



Integrating GIS and irrigation water quality index approaches for identifying groundwater irrigation potential zones in Central Gujarat, India

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Abstract In this study, groundwater irrigation potential zones are identified by measuring an integrated irrigation water quality index using a GIS platform in the Vishwamitri River Basin (VRB) region, Gujarat, India. Classification of different irrigation potential zones is about the collective paraphernalia of thematic maps, namely, electrical conductivity (EC), sodium adsorption ratio (SAR), Na^+ , Cl^- , and HCO_3^- , which principally regulate the groundwater quality for irrigation. The EC, SAR, and chloride values are $> 3000 \mu\text{S/cm}$, $> 9 \text{ meq/L}$, and $> 10 \text{ meq/L}$, respectively, indicating 98.78%, 41.78%, and 84.88% of the total area, respectively, belong to groundwater both hazardous and unsuitable for irrigation. Similarly, 39.55% of the total area is unsuitable for irrigation due to its high Na^+ concentration. The permeability, porosity, and infiltration risk usually appear when excessive sodium ions reduce the rate of flow of irrigation water which moves in the lower soil zones. Similarly, high bicarbonate and chloride concentrations have been denoted to hamper the development of several crops causing symptoms analogous to lime-induced chlorosis due

to toxic effects of the salt. The final irrigation potential map is marked by four levels, such as “most suitable,” “moderately suitable,” “moderately unsuitable,” and “unsuitable for irrigation.” Approximately, 56.69% of the total VRB region are covered with unsuitable for irrigation purposes. In such areas, irrigation must be avoided in usual conditions, and the halophytes, namely, Khati palak (*Atriplex stocksii*), Lamb’s quarters (*Chenopodium album*), and Rudravanti (*Cressa cretica*) should be recommended with high soil permeability and proper drainage facilities. The soil must be highly permeable for groundwaters with high salinity and sodicity. Based on this study, policymakers and environmental managers can estimate the resource implications for drinking and irrigation.

Keywords Groundwater · Irrigation water quality index (IWQI) · GIS · Salinity · Sodicity

Introduction

Among the world’s most significant, dynamic, and replenishing natural resources, groundwater forms the pivot of the ecological system (Singh et al., 2018a). A valuable, productive, and beneficial human activity like agriculture and livestock will be attained by properly established and purified groundwater supply system. Basically, both the quality and quantity of groundwater execute important function in attaining

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sustainable management of water resources (Mondal, 2012; Singh et al., 2018a). The quality of groundwater primarily depends upon the physical, chemical, and biological parameters. Natural and anthropogenic paraphernalia, in conjunction with local climate, geology, and irrigation practices, influence the quality of groundwater (Ramkumar et al., 2013; Verma et al., 2015). According to United Nations Conference on Trade and Development (2022), as the population has grown, the share of people living in developing countries has increased from 66% in 1950 to 83% now and should reach 86% by 2050. To date, the ability of existing resources and technologies to achieve the requirements of this blooming population for food and other agricultural commodities remains ambiguous. Global agricultural production is largely dependent on the availability of safe groundwater. The entropy-based groundwater irrigation quality index (EIWQI) has been studied in the Damodar fan delta (DFD), India (Mahammad et al., 2022). In this study, Shannon's entropy method has been used to assign the weights of the different parameters for constructing the EIWQI. Major agricultural indicators like total dissolved solids (TDS), potential salinity (PS), sodium absorption ratio (SAR), and residual sodium carbonate (RSC) have been integrated to study the IWQI in the arid and semi-arid regions of Makkah Al-Mukarramah province, Saudi Arabia (Osta et al., 2022). Here, the partial least squares regression model (PLSR) has been applied to study the all water quality indices.

Undoubtedly, agriculture is the key end user of India's groundwater with measured yearly extractions of 230 km³ (CGWB, 2014; Kumar et al., 2018). According to the Ministry of Water Resources (2022), approximately 85% of the freshwater of the country is extracted by irrigation, and it is anticipated that the irrigational requirements will upsurge by 56%. The net groundwater draft for irrigation uses was about 115 bcm and 85 per cent of drinking water supplies dependent on it. In the year 2050, despite the fact the portable water demand will rise two times with a water need for energy production will rise sixteen times (Asian Development Bank, 2003). Nevertheless, the chemical properties of irrigated soils are altered by irrigation-induced issues and problems such as salinity, sodium hazard, and water-logging. In India, the area under salt-affected soils is about 6.73 million ha with Gujarat (2.23 m ha) is the

most affected state, together accounting for almost 75% of saline and sodic soils in the country (Sharma & Singh, 2015). Therefore, regular groundwater quality monitoring is necessary for creating a green economy for the country.

Groundwater quality assessment is simple using a conventional way which requires a careful process reflecting the distinct parameters. Hence, the conventional technique is not enough for achieving a precise illustration of groundwater quality (Mohebbi et al., 2013). Therefore, water quality indexes (WQI) have been generated for getting information about groundwater quality in an effective and reasonable way (Saeedi et al., 2010). WQI delivers a specific figure that articulates the general groundwater quality of any location. This quality index can be considered as a fairly simple along with realistic technique for the policymakers and managers for understanding drinking water quality and its probable usages. Similarly, an irrigation water quality index (IWQI) is estimated to be relatively beneficial for policymakers, managers, engineers, and environmentalists in the evaluation, monitoring, and management of irrigation water (Singh et al., 2018b).

Numerous approaches are implemented to assess the impact of irrigation water on both agriculture as well as soil. Hydrochemical indices like sodium adsorption ratio (SAR), soluble sodium percentage, Kelley's ratio (KI), permeability index (PI), and irrigation water coefficient have been applied by several researchers (Brindhya & Elango, 2013; Cieszynska et al., 2012; Fakhre, 2014; Li et al., 2013). IWQI, including various different groups of indicators, has been applied to signify the quality of groundwater with a single unit (Meireles et al., 2010). The coupling of the geographic information system (GIS) tool to assess, examine, and map the process which allows policymakers and decision-makers to generate simple pictorial interpretation and make the general investigation more reliable, purposeful, and innovative (Waqed Hameed, 2014; Nampak et al., 2014).

