the need for region-specific evaluation techniques[26]. The studies reviewed highlight critical concerns such as nitrate contamination, microplastic infiltration, and toxic metal accumulation, which pose varying degrees of health risks, particularly for vulnerable populations such as infants[27–29]. Analytical approaches, including hydrogeochemical characterization, multivariate statistical techniques, and pollution indices, indicate that while anthropogenic activities contribute to contamination, natural processes such as silicate weathering, seawater intrusion, and mineral dissolution also play a significant role[30–32]. The Drinking Water Nutritional Quality Index (DWNQI) assessed the nutritional quality of drinking water alongside its contamination levels[31]. Studies indicate that while most parameters fall within WHO guidelines, concerns persist regarding potentially toxic elements, nitrates, fluoride, and organic pollutants, which can pose health risks, particularly for vulnerable populations. Various water quality indices, including the Heavy Metal Evaluation Index (HEI), Drinking Water Quality Index (WQI), and hazard quotients, were applied to assess contamination levels and health risks[33,34]. Geochemical and statistical analyses, such as Piper's diagram, Gibb's plot, principal component analysis (PCA), and cluster analysis, revealed that both natural processes (rock weathering, silicate dissolution) and anthropogenic activities (agriculture, sewage discharge) influence water quality[34–36]. The assessment and monitoring of groundwater quality using Geographic Information System (GIS) techniques have gained significant attention in recent years[37]. The integration of GIS with remote sensing technologies provides a systematic and cost-effective approach to managing water resources by transforming large datasets into spatially distributed maps that reveal trends, relationships, and sources of contamination[38]. The use of GIS-based statistical models has proven particularly effective in urban settings, where groundwater quality is increasingly impacted by industrial and domestic activities[39]. Additionally, researchers have developed GIS-based tools such as the Groundwater Quality Assessment Tool (GWQAT), designed to facilitate efficient groundwater resource management[40].

The application of GIS techniques in groundwater quality studies enables a comprehensive understanding of spatial variations in water quality across different regions[41]. Remote sensing and GIS-based groundwater quality index models have further demonstrated the influence of land use and land cover (LULC) changes on groundwater contamination[42]. In the present study, groundwater quality is assessed through the physico-chemical analysis of thirty-two groundwater samples collected from open wells and hand pumps. The WQI approach is employed to evaluate these parameters, comparing them against the international drinking water standards established by the World Health Organization (WHO). The primary objectives of this study are: (i) To analyze the spatial distribution of various groundwater quality parameters in Valsad District, South Gujarat. (ii) To determine the WQI based on field datasets, providing a comprehensive assessment of groundwater quality. By utilizing WQI, this study contributes to the broader discourse on water quality assessment in India, aiding stakeholders, policymakers, and the general public in making informed decisions regarding water resource management and conservation.

Study area

Valsad, located in southern Gujarat of India with latitudes 20.63°N to 20.67°N and longitudes 72.90°E to 72.97°E, is a region of significant agricultural and industrial activities, characterized by a tropical monsoon climate with hot and humid summers pronounced monsoon season and mild winters. The district's topography is predominantly flat with gentle undulations and consisting fertile alluvial plains that support diverse land use patterns including extensive agriculture, forested tracts and industrial developments. The hydrogeology of Valsad is influenced by the alluvial deposits of Tapi river, consisting of unconfined and confined aquifers of sands, gravel, and clays, which exhibit seasonal fluctuations due to monsoonal recharge and extensive groundwater extraction. Groundwater serves as primary source for irrigation, domestic supply, and industrial use, yet increasing water demand and contamination from industrial effluents and agricultural runoff pose significant challenges to sustainable water management. Given these pressures, aquifer system modeling is crucial for understanding groundwater dynamics, predicting future trends, and informing effective resource management strategies. This study aims to integrate hydrogeological, geospatial, and water quality data to develop a groundwater flow model for Valsad, facilitating sustainable aquifer management and mitigating depletion and contamination risks.

Materials and methodology

This study employs an integrated approach to assess the water quality of Valsad District, Gujarat, India. Field data collection, laboratory analysis, GIS-based spatial mapping, and statistical techniques were utilized to evaluate hydrogeological characteristics and identify regional water quality challenges. Groundwater samples were systematically collected from representative locations and analyzed for physicochemical parameters to determine contamination levels and seasonal variations. GIS tools facilitated the spatial visualization of water quality distribution, while statistical methods helped identify correlations and trends. The comprehensive analysis provides critical insights into the region's water quality dynamics, supporting data-driven decision-making for sustainable groundwater management and environmental conservation efforts in Valsad and similar hydrogeological settings.

Sample collection

Field surveys were conducted to collect groundwater samples using the catch-and-grab method from predetermined locations within the study area. The sampling sites were selected based on hydrogeological characteristics, land use patterns, and potential sources of contamination to ensure a representative assessment of groundwater quality. A total of 32 samples were collected from 16 villages between February 2020 to January 2021, with each village contributing two samples. Groundwater samples were obtained from tube wells, hand pumps, and traditional open wells to capture the variability in groundwater sources. To preserve sample integrity, all collected samples were stored in high-quality polypropylene bottles and maintained at a controlled temperature of 4 °C to prevent chemical or biological alterations before analysis. The precise locations of the sampling sites were mapped using ArcGIS 10.8 (Fig. 1), enabling a detailed spatial representation of groundwater quality distribution. This geospatial analysis was instrumental in identifying spatial variability and potential contamination sources within the region.

Hydro-geochemical analysis

In the laboratory, the collected field samples were prefiltered before analysis to ensure accuracy and consistency in results. To obtain reliable measurements of pH, electrical conductivity, and temperature, hand pumps were operated for a sufficient duration before sample collection. High-quality chemicals, specifically analytical grade from Merck Darmstadt, Germany, were utilized throughout the analysis, which was conducted following the standard procedures prescribed by APHA (2012). The Nitrate (NO_3^-), Fluoride (F^-), and Sulphate (SO_4^{2-}) ion concentrations were precisely measured using a spectrophotometer while Chloride (Cl^-) levels were quantified using the Mohr's titration method with Silver Nitrate ($AgNO_3$). The hardness, alkalinity, and concentrations of Magnesium (Mg^{2+}), Calcium (Ca^{2+}), Sodium (Na^+), and Potassium (K^+) ions were assessed through titration and flame photometry. The pH and Total Dissolved Solids (TDS) values were measured using a digital multi-parameter kit. To ensure the accuracy and reliability of the hydrogeochemical data, the ion balance error was carefully calculated and maintained within ± 5% for all samples.

