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Hydrochemical Characteristics and Sustainable Quality Assessment of Reservoir Water in the Junagadh District of Saurashtra Peninsula, India

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Freshwater is an important natural resource for sustaining human life. The study explores the hydrochemical characteristics, water quality status and irrigation suitability of 13 surface-water reservoirs in the Junagadh District of Saurashtra Peninsula, Gujarat state, India, in pre-monsoon 2025. APHA (2017) protocols and standard values of WHO-2017 and BIS-2012/2015 were used throughout the analysis. In water quality index (WQI), 84.62% of the samples fall within the good category and 15.38% within the excellent category for domestic purposes. Sodium adsorption ratio (SAR), the sodium percentage (Na%) and residual sodium carbonate (RSC) were evaluated for irrigation suitability. In the USSL plot, most samples were in the C2S1 category, indicating low sodium hazard; few show moderate salinity. In Piper diagram, Ca^{2+}–Mg^{2+}–HCO_3^- and Ca^{2+}–Mg^{2+}–Cl^- are dominant facies. Rock weathering is a geochemical process primarily identified by the Gibbs diagram. Based on the findings, the surface waters of Junagadh District are suitable for both domestic use and irrigation applications.

Keywords: Surface water, Hydrogeochemical evolution, Irrigation, Water quality index.

INTRODUCTION

Freshwater is a vital renewable resource, constituting only about 3% of the Earth's total water supply [1]. Its limited availability, followed with increasing demand for drinking, agriculture, industry and domestic use, underscores its critical importance for sustaining human life [2]. Agricultural needs consume more than half of the freshwater and the rest is used for daily consumption and industrial growth [3]. Alongside groundwater, surface waters such as rivers and lakes serve as essential sources for the global population. Rivers are also especially important as they serve as a source of freshwater [4,5]. In terms of India, climate change, population growth and rapid urbanisation put high stress on water resources. India has only 4% of the world's fresh water [6]. In arid and semi-arid regions when surface water is seasonal, in this type of condition surface water management becomes crucial for human beings.

In the coastal districts of Gujarat, India, seawater intrusion into groundwater further complicates water resource management and increases the importance of effective surface water management [7,8]. Due to the limited availability of surface water quality data in Gujarat state, this study evaluates the hydrochemical characteristics of the Junagadh district (JND) region in the Saurashtra peninsula. Thirteen dams and reservoirs were selected for sampling during the pre-monsoon season of 2024. A comprehensive analytical approach was adopted in accordance with the standard procedures to evaluate 16 physico-chemical parameters [9]. Water quality status of the Junagadh district (JND) waterbodies was assessed using the Water Quality Index (WQI) method [10,11], with reference to guideline values prescribed by the World Health Organization and the Bureau of Indian Standards for desirable and permissible limits [12-14]. To determine irrigation suitability, indices including sodium hazard (SH), sodium percentage (Na%), sodium adsorption ratio (SAR) and residual sodium carbonate (RSC) were calculated [5,15]. The hydrochemical facies were interpreted using Piper trilinear diagrams, while Gibbs plots were employed to identify dominant geochemical processes such as rock-water interaction and evaporation [16]. Moreover, irrigation water classification based on the USSL diagram provided insight into salinity and sodicity hazards [15]. This study integrates spatial sampling and hydrochemical tools to evaluate the quality and suitability of surface water in JND, highlighting the importance of effective water resource management for public health, agriculture and environmental sustainability.