The objective of this research is to develop a groundwater irrigation potential map using IWQI that articulates probable modifications in groundwater quality for irrigation and consequently facilitates evaluation and mitigation of promising issues as well as problems produced to irrigate soil.

Materials and methods

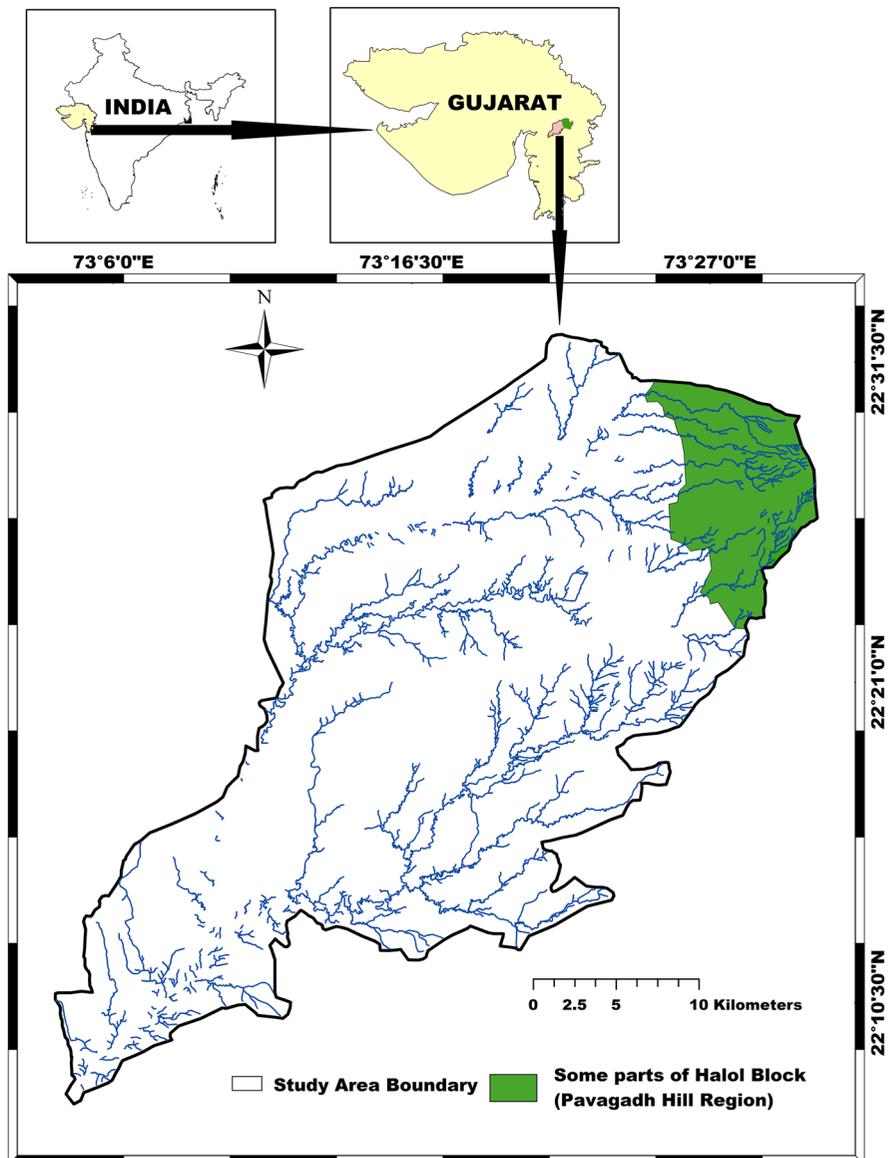
Study area

The IWQI study was commenced in the Vishwamitri River Basin (VRB) located in central Gujarat which is comprising an extent of 986 sq. km comprising the Vadodara and Panchmahal districts (Fig. 1). It falls between 22°00' N and 22°30' N latitudes as well as 73°10' E and 73°38' E longitudes. The river Vishwamitri is a seasonal one which starts from the Pavagadh Hill which is situated in the Halol block

of Panchmahal district and runs through the city of Vadodara. It is one of the tributaries of the Dhadhar River (Siddha & Sahu, 2020a, b).

According to the report of CGWB (2014), a major portion of the population resides in villages which are mainly dependent on groundwater for their daily usage like drinking and household activities. Seventy-two percent of the total area is cultivable land, and 95% water need for the irrigation purpose is met by groundwater (CGWB, 2014). The groundwater draft from irrigation and domestic/industrial sources is 12,136.00 ha m. Major sources of groundwater

Fig. 1 Location of study area and groundwater sample points



withdrawal are agriculture, urbanization, and industrialization. This region has diverse agricultural crops including food crops as well as non-food crops. Chief food crops comprise of cereals and food grains like paddy, wheat, jowar, bajra, maize, pulses, sugarcane, fruits, and vegetables; whereas, non-food crops include cotton, ground nuts, castor, tobacco, and fodder. Major industries include fertilizer, chemical, pharmaceutical, rubber, pulp, and paper industries.

Chemical analysis of groundwater samples

Groundwater samples were collected from 60 borewells to assess the groundwater quality of the VRB region using fishnet technique where the grid size is 15×15 sq. km, in ArcGIS 10.3 software. Chemical parameters such as pH, EC, TDS, SAR, Na^+ , Cl^- , and HCO_3^- were analyzed (Siddha & Sahu, 2020a, b) using American Public Health Association Standard Methods (American Public Health Association (APHA), 2012).

Delineation of irrigation potential zones

The demarcation of distinctive irrigation potential zones is reliant on the combined paraphernalia of five thematic maps, namely, electrical conductivity (EC), sodium adsorption ratio (SAR), Na^+ , Cl^- , and HCO_3^- . To delineate the entire VRB region into distinctive irrigation potential zones, primarily the above-mentioned thematic maps of the region had been made using the inverse distance weighting (IDW) interpolation tool in ArcGIS 10.3 software and the chemical data derived from the analysis.