Water quality index

The Water Quality Index (WQI) is a comprehensive tool used to evaluate groundwater suitability for consumption by integrating multiple water quality parameters into a single numerical value. This index simplifies complex hydrochemical data, providing an overall assessment of water quality. Key parameters considered in the WQI calculation include Total Dissolved Solids (TDS), pH, Total Hardness, and concentrations of major contaminants such as Nitrates (NO_3^-), Lead (Pb), and Arsenic (As). Each parameter is assigned a weight based on its relative significance to human health, and the final index value is derived using standardized equations. In this study, the WQIs were calculated using 14 parameters measured at each site. The initial step in WQI estimation involved determining the relative weight of each parameter, which was crucial for accurately reflecting the importance of different water quality variables as described in Eq. (1)[46][47]

$$W_i = \frac{w_i}{\sum_{i=1}^{n} w_i} \qquad (1)$$

where w_i denotes the weight given to each groundwater parameter, while W_i denotes the relative weight of those parameters. The variable n signifies the total number of groundwater parameters being considered in the analysis.
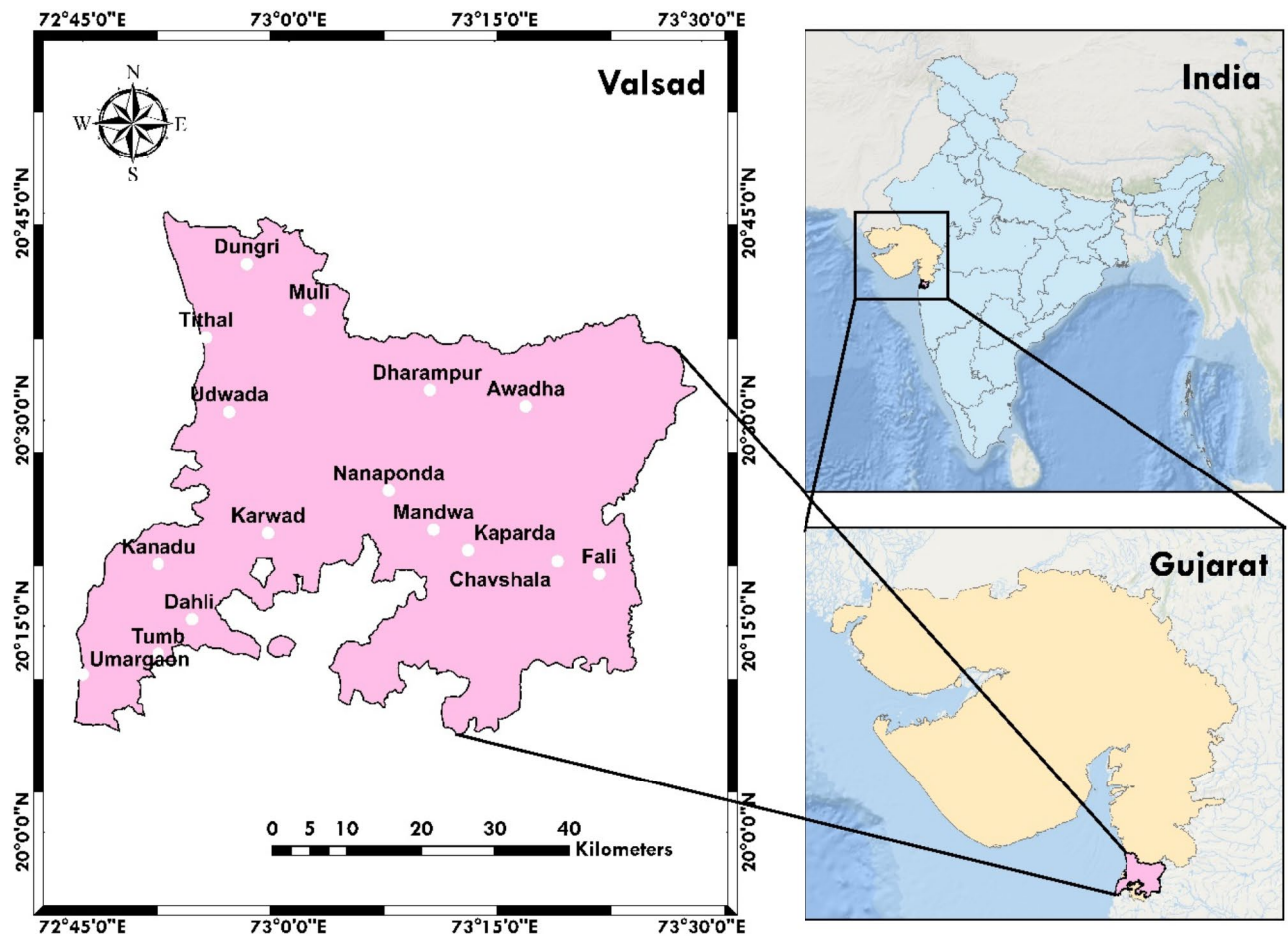
Fig. 1. Sampling Point location in Valsad District, located in southern Gujarat of India,

The following step involved calculating the quality rating scale, denoted as q_i, for each parameter. This calculation was performed using Eq. (2)[46][47]. This process allows us to quantitatively assess the involvement of each parameter in the overall groundwater quality, ensuring a comprehensive evaluation based on the predefined weights and ratings.

$$q_i = [\frac{V_i - V_{id}}{S_i - V_{id}}] \times 100 \qquad (2)$$

where q_i represents the quality rating for the ith water parameter, V_i is the actual measured value of the ith parameter at the sampling location. Meanwhile, S_i is the typical permissible value for the ith parameter as defined by the WHO and V_{id} represents the perfect value of the ith parameter in clean water. The formula for calculating the WQI can be expressed as given in Eq. (3).

$$WQI = \sum_{i=1}^{n} W_i \times q_i \qquad (3)$$

Spatial variation mapping

Spatial distribution maps of groundwater quality parameters were generated using Geographic Information System (GIS) software, ArcGIS 10.8. The inverse distance weighted (IDW) interpolation method was employed to map spatial variations in groundwater quality across the study area. IDW is a widely used deterministic spatial interpolation technique that assigns weights to data points based on the inverse of their distance from the estimation location, ensuring that nearer points exert a greater influence on predicted values[48–51]. This deterministic method assigns weights to many parameters at each sampling site based on the inverse of their distance from the point being estimated, ensuring that nearer points have a greater influence on the predicted value. This approach allows for an accurate representation of spatial variations in groundwater quality by delineating different zones on the spatial distribution map. Each zone indicates the groundwater quality in terms of acceptable/desirable and permissible limits, as per the BIS standards (2012, 2015) and the guidelines

suggested by the WHO (2017). The resulting spatial maps provide a visual representation of groundwater quality variations, aiding in water resource management and the identification of contamination-prone areas.

The hydrogeological framework of Valsad comprises alluvial aquifers along river valleys and fractured rock aquifers within sedimentary formations. Groundwater serves as the primary water source for domestic, agricultural, and industrial purposes with Bhogavo river and its tributaries serving as significant groundwater recharge zones, replenishing aquifers in monsoon season. However, Natural and anthropogenic contaminants, such as Fluoride, Nitrate, and salinity, affect the groundwater quality which poses significant threats to human health and water security. Therefore, a systematic approach integrating field data, hydrogeochemical analysis, and GIS-based spatial assessment was adopted to evaluate groundwater quality in the region. The overall workflow for groundwater quality assessment for the Valsad region is illustrated in Fig. 2.