EXPERIMENTAL

Study area profile: The Junagadh district (JND) of Saurashtra Peninsula, Gujarat state, falls within a semi-arid to subtropical steppe climate (Köppen BSh classification). Geographically, it extends between 20º55′-21º40′ N latitude and 69º56′-71º08′ E longitude, covering approximately 5093 Km^2 and comprising nine administrative subdistricts and 547 villages [17]. The district is bordered by Porbandar to the west, Rajkot to the north, Amreli to the northeast and Gir Somnath to the east and south-east. Physiographically, JND includes the Girnar Hills, Gir National Park forest zone, Ghed floodplains and the southern coastal stretch along the Arabian Sea, forming a diverse ecological and hydrological setting. The Girnar Hills, a prominent volcanic massif, significantly influence regional drainage patterns and groundwater recharge (Fig. 1), with surface runoff descending toward the Arabian Sea. Major rivers such as the Ozat, Megal, Raval, Madhuvanti, Machhundri, Shingoda and Hiran traverse the district and contribute to reservoir recharge [18]. The region receives an average annual rainfall of 650-750 mm, with temperatures ranging from approximately 16 ºC in winter to 38 ºC in summer. Geologically, the area comprises alluvium, miliolite limestone, laterites and Deccan Trap formations [19,20]. Agriculture forms the backbone of the local economy, with major crops including groundnut, cotton, wheat, pulses, pearl millet and horticultural produce such as Kesar mango and coconut.

This hydrochemical investigation was conducted during the pre-monsoon season (May 2025) to assess surface water quality in JND. Sampling and analysis followed the standard protocols outlined by APHA (2017) to ensure methodological consistency and analytical reliability [9]. Thirteen surface water samples (R1-R13) were collected from selected reservoirs across the district (Fig. 2), with geographic coordinates provided in Table-1. Samples were collected in 1 L high-density polyethylene (HDPE) bottles pre-cleaned with a 1:1 HCl and distilled water solution. To minimize contamination, bottles were rinsed with the respective source water prior to collection. After on-site measurement of field parameters, samples were stored at 0-4 ºC and transported for laboratory analysis.

***In situ* measurements and laboratory analysis:** All the physico-chemical parameters were analysed by following APHA 23rd Edition-2017 standard protocols to ensure accuracy and reproducibility [9]. Portable water testing device (Systro-