In the present study, a weighted overlay analysis method in GIS platform had been implemented to demarcate the suitable areas for irrigation. This technique permits a linear amalgamation of probability weights of the individual thematic map (W) with the individual impact value (IV) (Islam et al., 2018; Sarkar & Deota, 2000; Sikdar et al., 2004) which is based on multi-criteria decision-making (MCDM) technique using the overlay analysis tool in ArcGIS 10.3 software (Das et al., 2022; Nayak et al., 2023). Here, the IWQI model developed by Meireles et al. (2010) had been employed to compute the irrigation potential zones. According to this model, the

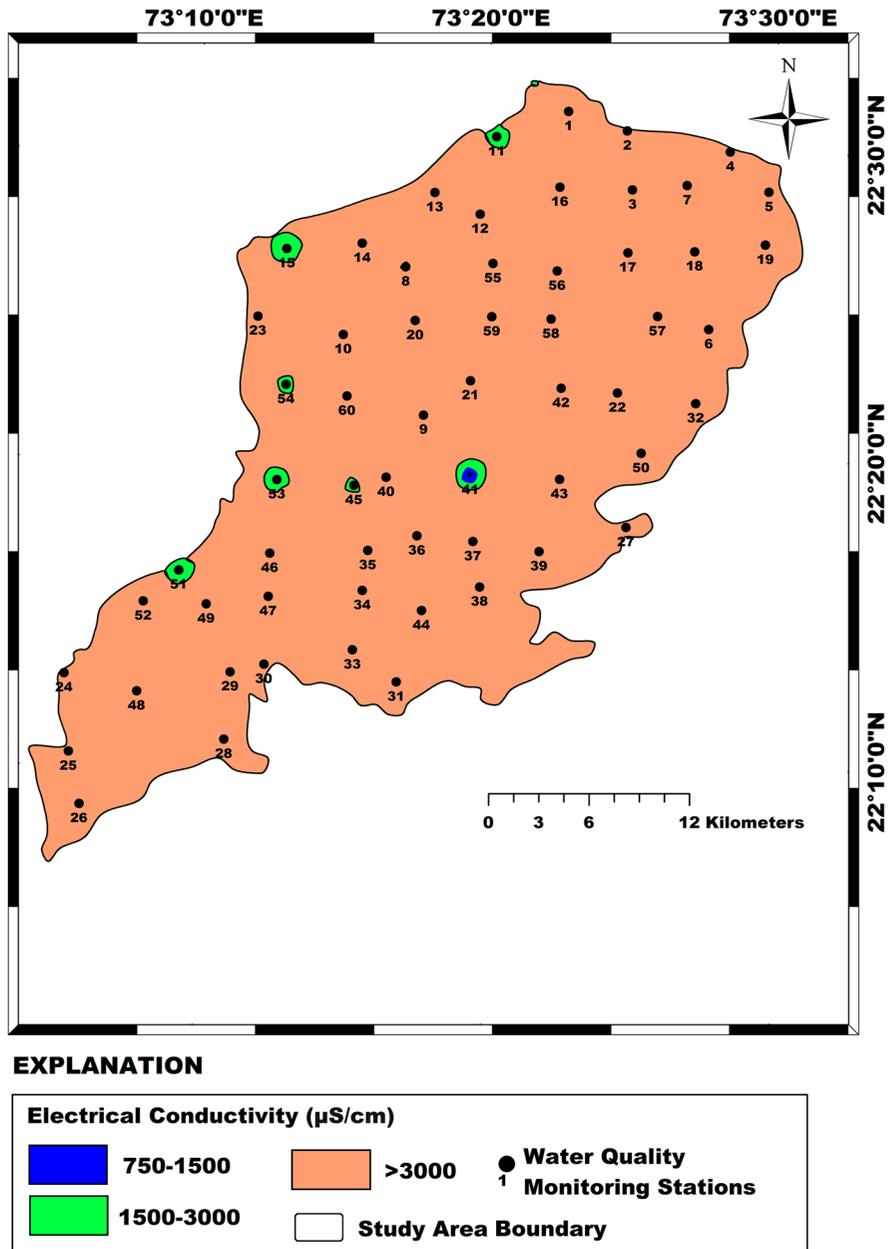
factors like EC, Na^+ , Cl^- , SAR, and HCO_3^- have been selected for the computation of this index. Here, the defined groundwater quality calculation varies from the other WQI-related procedures applied by the World Health Organization (WHO) (Meireles et al., 2010). The data on water quality suitable for irrigation, recommended by the University of California Committee of Consultants (UCCC) as well as the calculated standards of individual factors originating from the standards quantified by Ayers and Westcott (1999), can be applied to evaluate the impact values which deliver a root for this technique.

Results and discussion

The hypothesis related to irrigation water quality is reliant on the dissolved salt concentrations in groundwater. The cumulative salt concentration in groundwater can create acute crisis in relations with the irrigation water quality (Simsek & Gunduz, 2007). Hence, the five factors such as EC, SAR, Na^+ , Cl^- , and HCO_3^- are pre-dominantly controlled the groundwater quality for agricultural usages had been counted for figuring irrigation potential zones.