Results and discussion

The groundwater quality assessment in this study was based on a comprehensive analysis of key physicochemical parameters, each selected for its relevance to human health and its ability to indicate potential contamination. The measured parameters include pH, Total Dissolved Solids (TDS), Total Hardness (TH), major cations (Ca^{2+}, Mg^{2+}, Na^+, K^+), major anions (Cl^-, SO_4^{2-}, NO_3^-, F^-), and potentially toxic elements such as Lead (Pb) and Arsenic (As). These parameters provide critical insights into groundwater chemistry, identifying spatial variations and potential contamination sources.

Groundwater quality assessment

In the current research, groundwater quality maps were generated using GIS Environment (ArcGIS 10.8) to provide a detailed spatial representation of the groundwater quality across the Valsad district (Figs. 3, 4 and 5). These maps visually depict variations in key water quality parameters, facilitating the identification of contamination hotspots and spatial trends. The assessment was conducted by referencing the drinking water standards established by the Bureau of Indian Standards (BIS 2012, 2015) and the guidelines recommended by the World Health Organization (WHO 2017). These benchmarks enabled a comparative evaluation of the measured groundwater parameters, ensuring a systematic assessment of water suitability for consumption. The spatial analysis helped in pinpointing areas where groundwater quality deviates from permissible limits, highlighting potential health risks and guiding future water resource management strategies.

Bicarbonate (HCO_3^-)

In the study area, Bicarbonate concentrations ranged from 63.24 to 487.90 mg/L, and were within the permissible limit of 600 mg/L as prescribed by drinking water standards. These concentrations primarily result from the interaction of infiltrating water with carbonate-rich rocks, such as limestone and dolomite. During
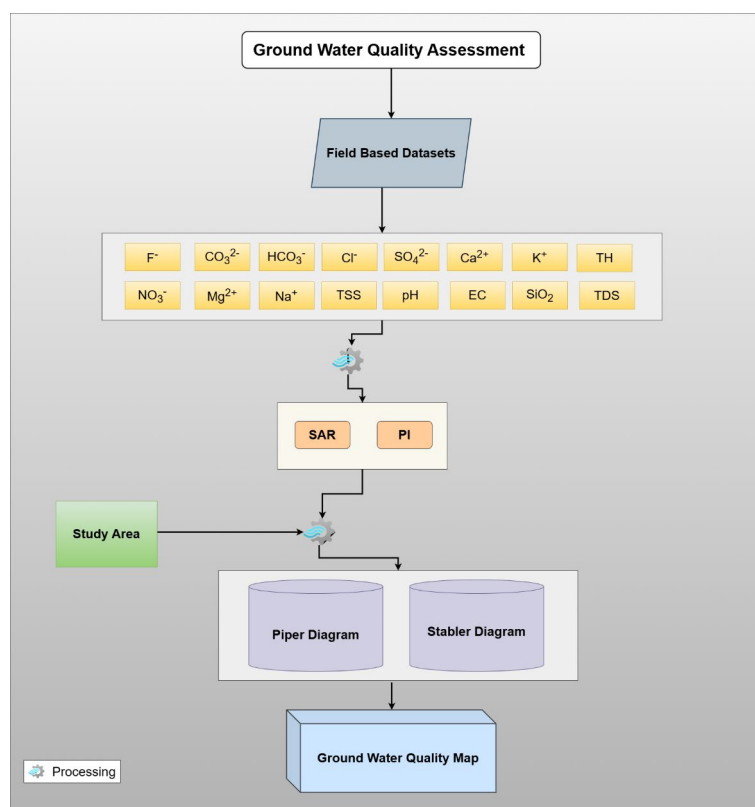

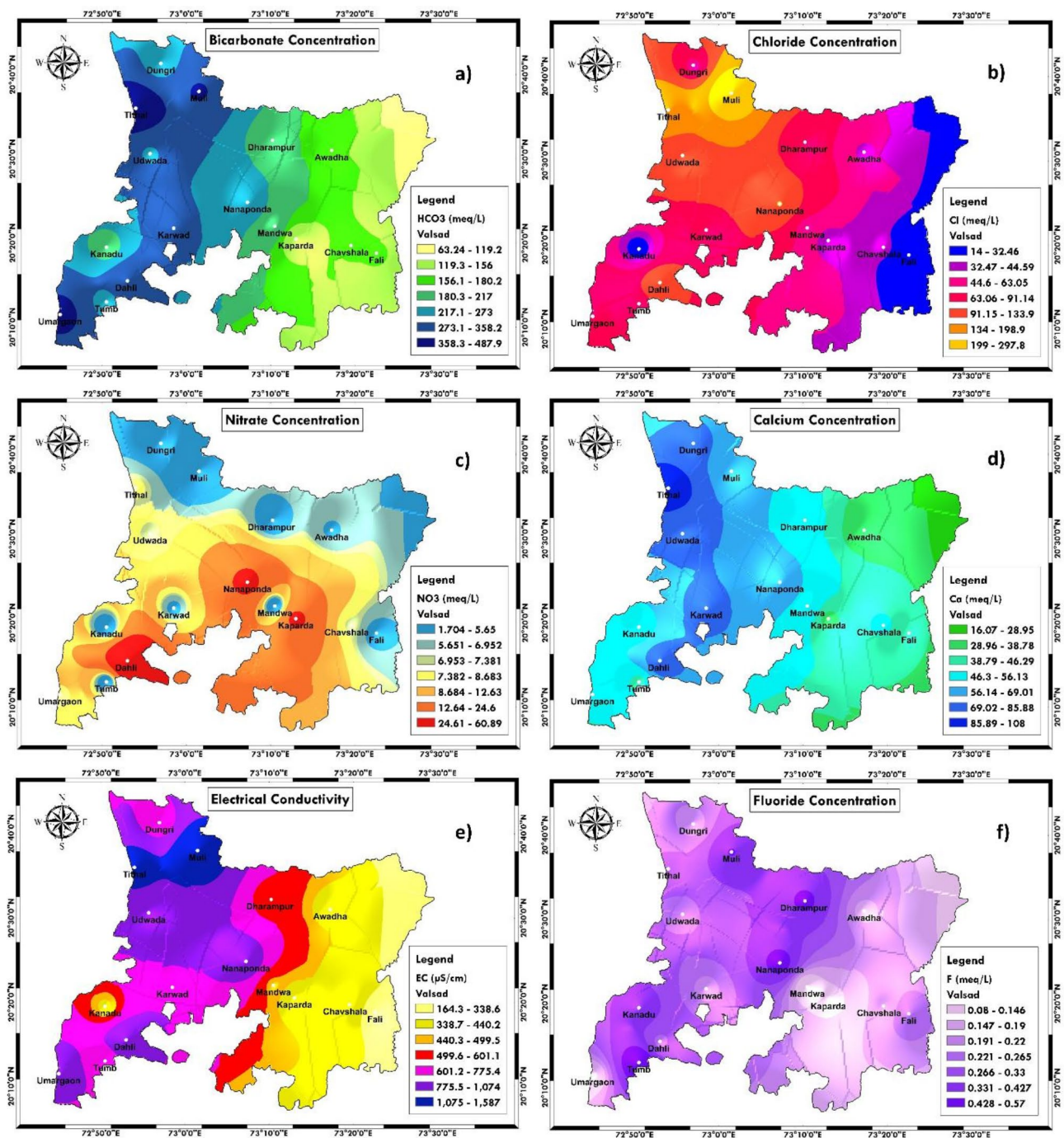**Fig. 2.** Workflow adopted for groundwater quality assessment.