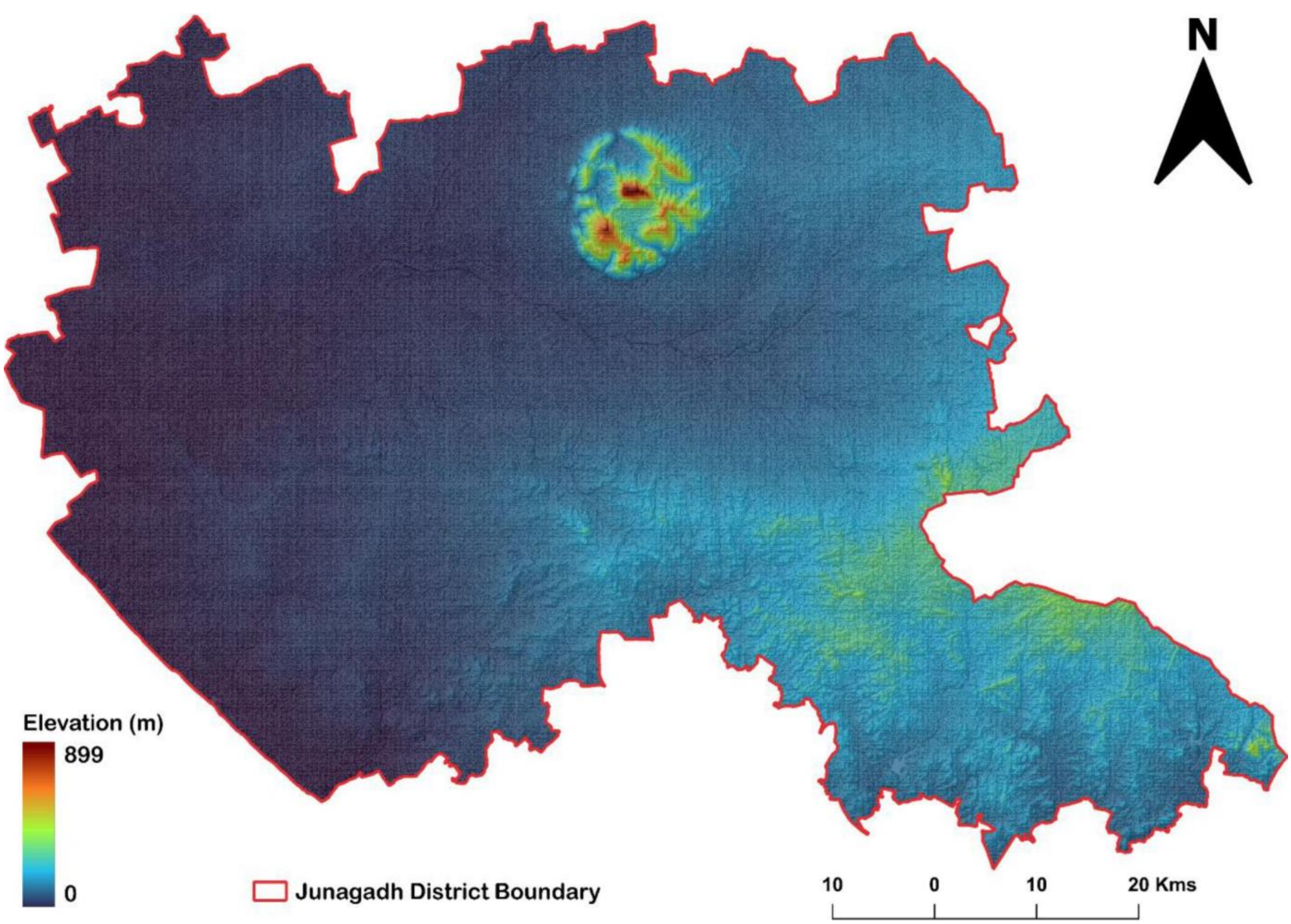

Fig. 1. Junagadh district topographic elevation map of Gujarat state, India

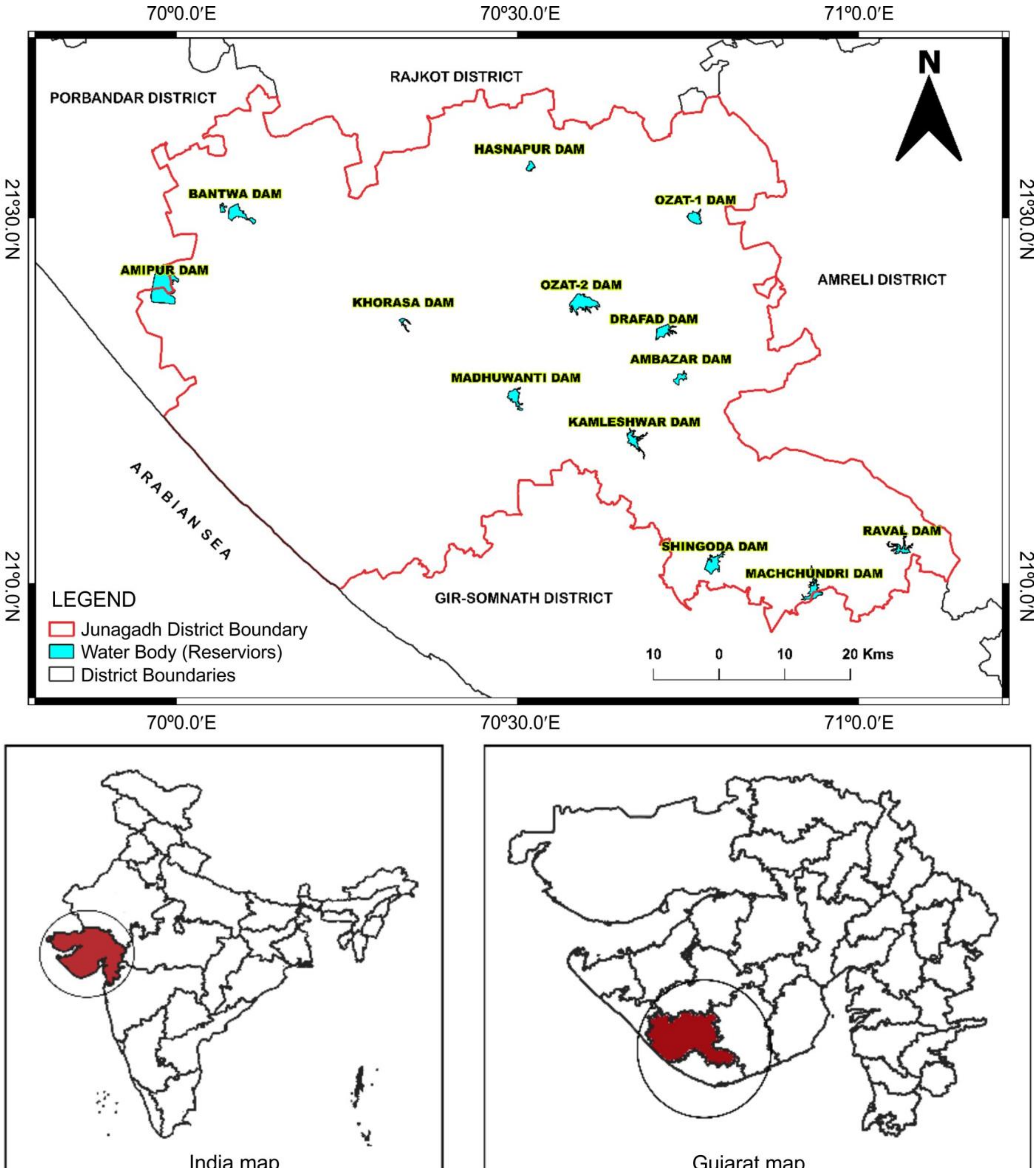

Fig. 2. Study area map of Junagadh district of Gujarat state in Saurashtra Peninsula, India

nics Water Analyzer 371, India) used to measure pH, electrical conductivity (EC) and total dissolved solids (TDS) on-site. EDTA volumetric titration method to measure total hardness (TH), calcium (Ca^{2+}) and magnesium (Mg^{2+}). Acid-base titration with standard H_2SO_4 was used to measure total alkalinity (TA), carbonate (CO_3^{2-}) and bicarbonate (HCO_3^-), while argentometric titration used to measure chloride (Cl^-). Sodium (Na^+) and potassium (K^+) ions were analysed in a Systronics Flame Photometer (Model 128, India). For anions, spectrophotometric methods were preferred since they were more sensitive and accurate. Sulphate (SO_4^{2-}) concentrations were determined using the $BaCl_2$ turbidimetric method, nitrate (NO_3^-)

TABLE-1
LISTS OF SAMPLING LOCATION SITES OF STUDY AREA (JUNAGADH DISTRICT OF WESTERN GUJARAT)

Site	Reservoir Name	Latitude	Longitude
R1	Bantwa Dam	21.507710	70.085050
R2	Hasnapur Dam	21.568919	70.519129
R3	Ambazar Dam	21.282011	70.738074
R4	Amipur Dam	21.403680	69.981340
R5	Drafad Dam	21.336872	70.698450
R6	Khorasa Dam	21.359312	70.331197
R7	Ozat-1 Dam	21.499500	70.759650
R8	Ozat-2 Dam	21.383560	70.595210