The electrical conductivity values range between 1170 and 30,736 $\mu\text{S}/\text{cm}$. The spatial distribution of the EC map is shown in Fig. 2. The majority of the study area, 974 sq. km (98.78% of the total area) is covered with $\text{EC} > 3000$ $\mu\text{S}/\text{cm}$, which is not suitable for irrigation. Only 0.002% of the total area (2 sq. km) is covered with electrical conductivity ranging between 750 and 1500 $\mu\text{S}/\text{cm}$ which is suitable for irrigation (Karakus & Yildiz, 2019). Higher electrical conductivity value due to higher rate of evaporation indicates soil salinization (Shammi et al., 2016). As the study area falls under the semi-arid region, only scanty rainfall occurs, and soluble salts are further accumulated and persisted on the surface of the soil, developing in high EC. Higher salt accumulation in the root zone of crops is hostile to the employment of high-salinity groundwater for irrigation. The rigorous application of artificial fertilizers (NPK), industrial discharges, and rock-water interactions led to the higher volume of salt concentration taken by irrigation water. These salts are accumulated in the soil which are leached into groundwater aquifer system changing its physicochemical quality. The high EC value reveals the

Fig. 2 Spatial distribution of electrical conductivity map, VRB, Gujarat, India



dissolution of mineral ions present in the groundwater through rock-water interaction and also contributes to higher salinity in groundwater causing lethal effects to plants by creating physiological drought condition (Siddha & Sahu, 2022). Higher EC such as 6000 to 10,000 $\mu\text{S}/\text{cm}$, in the root zone, decreases crop yield due to a decrease in stomatal conductance as well as a reduction in leaf area (Kachi et al., 2016).

Soluble salts damage crop plants through the effect of osmotic pressure. Water passages from the lesser salt concentration zone like the root of the plant to a zone of greater salt concentration like the soil. This can cause crops to be in a water-stressed condition and then wilt even if the soil is moist. High concentrations of salts in the groundwater, utilized for irrigation can dehydrate or blister the tissue of the leaf once put into operation to foliage. The accumulated

salts on the agricultural fields affect foliage and fruits by discoloring which reduces their market price (Machado & Serralheiro, 2017).

Another important component is SAR which specifies the affinity of Na^+ ions to adsorb on the surface of the soil. The SAR amounts in the VRB region ranged from 0.11 to 37.0. The spatial distribution of SAR map is illustrated in Fig. 3. The SAR values range between 0 and 6 is categorized as “good,” 6–9 as “hazardous,” and >9 as “unsuitable” for irrigation purposes (FAO, 1989; Karakus & Yildiz, 2019; Siddha & Sahu, 2020a, b). In this region, 58.21% of the total study area (574 sq. km) is suitable for irrigation. Again, 41.78% of the total area (412 sq. km) belongs to both hazardous and unsuitable for irrigation category. A high SAR value disturbs the

permeability of the soil, decreases the capability to create soil aggregates with stable forms, and also breaks the soil masses (Wang et al., 2012; Zaidi et al., 2016). Their convertible characteristics in the soil direct the understanding that they have a harsh impact on the structure of the soil (Akinyemi & Souley, 2014). The soil grows stiff and compact when dry and decreases the infiltration rate of groundwater and air into the soil pore disturbing its structure.

To evaluate the agricultural groundwater quality, Na^+ ions serve an important role (Bauder et al., 2010). Here, the spatial distribution of the sodium map is demonstrated in Fig. 4. According to Abbasnia et al. (2018) Na^+ ion concentration >9 meq/L is unsuitable for irrigation which covers 39.55% of the total area (390 sq. km) and slight to moderate