Fig. 3. Spatial Distribution maps of (**a**) Bicarbonate concentration, (**b**) Chloride concentration, (**c**) Nitrate concentration, (**d**) Calcium concentration, (**e**) Electrical Conductivity and (**f**) Fluoride concentration.

infiltration, water absorbs carbon dioxide (CO_2) from both the atmosphere and the soil, where microbial activity and root respiration contribute to elevated CO_2 levels. This leads to the formation of carbonic acid (H_2CO_3), which subsequently reacts with carbonate minerals, dissolving them and releasing Bicarbonate ions into the groundwater. The presence of high Bicarbonate concentrations in western Valsad contributes to the alkalinity of groundwater by neutralizing acidic components, thereby increasing the pH and creating an alkaline environment. This process is particularly prominent in regions with abundant carbonate rock formations, where the buffering capacity of Bicarbonate ions plays a crucial role in maintaining groundwater chemistry.

Chloride (Cl⁻)
The concentration of Chloride ions (Cl⁻) in groundwater across the study area ranged from 14.0 mg/L to 297.8 mg/L. Notably, in the northern part of the region, particularly in Muli village, Chloride levels exceeded
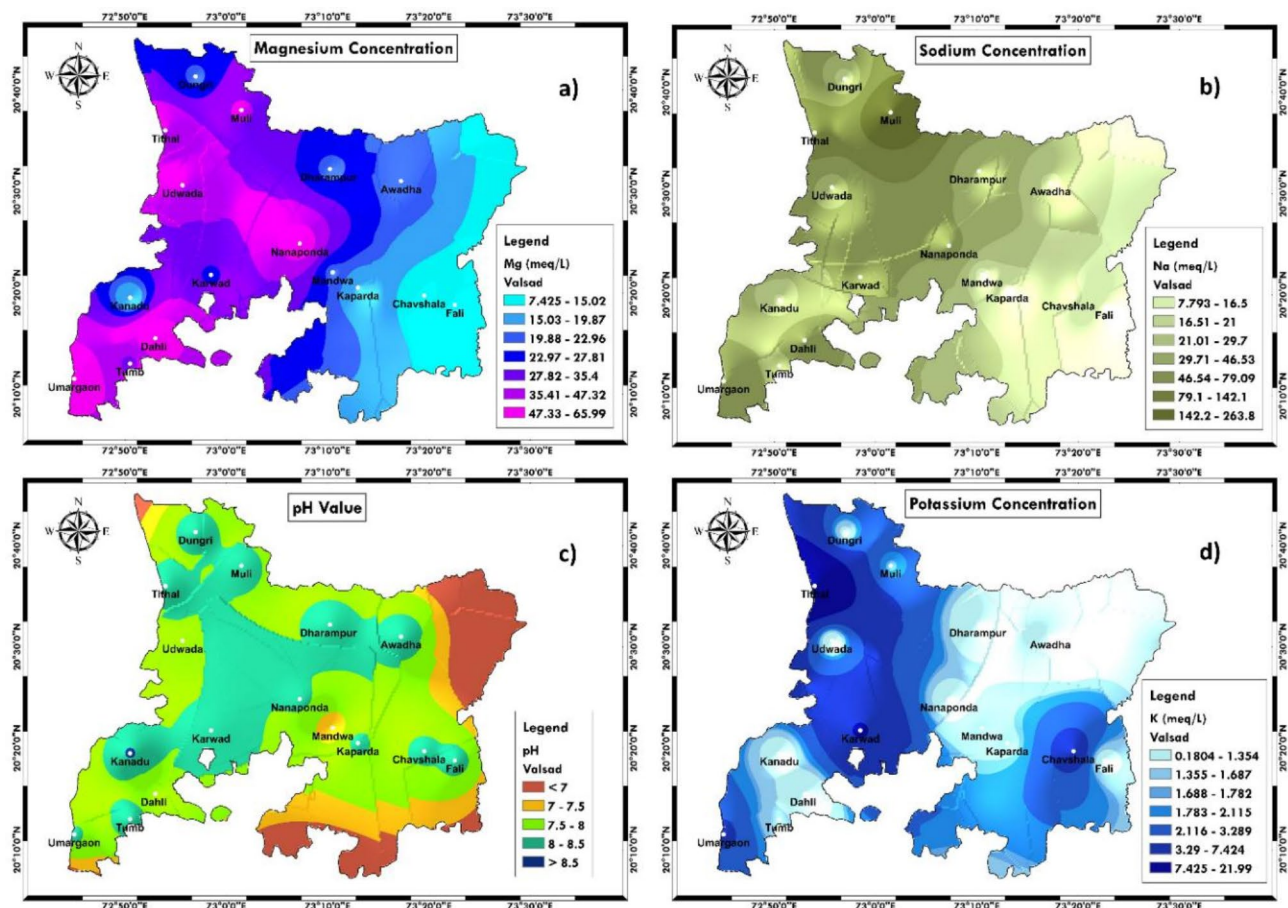
Fig. 4. Spatial Distribution map of (**a**) Magnesium concentration, (**b**) Sodium concentration, (**c**) pH Value, (**d**) Potassium concentration.

the permissible limit of 250 mg/L as prescribed by BIS (2012) and WHO (2017). The increase in concentrations of Chloride in these areas may be attributed to natural processes such as rock-water interactions, as well as anthropogenic sources, including agricultural runoff, industrial discharge, and improper wastewater disposal. Excessive Chloride levels in drinking water pose significant health risks, including hypertension, cardiovascular complications, and gastrointestinal discomfort, particularly in individuals with existing health conditions[52]. Additionally, high Chloride concentrations can alter the taste of water and contribute to increased corrosivity, potentially affecting plumbing systems and infrastructure.

Nitrate (NO_3^-)
Nitrate is a naturally occurring ion that plays a crucial part in the nitrogen cycle. Despite its importance in the environment, the presence of nitrate ions in groundwater is a significant concern due to their potential health impacts. One of the most critical concerns is methemoglobinemia, or blue baby syndrome, which primarily affects infants under six months old. This condition occurs when ingested Nitrate is converted into Nitrite (NO_2^-) in the body, interfering with the blood's ability to carry oxygen[52]. The allowable limit for concentration of Nitrate in drinking water is 45 mg/L which leads to severe health hazards[37]. In the study area, the nitrate concentration levels in groundwater ranged from 1.70 to 60.89 mg/L Dahil and, Nanaponda villages exhibited higher values of nitrate concentration. Elevated Nitrate levels in drinking water are linked to gastric ulcers, cancer risks, and adverse reproductive outcomes, particularly affecting vulnerable groups such as infants, pregnant women, and individuals with pre-existing health conditions[53,54]. Prolonged consumption of nitrate-contaminated water has also been associated with hypertension and birth defects, emphasizing the need for regular groundwater monitoring and remediation strategies to ensure safe drinking water in affected areas.