R9	Machchundri Dam	20.989080	70.933380
R10	Shingoda Dam	21.025970	70.787540
R11	Kamleshwar Dam	21.196441	70.669584
R12	Raval Dam	21.047390	71.062080
R13	Madhuwanti Dam	21.256930	70.496290

was analysed by spectrophotometric screening and fluoride (F^-) was quantified using the SPADNS spectrophotometric method with a UV-visible spectrophotometer (Jasco V-630, Kyoto, Japan).

Quality control and calibration: The truthfulness of the analytical record is maintained through quality assurance and quality control (QA/QC) methods throughout the whole sampling and analysis process. Field readings were digitally logged using handheld devices for minimizing statistical error. Before laboratory analysis, water samples were pre-filtered to remove suspended particulate matter. The portable pH meter calibration occurs by with three-point buffer solutions (pH 4.0, 7.0 and 9.2) and an EC meter was calibrated with a 1413 µS/cm KCl solution. All analyses were performed using analytical grade reagents and deionised water was employed for the preparation of solutions and laboratory procedures. To ensure analytical accuracy and minimise potential bias, reference standards, replicate samples and procedural blanks were included in each batch of analysis. The fluoride and nitrate concentrations were cross-validated using both standard addition and spectrophotometric methods to confirm data reliability.