Fig. 3 Spatial distribution of SAR map, VRB, Gujarat, India

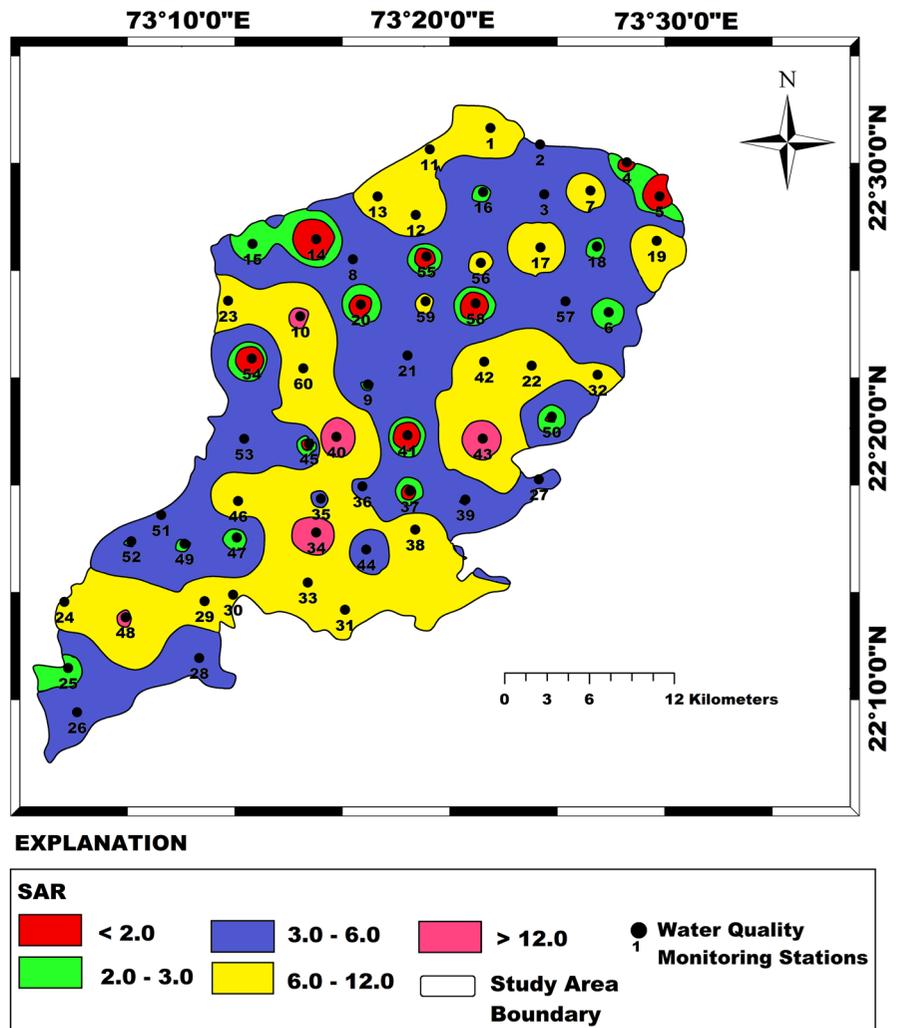
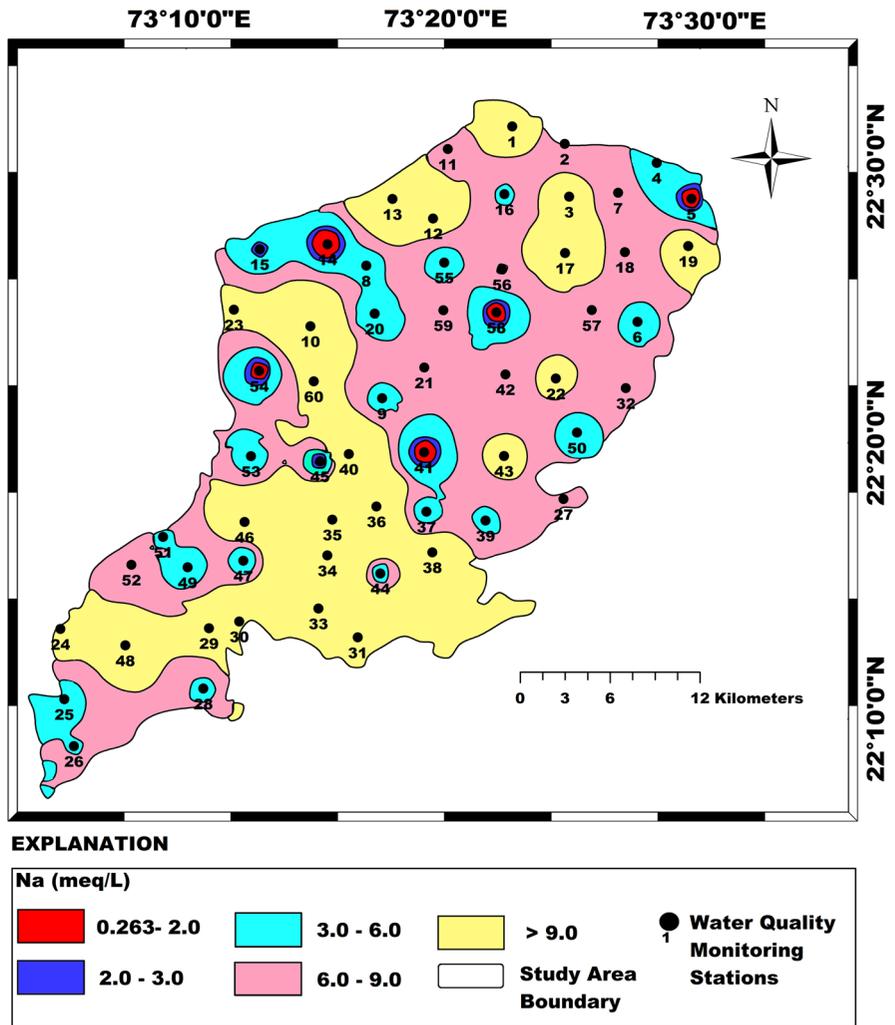