Calcium (Ca^{2+})
Calcium breaches the groundwater system through the leaching of calcium-bearing minerals calcite ($CaCO_3$), gypsum ($CaSO_4 \cdot 2\ H_2O$), and fluorite (CaF_2). These minerals undergo chemical weathering and dissolution, releasing calcium ions into the groundwater system. In the study area, Calcium ion concentration in groundwater ranged from 16.07 mg/L to 108 mg/L, well within the permissible limit for drinking water of 200 mg/L. This relatively low concentration of Ca^{2+} suggested moderate chemical weathering of these minerals. Additionally, the dissolution of fluorite (CaF_2) likely contributed to the calcium content. This process underscores the
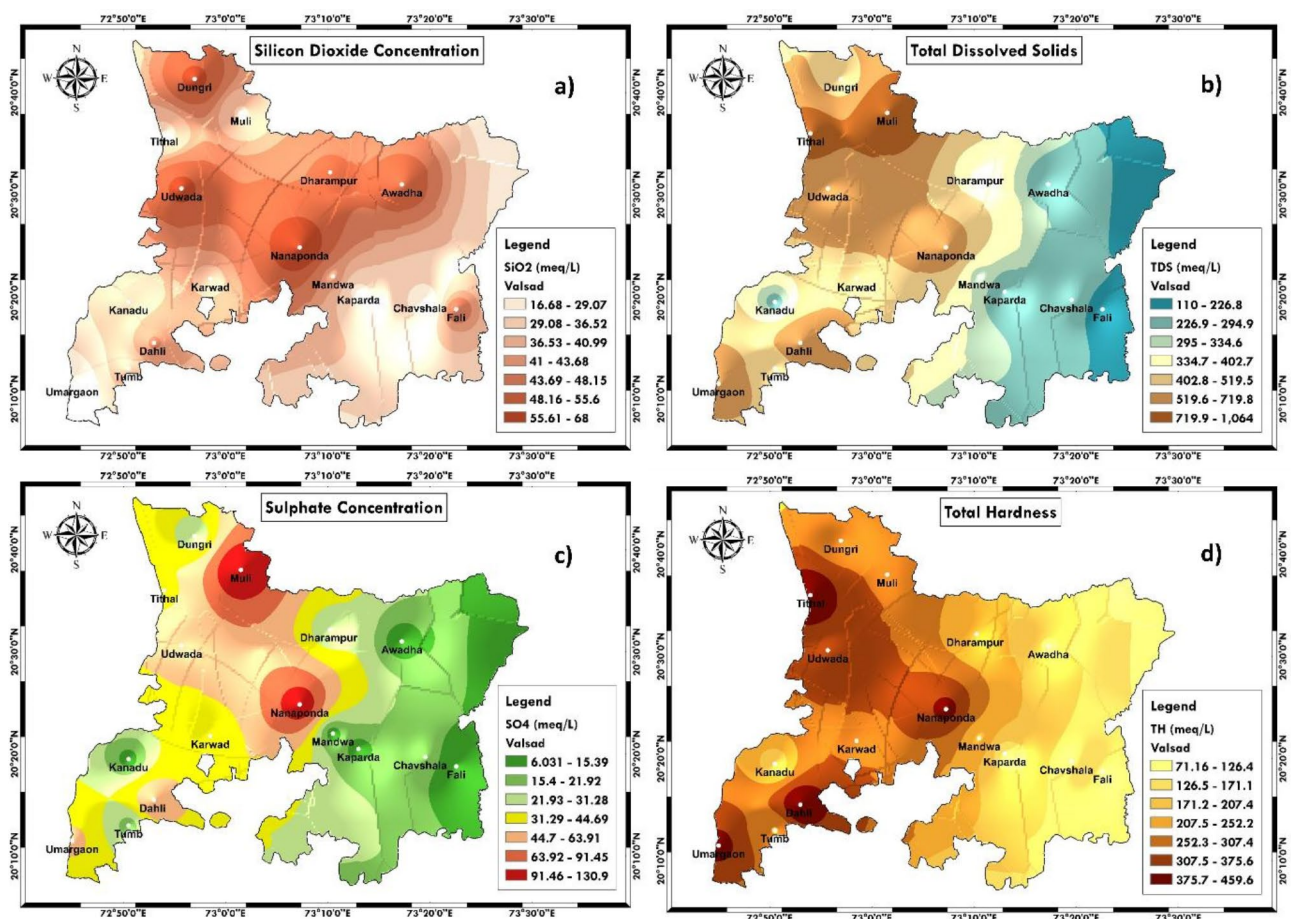
Fig. 5. Spatial Distribution map of (**a**) Silicon Dioxide concentration, (**b**) Total dissolved solids, (**c**) Sulphate concentration, (**d**) Total Hardness.

interconnected nature of groundwater geochemistry, where the dissolution of one mineral can influence multiple water quality parameters. Understanding these interactions is essential for assessing water suitability and predicting long-term hydrogeochemical changes in the region.

Electrical conductivity (EC)

The EC serves as a key indicator of a solution's ability to conduct electrical current, which is directly influenced by the concentration of dissolved ions. Higher levels of dissolved solids result in greater conductivity, making EC a useful parameter for assessing groundwater quality. The preferred threshold for drinking water is 750 μS/cm (BIS, 2012), beyond which water may indicate excessive mineralization or contamination. In this study, EC values varied from 164.3 μS/cm to 1587 μS/cm, with notably high readings in Muli and Tithal villages. These locations, situated near densely urbanized areas, exhibited elevated conductivity, suggesting sewage infiltration into the groundwater system. Such contamination can arise from leaking sewer lines, unregulated wastewater disposal, or surface runoff, highlighting the urgent need for better urban water management practices.

Fluoride (F⁻)

Fluoride in groundwater is primarily of geogenic sources that naturally occur in the crust of the Earth. In the halogen group, Fluoride is the lightest member and one of the most chemically reactive elements[55] and its presence in groundwater can vary significantly, appearing either in trace amounts or in high concentrations as a major ion. The Fluoride ion content in groundwater largely results from the contact between groundwater and fluoride-bearing rock or minerals[55]. The study area, characterized by granite and granitic gneiss formations, contains fluorite (CaF_2) as an accessory mineral, contributing to Fluoride dissolution in groundwater[56]. In this research, Fluoride concentrations ranged from 0.08 mg/L to 0.57 mg/L, indicating spatial variability based on mineral composition, rock-water interactions, and hydrogeochemical conditions. These values remain well within the permissible limit of 1.5 mg/L (BIS, 2012; WHO, 2017), suggesting no immediate health concerns. However, given the potential for long-term accumulation and geochemical evolution, continued monitoring of Fluoride levels is essential to prevent future risks of dental and skeletal fluorosis in the region.

Magnesium (Mg^{2+})

Water hardness is a concentration of hardness-causing minerals such as Calcium (Ca^{2+}) and Magnesium (Mg^{2+}) ions and a crucial parameter for assessing water quality. In the study area, measured total hardness ranged from 7.42 mg/L to 65.99 mg/L, which is well below the permissible drinking water limit of 100 mg/L (BIS, 2012). This indicates that groundwater in the region falls within the soft water category, making it suitable for domestic and industrial use. Soft water is generally preferred for household applications as it minimizes scale formation in pipes, boilers, and household appliances, reducing maintenance costs.