Fig. 4 Spatial distribution of Na map, VRB, Gujarat, India

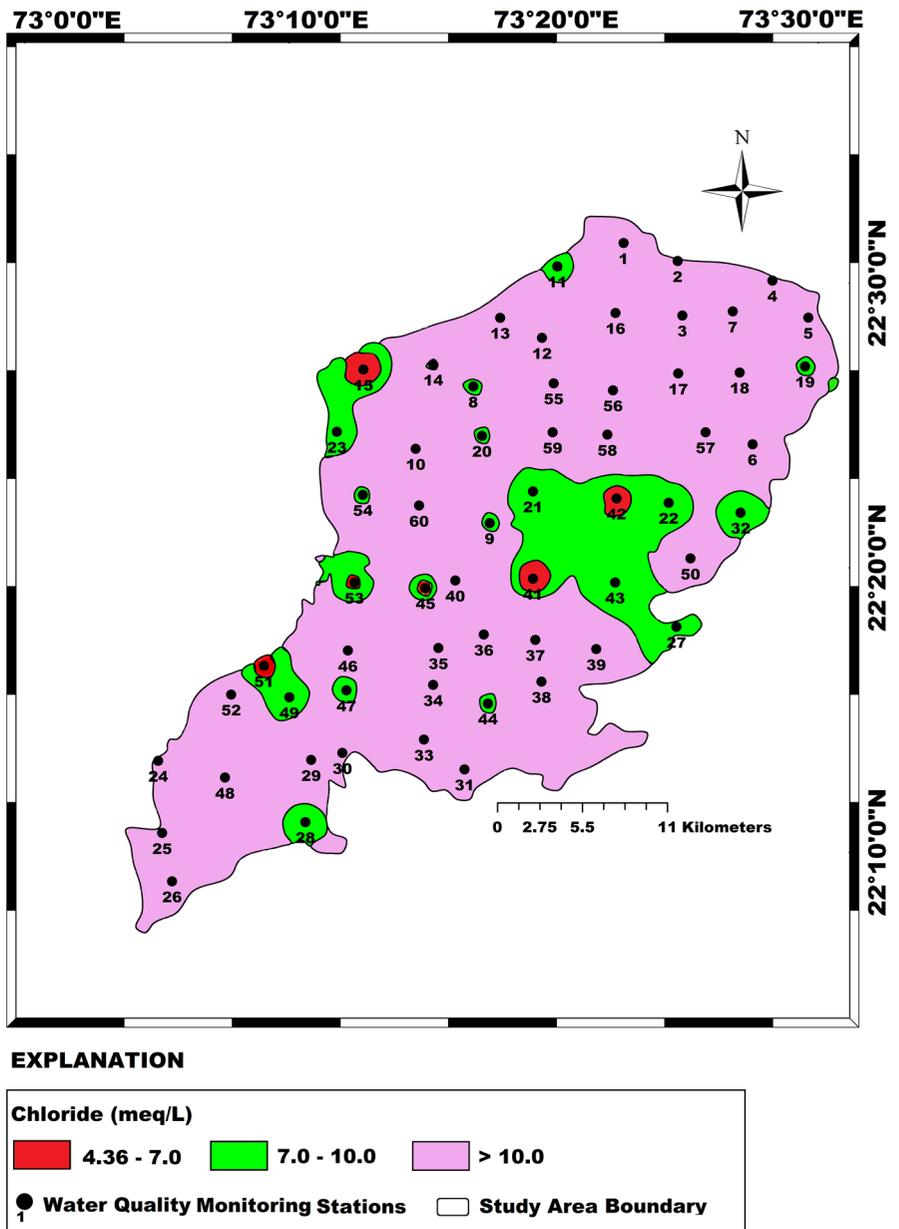


restriction will be carried out where the value ranges between 3 and 9 meq/L which covers 45% of the total area (445 sq. km). Due to high Na⁺ ion concentrations in irrigation, water clay particles are absorbed thus causing the transfer of Mg²⁺ and Ca²⁺ ions leading to a decrease in the permeability of the soil and weaken the internal drainage system (Ahamed et al., 2014). High Na⁺ ions also bring a rise in the hardness of soil (Varol & Davraz, 2015). The permeability, porosity, and infiltration risk usually appear when excessive sodium ions reduce the rate of flow of irrigation water which moves in the lower soil zones. The decreased rate of infiltration begins to manifest adverse effects as soon as groundwater cannot permeate to the root zones of crops to a particular amount that the crop needs. Consequently, these salts

commence storing at the exterior of the soil surface. Once the crop plant is unable to obtain the essential volume of groundwater within the soil, it is very difficult to sustain an adequate crop which triggers a reduction in agricultural yield (Simsek & Gunduz, 2007). The identification of toxicity due to sodium is comparatively difficult in comparison with the harmfulness of other ions. Distinctive hazard indicators on the plants are burn on the leaf, blacken sear marks and dead tissues along the exterior edges of the leaf.

Among micronutrients, Cl⁻ is an influential nutrient. All crops need Cl⁻ in minor amounts. Nevertheless, Cl⁻ is frequently connected with harm due to salinity and toxicity. In the study area, the chloride ranges between 4.32 and 231.41 meq/L. The spatial distribution map for chloride is shown in Fig. 5. Here,

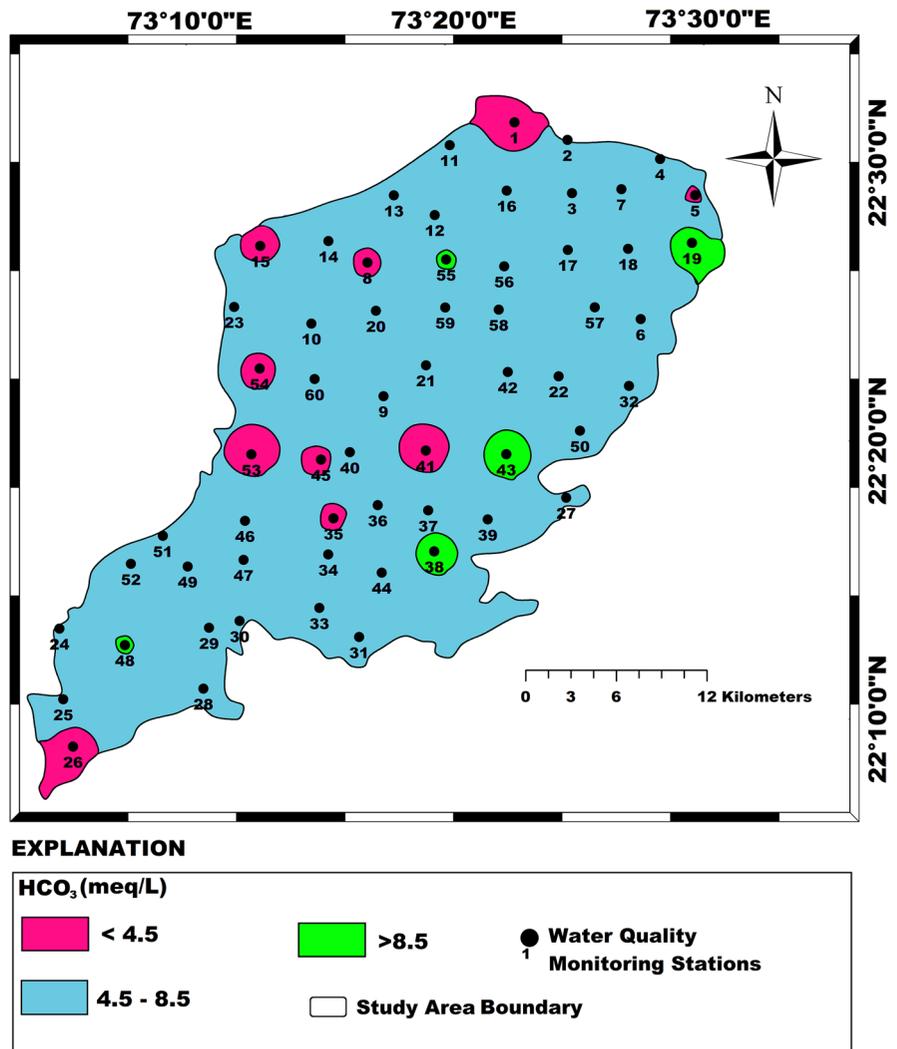
Fig. 5 Spatial distribution of chloride map, VRB, Gujarat, India



the major portion of the VRB that is 84.88% of the total area (837 sq. km) is covered with > 10 meq/L chloride concentration in groundwater which is categorized as “unsuitable for irrigation purposes” due to toxic effects of the salt (Abbasnia et al., 2018; FAO, 1989). Vegetables like sugar beet, asparagus, cauliflower, and cereals like barley are extremely sensitive to chloride concentrations > 350 mg/L or 5.7 meq/L. Moderate sensitive plants are potato, alfalfa, Sudan grass, squash, wheat, sorghum, corn, and tomato

which can tolerate chloride levels ranging between 140 and 350 mg/L or 2.3–5.7 meq/L. Plants consume Cl^- as chloride ions through the soil (Wali et al., 2021). It enacts significant characteristics in plants which include photosynthesis, osmotic regulation, as well as control of plant diseases. Still, excessive level of Cl^- can affect crops by reducing production. The noxiousness develops from the accretion of Cl^- in the foliage. Its toxic features are directly observed as burns in the leaf or death of the leaf tissues and