Sodium (Na$^+$)

Sodium (Na$^+$), a highly reactive alkali metal, is commonly found in groundwater due to the dissolution of Sodium-bearing minerals and soil salts. In the study area, Sodium concentrations ranged from 7.79 mg/L to 263.8 mg/L, reflecting spatial variability influenced by mineral weathering, evaporation, and cation exchange processes. High concentrations of sodium ions (Na$^+$) in groundwater indicated the weathering of rock-forming minerals such as silicate minerals (particularly alkali feldspars). This process involves the breakdown of minerals, releasing Sodium ions into the water. Additionally, the dissolution of soil salts due to evaporation can also contribute to elevated sodium levels. Within aquifers, the mechanism of cation exchange can further increase sodium concentrations. This process involves the exchange of sodium ions with other cations on the surfaces of minerals (clay) and other aquifer materials. As sodium ions replace these cations, their concentration in the groundwater rises[57].

pH value

Hydrogen ion concentration, expressed as pH, serves as a key indicator of groundwater quality, influencing interactions, solubility of minerals, and potential contamination levels within an aquifer system. The pH reflects the alkalinity or acidity of water, ranging from 0 to 14, with a value of 7 representing neutrality. This measurement is intricately linked with other chemical compounds available in the water. In this study, the pH of groundwater varied between 6.50 and 8.61, with an average of 7.4, aligning well within the acceptable drinking water range of 6.5 to 8.5 (BIS, 2012; WHO, 2017). Spatially, lower pH values (acidic conditions) were recorded in the easternmost and southernmost parts of the study area, whereas Kanadu Village exhibited higher pH values (alkaline conditions). These variations can be attributed to natural geochemical processes, including carbonate equilibrium, rock-water interactions, and anthropogenic influences such as agricultural runoff and industrial effluents. Maintaining groundwater pH within the recommended limits is essential for potability and infrastructure longevity, as excessive acidity can corrode pipelines, while high alkalinity may affect the solubility and bioavailability of essential nutrients.

Potassium (K$^+$)

Potassium (K$^+$) is a naturally occurring element found in various rock-forming minerals, including feldspars, micas, and clay minerals. Due to its relatively high solubility, potassium is gradually released into groundwater through the processes of weathering and dissolution. The breakdown of these potassium-bearing minerals contributes to the accumulation of potassium ions in groundwater over time. In this study, potassium concentrations ranged from 0.18 mg/L to 21.99 mg/L, indicating spatial variability in its distribution across the study area. Notably, the western region exhibited higher potassium levels compared to the north-eastern part. This difference can be attributed to variations in lithology, mineral composition, and localized geochemical conditions. Additionally, anthropogenic influences such as fertilizer application in agricultural areas and industrial discharge may further contribute to elevated potassium levels in certain locations.

Total dissolved solids (TDS)

TDS refers to the total concentration of dissolved minerals and salts in water, which include magnesium, potassium, sodium, calcium, carbonate, bicarbonate, sulphate, and chloride. TDS is measured by evaporating a water sample to dryness and weighing the remaining solid residue. The presence of these dissolved constituents is influenced by natural geological processes, such as rock weathering and mineral dissolution, as well as anthropogenic factors, including agricultural runoff, industrial discharge, and sewage infiltration. In this study, TDS levels ranged from 110 mg/L to 1064 mg/L, demonstrating significant spatial variability across the study area. As per the Bureau of Indian Standards (BIS 2012, 2015), the acceptable limit for TDS in drinking water is 500 mg/L, beyond which water may become unsuitable for human consumption without treatment. Notably, the northern part of the study area exhibited the highest TDS values, indicating potential sources of contamination or increased mineral dissolution in this region. Excessive TDS in groundwater can lead to poor taste, scaling in pipelines, and adverse health effects when consumed over extended periods.

Sulphate (SO$_4^{2-}$)

Sulphate in groundwater primarily originates from the dissolution and leaching of sulphur-bearing minerals such as iron sulfides (pyrite) and gypsum (CaSO$_4$·2 H$_2$O), which are naturally present in geological formations. Weathering, oxidation, and anthropogenic activities such as agricultural runoff and industrial discharges can further contribute to sulphate concentrations in groundwater. In this study, sulphate concentrations ranged from 6.03 mg/L to 130.9 mg/L, remaining well within the acceptable limit of 200 mg/L, as per the Bureau of Indian Standards (BIS 2012, 2015). This indicates that sulphate levels in the study area do not pose a significant threat to water quality. However, continuous monitoring is necessary, as excessive Sulphate concentrations can lead to laxative effects, corrosion of pipelines, and undesirable taste in drinking water.

Total hardness (TH)

Total Hardness (TH) in groundwater is primarily attributed to the concentration of dissolved Calcium (Ca^{2+}) and Magnesium (Mg^{2+}) ions, which originate from the weathering and dissolution of carbonate and silicate minerals present in rock and soil formations. As groundwater percolates through these formations, it absorbs these naturally occurring minerals, leading to variations in water hardness. In this study, TH values ranged from 71.16 mg/L to 459.6 mg/L, remaining well within the permissible limit of 600 mg/L, as prescribed by BIS (2012, 2015). Although these values indicate that the groundwater is suitable for consumption, prolonged exposure to elevated TH levels may have adverse health effects, including an increased risk of kidney stones, cardiovascular issues, and digestive discomfort. The spatial distribution of TH across the study area suggests that regions with higher hardness levels correspond to areas with carbonate-rich geological formations.

Water quality index

The WQI results of groundwater from different villages in Valsad District suggested that around 31.25% of the collected field data were found in the excellent range of water quality (WQI < 25). In the remaining data about 68.75% were in the category of good quality (WQI = 25–50) and none of the villages were identified in the categories of poor (WQI = 51–75), very poor (WQI = 76–100), and unsuitable (WQI > 100) as shown in Fig. 6. However, the use of the arithmetic mean in WQI calculation has certain limitations. It assumes equal weight for all water quality parameters, which may not accurately reflect the relative importance of different parameters in influencing water quality or public health. Additionally, the Arithmetic Mean does not account for extreme values or outliers, which could skew the overall WQI, potentially underestimating the risk in areas where specific contaminants exceed safe thresholds. This simplification may lead to less reliable assessments, particularly in regions where water quality is highly variable or influenced by localized pollution sources. To improve accuracy, alternative approaches such as Weighted Arithmetic WQI or PCA are emerging, allowing for a more precise evaluation by assigning appropriate weightage to critical parameters based on their health impacts.