Fig. 6 Spatial distribution of bicarbonate map, VRB, Gujarat, India



necrosis of tips and leaf margins ultimately causing leaf drop (Jennings, 1976). However, it is much tougher to identify the toxic effects of chloride as it is seldom difficult to differentiate whether the symptom of toxicity is exactly associated with Cl^- or Na. Cl^- can too affect foliage injury once accumulated on a leaf in large irrigation (Flood, 1996). The conventional sources of Cl^- in groundwater consist of rock weathering, atmospheric accretion, and precipitation. As the VRB region is semi-arid, the accessible groundwater is salty. An anion of Cl^- conveys a negative charge, and hence, it does not adsorb to the soil elements and passages quickly with the groundwater within the soil.

Alkalinity is the degree of groundwater’s ability to neutralize by adding acid components. The carbonates and bicarbonates are the key constituent of alkalinity which are largely accountable for $pH > 8.5$ in groundwater. High concentration of bicarbonates causes Ca^{2+} and Mg^{2+} ions to develop insoluble minerals separating Na^+ as the dominant ion in the solution (Simsek & Gunduz, 2007). In the VRB region, the HCO_3^- concentration in groundwater samples ranged between 2.38 and 10.50 meq/L. Typically, HCO_3^- concentrations > 1.5 meq/L are counted to be best for irrigation which is absent in the study area, and > 8.5 meq/L values are unsuitable for irrigation purposes (Ayers & Westcot, 1985; FAO, 1989), and it

Table 1 Thematic map weights and impact values for irrigation potential zoning

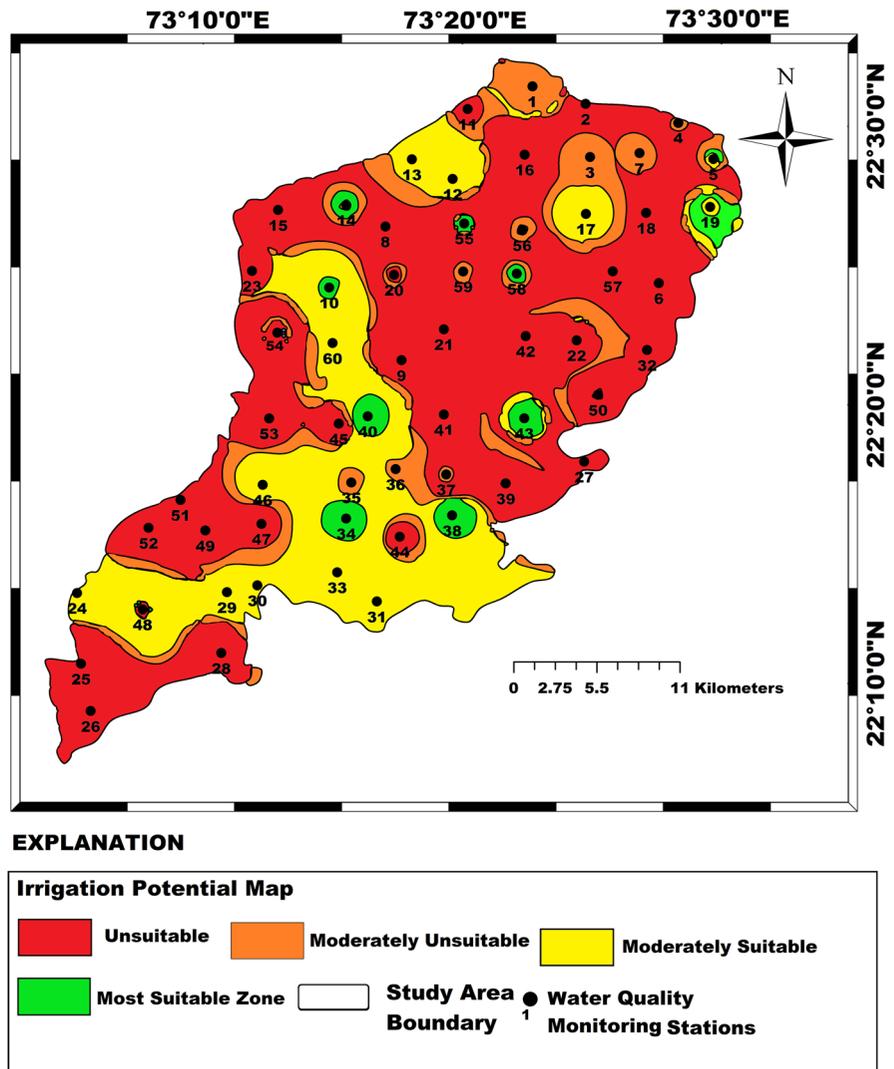
Parameters	Impact	Range	Categories	Impact values
EC	0.211	1170.00–30,736.00	<200	0
			200–750	0
			750–1500	0.5
			1500–3000	0.4
			>3000	0.1
SAR	0.189	0.11–37.0	<2	0.05
			2–3	0.4
			3–6	0.3
			6–12	0.2
			>12	0.05
Na ⁺	0.204	0.24–139.43	<2	0.05
			2–3	0.4
			3–6	0.3
			6–9	0.2
			>9	0.05
Cl ⁻	0.194	4.32–231.41	<1	0
			1–4	0
			4–7	0.5
			7–10	0.4
			>10	0.1
HCO ₃ ⁻	0.202	2.38–10.50	<1	0
			1–1.5	0
			1.5–4.5	0.5
			4.5–8.5	0.4
			>8.5	0.1

covers 2.53% of the total area (25 sq. km). The spatial distribution map of HCO₃⁻ ion concentrations is illustrated in Fig. 6 in the meq/L unit. A major portion of the study area, i.e., 91.88% of the total area (906 sq. km) covers HCO₃⁻ concentrations ranging between 4.5 and 8.5 meq/L categorized as “slight to moderate risk zones” by FAO (1989). High concentrations of bicarbonate ions have been shown to inhibit the development of numerous crop plants, causing symptoms analogous to lime-induced chlorosis (Lee & Woolhouse, 1969). Lime deposition arises when carbonates of Ca²⁺ or Mg²⁺ precipitate out of irrigated groundwater, putting white scum. Hence, the accretion of lime from irrigated groundwater takes place as numerous environmental influences like the evaporation of water, loss of CO₂ as a gas, augmented temperature, and enlarged pH represent to diminish the solubility of lime in groundwater (Balathandayutham et al., 2015). Due to the weathering of limestone and dolomite, HCO₃⁻ comes into the soil solution. These

environmental influences alter as water passages over an irrigated scheme and lime is accumulated on vegetation, apparatus used in irrigation or in the soil (Hopkins et al., 2007) causing plugging in pipes and tubes. Both micro and drip irrigation systems are further susceptible to plugging than the pivot sprinkler systems. For fruits, vegetables, and crops, the occurrence of lime scum decreases their market value.

The final irrigation potential map was prepared by using multi-criteria decision analysis and analytical hierarchical processes integrating all the above-mentioned thematic maps. The impact value of each thematic layer is established using the standard described by Meireles et al. (2010) depending on their suitability for irrigation (Abbasnia et al., 2018). Again, different categories of derived thematic maps have been assigned impact values where lesser value denotes the poor quality of groundwater and vice versa in relation to their suitability for agricultural usage (Table 1). The spatial distribution of the irrigation potential map

Fig. 7 Irrigation potential map, VRB, Gujarat, India



is illustrated in Fig. 7. This map is labelled into four categories, namely, “most suitable,” “moderately suitable,” “moderately unsuitable,” and “unsuitable for irrigation,” and areal extent of each class is given in Table 2.

Pockets of areas are found to be excellent covering 3.36% of the total area. In these locations, no harm of salinity and sodicity to crop plants, vegetables, and cereals is observed (e.g., least salt-tolerant plants like dry beans, soybeans, corn, and field peas (Egamberdieva et al., 2019)). 27.18% area is moderately suitable in terms of irrigation utilities. Hence, the groundwater from these areas can be utilized in light to moderate permeability soils, and its application should be prevented for plants which are sensitive to salinity and unsuitable for raw eaten vegetables and fruits. The

moderately unsuitable groundwater is distributed in patches in all over the study area. These regions should be used for moderate to high salt tolerance plants like melons, tomatoes, and cucumbers. Most part of the VRB region that is 56.69% of total area is enclosed with “unsuitable” quality groundwater. In these areas,

Table 2 Areas covered by different irrigation potential zones

Irrigation potential zones	Area (sq. km)	% of total area
Most suitable	33	3.36
Moderately suitable	268	27.18
Moderately unsuitable	126	12.77
Unsuitable	559	56.69

irrigation should be avoided in usual conditions and high halophytes like Khati palak or kharo tanko (*Atriplex stocksii*), lamb's quarters or bathua (*Chenopodium album*), medicinal plants like Rudravanti or machul (*Cressa cretica*) should be recommended with high permeability and proper drainage facility in the soil. The soil must have highly permeable for groundwater with high salinity and sodicity. High-sodium groundwaters can be treated by adding gypsum or different sources of water-soluble calcium like CaCl_2 (Hopkins et al., 2007).

Conclusion

In this research, groundwater resources of the VRB region had been assessed for irrigation water potential integrated with GIS. Assessment of GIS-based IWQI through pragmatic models at a technically reliable stage has grave significance for monitoring and scrutinizing both soil and irrigation water quality. Five key factors, namely, EC, SAR, Na^+ , Cl^- , and HCO_3^- have been estimated to investigate the irrigational suitability of the VRB region. The result of this study indicates that most of the groundwaters of this region are unsuitable in terms of irrigational utility. The EC values indicate approximately 98% of the area is unsuitable due to high salt content in the groundwater. Dilution of source water is the merely cost-effective technique to lessen the salt concentration in irrigation water. The SAR values indicate 41.78% of the total area is covered with high sodium concentration in groundwater which reduces the crop yield. Similarly, for chloride, 84.88% of the total area is unsuitable for irrigation, and for bicarbonate, 91.88% of the total area falls under "slight to moderate risk" zones. The injury triggered by high concentration of chloride in irrigated groundwater can be abated by developing fewer sensitive crops, preventing foliar interaction by using drip irrigation and furrow. Finally, the irrigation potential map indicates that most of the groundwater in the VRB region is hazardous for irrigation practice.

Therefore, a systematic assessment of water quality for irrigation systems needs proper planning, strategies, management, and actions entailed. The groundwater suitability for irrigational usages is extremely

vital for enhancement of soil environments, achievement of extremely productive crops, thus for the economic progress of the agriculture. The outcomes of this investigation have allowed irrigation water to be assessed with the aim that to choose suitable irrigation management knowledge, skills and technologies in circumstances where the groundwater resources are employed for irrigational utilities.

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Author contribution Paulami Sahu has supervised the entire work. Both Swayam Siddha and Paulami Sahu have prepared the main manuscript text. Swayam Siddha has prepared the figures, and both authors reviewed the manuscript.

Data availability Data will be available from any of the authors on request and will be permitted to use strictly for academic purpose.

Declarations

Ethics approval All authors have read, understood, and have complied as applicable with the statement on "Ethical responsibilities of Authors" as found in the instructions for authors and are aware that with minor exceptions, no changes can be made to authorship once the paper is submitted.

Competing interests The authors declare no competing interests.

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