Water quality assessment

The Piper diagram analysis of water samples collected from the field indicated unique geochemical compositions and water types. The analyzed major ions were evenly distributed and plotted on a Hill-Piper Trilinear diagram as illustrated in Fig. 7. The diagram, comprising two triangles at the base and a diamond shape at the top, represents the key cations and anions that influence the characteristics of the groundwater[58,59]. The Piper diagram classified
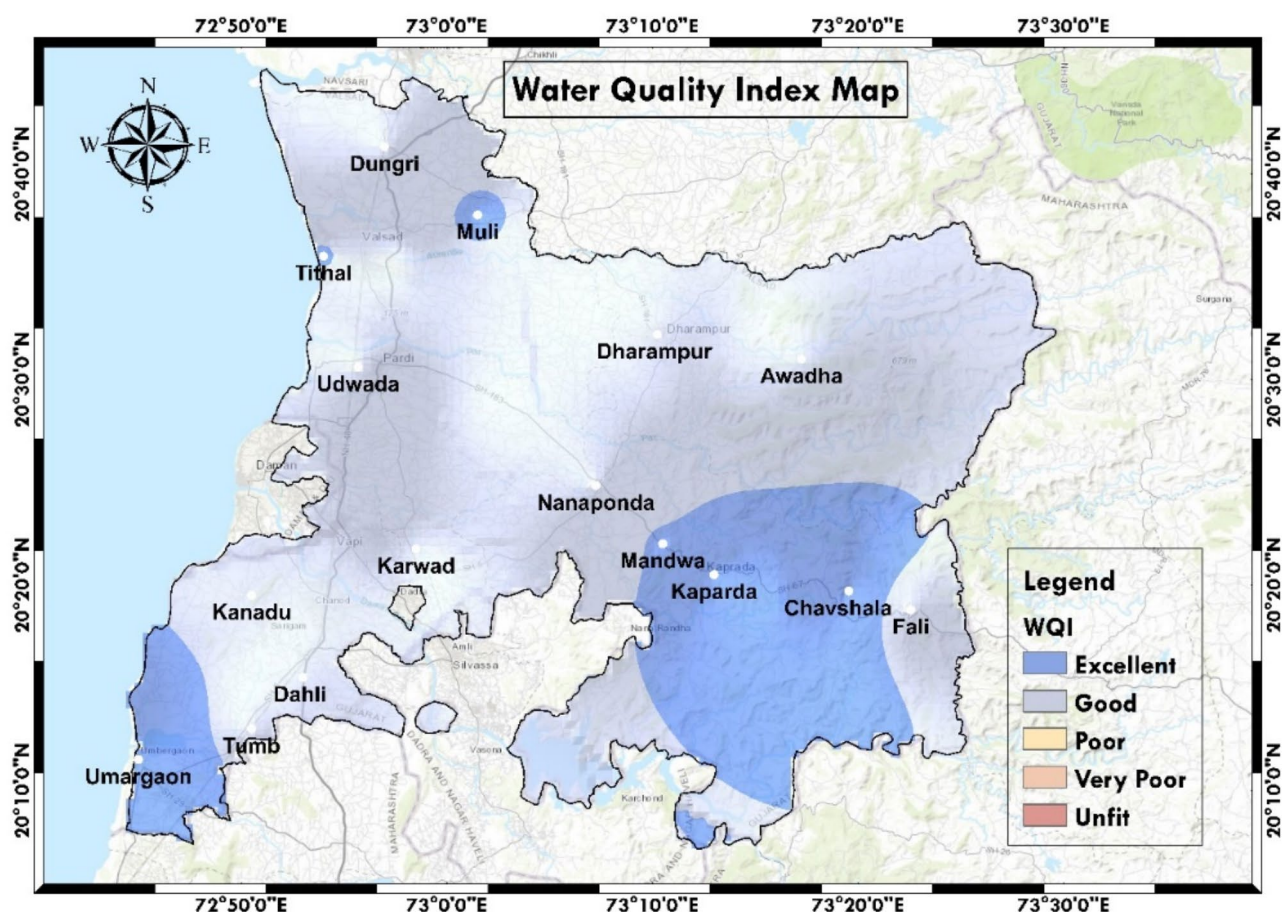

Fig. 6. WQI results of groundwater from all studied 16 villages in Valsad district.

the groundwater into six categories: Ca^{2+} type, Na^+-Cl^- type, mixed Ca^{2+}-Mg^{2+}-Cl^- type, Ca^{2+}-Na^+ type, Na^+ type, and Ca^{2+}-Cl^- type. A thorough evaluation of the Piper diagram revealed that 6.25% of the samples were categorized as Na^+-Cl^- type, another 6.25% as mixed Ca^{2+}-Mg^{2+}-Cl^- type, and 87.5% as Ca^{2+}-HCO_3^- type. None of the samples fell into the mixed Ca^{2+}-Na^+-HCO_3^-, Na^+-HCO_3^-, or Ca^{2+}-Cl^- types. The analysis highlighted that most samples belonged to the Ca^{2+}-HCO_3^- category, indicating a dominance of bicarbonates and calcium-rich minerals. The hydrochemical assessment showed that the major cations were ranked in decreasing order as Ca^{2+} > Na^+ > Mg^{2+}, while the anions followed the sequence HCO_3^{--} > SO_4^{2-} > Cl^-. These findings suggested that the groundwater's ionic composition was largely controlled by the presence of calcium and bicarbonate, primarily resulting from the weathering of calcite and dolomite minerals, along with ion exchange processes.

The Stabler diagram was employed to illustrate the dominant ionic composition in the groundwater samples from the study area (Fig. 8). In this diagram, the concentrations of the key cations (K^+, Na^+, Mg^{2+}, and Ca^{2+}) were plotted on the upsides, while the anions (HCO_3^-, SO_4^{2-}, NO_3^-, and Cl^-) were plotted on the downsides of the study locations. The results of the Stabler diagram revealed that Calcium (Ca^{2+}) is the predominant cation, followed by Potassium (K^+), Magnesium (Mg^{2+}), and Sodium (Na^+). Among the anions, Bicarbonate (HCO_3^-) shows the highest concentrations, followed by Sulphate (SO_4^{2-}), Nitrate (NO_3^-), and Chloride (Cl^-). These patterns of ionic dominance suggested that the groundwater was largely affected by the weathering of minerals like calcite and dolomite, along with ion exchange processes. The Stabler diagram, therefore, provides a clear visual representation of the major ionic composition and helps in understanding the geochemical processes affecting the groundwater quality.

While the present study provides valuable insights into groundwater quality in the Valsad district, a few limitations are acknowledged. First, the research focused primarily on a limited number of water quality parameters, which may not comprehensively reflect the full spectrum of potential contaminants or emerging pollutants (e.g., pharmaceuticals, pesticides, potentially toxic elements) that can affect groundwater quality. Second, the study relies on data from a single field sampling period, which may not account for seasonal variations in groundwater quality, as water quality can fluctuate over time due to factors like rainfall, agricultural practices, or industrial activities. Third, the study only considered groundwater from specific villages, which may not fully represent the broader hydrological conditions or water quality across the entire district, particularly in areas with different geochemical or anthropogenic influences. Future research incorporating a wider range of contaminants, seasonal monitoring, and expanded spatial coverage would enhance the understanding of groundwater quality dynamics in the region.

Conclusion

The present study comprehensively assessed the groundwater quality of Valsad district through physicochemical analysis, geospatial mapping, and hydrochemical modeling. The results revealed that most groundwater parameters were within the permissible limits set by BIS (2012, 2015) and WHO (2017), making the water generally suitable for drinking and domestic use. However, localized contamination was observed, particularly
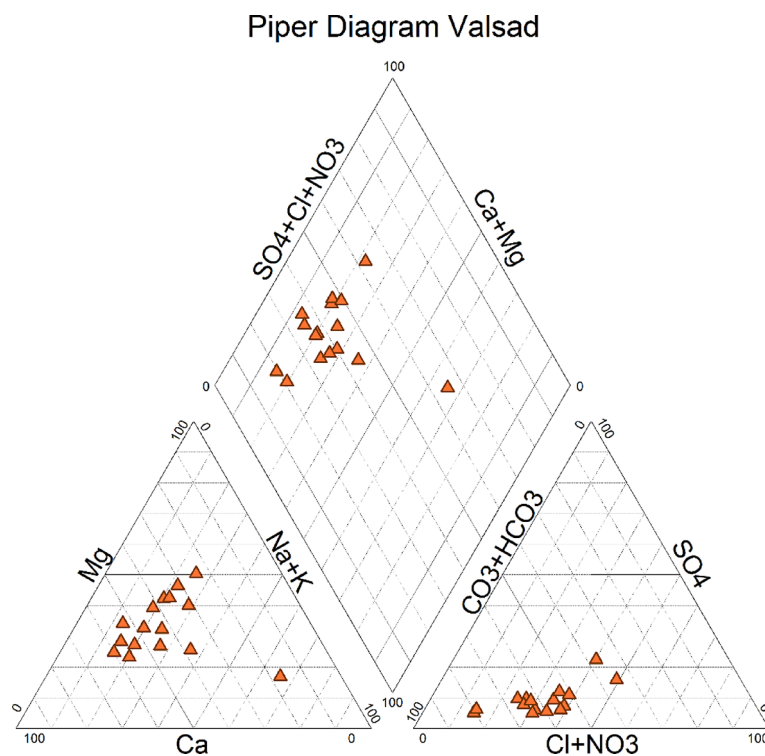

Fig. 7. Classification of groundwater water quality based on Piper diagram.
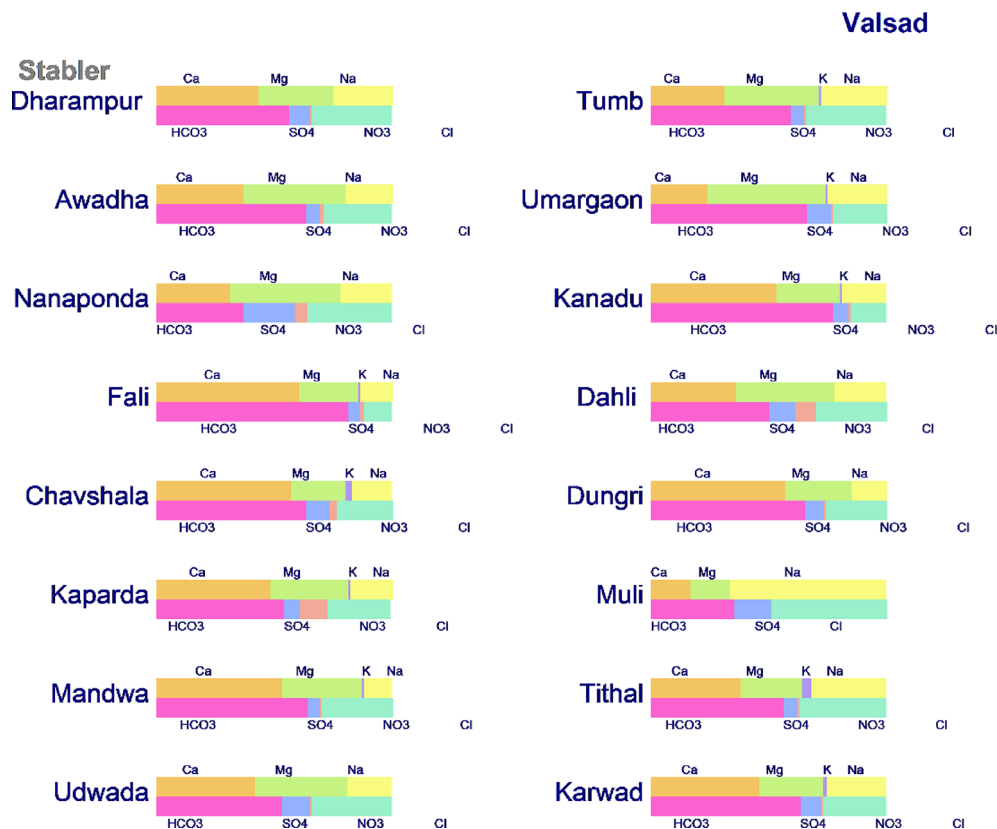
Fig. 8. Stabler diagram for presenting major ionic dominance in the groundwater samples.

in areas such as Muli, Nanaponda, and Dahil villages, where chloride concentrations exceeded 250 mg/L and nitrate levels reached up to 60.89 mg/L, posing potential health risks. Elevated EC values, with a maximum of 1587 μS/cm, were recorded in urbanized regions like Muli and Tithal, indicating possible sewage infiltration. The Water Quality Index (WQI) analysis showed that 31.25% of the samples were in the excellent category (WQI < 25), while 68.75% fell within the good range (WQI = 25–50), with no samples classified as poor or unsuitable for drinking. Hydrochemical facies analysis using Piper and Stabler diagrams revealed that the groundwater was predominantly of the calcium-bicarbonate (Ca^{2+}-HCO_3^-) type (87.5% of samples), suggesting that carbonate rock weathering, particularly from limestone and dolomite formations, played a significant role in water chemistry. The ionic dominance pattern followed the order $Ca^{2+} > Na^+ > Mg^{2+}$ for cations and $HCO_3^- > SO_4^{2-} > Cl^-$ for anions. The findings indicated that natural processes such as mineral dissolution, ion exchange, and anthropogenic influences like agricultural runoff contributed to groundwater chemistry variations. While this study provides a comprehensive understanding of groundwater quality in the Valsad District, it acknowledges certain limitations, including the exclusion of emerging contaminants, reliance on a single sampling period, and limited spatial coverage. To improve groundwater quality management, continuous monitoring across different seasons, the inclusion of additional contaminants like pesticides and potentially toxic elements, and the application of advanced modeling techniques are recommended. These findings serve as a crucial reference for policymakers and water resource managers to implement sustainable groundwater management strategies, ensuring long-term water security for the region.

Data availability
Upon request, all data and materials utilized in this study will be made readily accessible. If someone wants to request the data from this study, the data is available with all the authors or may contact to Dr Nitesh Gupta (corresponding author, email: niteshraz@gmail.com).

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Author contributions

KHJ, NG, SD and HP participated in the conception and design of the study. Material preparation, data collection and analysis, methodology, and original paper drafting were all done by KHJ, NG, SD and HP. DPP and PJ supervised and reviewed the work. SKS and UR edited and reviewed the work. The final manuscript was read and approved by all authors.

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Declarations

Competing interests

The authors declare no competing interests.

Ethics approval and consent to participate

The authors followed the ethical guidelines and no ethical approval was required and all the authors agreed to participate.

Consent for publication

All authors are agreeing to publish the content.

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