Softwares and hydrochemical analytical tools: Microsoft Excel used for statistically processed of various indices such as a water quality index (WQI), sodium percentage (Na%), sodium adsorption ratio (SAR) and residual sodium carbonate (RSC). In ArcGIS 3.1.5 software, the Inverse Distance Weighted (IDW) interpolation technique was used to prepare an individual Indices spatial distribution map of the JND study area. This modern integrated methodological approach helps with the identification of spatial contamination hotspots and the evaluation of surface water suitability for drinking and agriculture across the study area JND. QGIS 3.28 software was used for preparing the study area map, which provides information on the coordinates that were used in sample collections. Identification of hydrogeochemical characteristics was carried out by using Piper and Gibbs diagrams, which are prepared in Grapher software 24.1.213. This graphical representation highlights hydrochemical facies, classification of water types and illustrate about dominant geochemical processes involved in the study area JND. Furthermore, other graphs like the USSL diagram and box-whisker plots were also prepared in Grapher. This methodological framework ensured a comprehensive image of hydrochemical processes and surface water suitability for drinking and agricultural purposes in the study area (JND).

Physico-chemical parameters investigation: Total 16 physico-chemical parameters were analysed in this study using box-whisker plots, which represent the statistical distribution of the parameters of the study area JND. Each individual box represents the interquartile range (IQR), indicating the span of the middle 50% of data values that fall between the 25th and 75th percentiles [21]. The whiskers indicate the minimum and maximum values, whereas the central marker denotes the mean value of individual parameters. The suitability of surface water in the region is largely governed by its ionic composition. The semi-arid climate, characterised by limited rainfall, restricts natural recharge, making reservoirs dependent on monsoonal inflow from local rivers. These reservoirs play a crucial role in sustaining water availability and serve as important sources for both drinking and irrigation purposes throughout the year.

Irrigation indices evolution: The ionic framework of water impact on crop life and influences the overall potential of soil fertilisation in agriculture activities. Chemical analysis of irrigation water is essential prior to its application, as it enables assessment of its potential impact on soil characteristics, nutrient dynamics and the overall crop productivity. Irrigation suitability indices, including salinity hazard (SH), sodium adsorption ratio (SAR), residual sodium carbonate (RSC) and sodium percentage (Na%), were evaluated to assess the irrigation water quality and ensure the long-term sustainability of agricultural lands in the JND region [22-24]. All the parameters analysed in ppm (mg/L) were converted into milliequivalents per litre (meq/L) by using eqn. 1. The mathematical formulas of evaluated irrigation indices are shown in eqns. 2 to 4; ion concentration is in meq/L, except for SH (µS/cm). Furthermore, the United States Salinity Laboratory (USSL) diagram (SAR *vs.* EC) helps to deepen insight into understanding of salinity and sodium hazards that affect the irrigation suitability of each reservoir of the JND region [25]:

$$\text{meq/L} = \frac{\text{Ion (ppm)} \times \text{Charge of ion}}{\text{Molecular weight of ion}} \quad (1)$$

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

$$\text{RSC} = (CO_3^{2-} + HCO_3^-) - (Ca^{2+} + Mg^{2+}) \quad (3)$$

$$\text{Na (\%)} = \frac{(Na^+ + K^+)}{(Na^+ + K^+ + Ca^{2+} + Mg^{2+})} \times 100 \quad (4)$$

Water quality index (WQI): The water quality index (WQI) is complex of multiple physiochemical parameters to quantify the combined effects of natural and anthropogenic influences on waterbodies [11,26]. Firstly, the WQI proposed by Horton and later re-modified by Brown provides a proper framework to show overall water quality at the individual sampling sites [27,28]. It makes complicated hydrochemical data easier to understand so that it can help with ecological surveys and raising awareness about health. The weighted arithmetic method was employed to compute the WQI, which provides a quantitative measure of drinking water suitability by integrating health-related physico-chemical parameters into a single numerical value [29,30]. The WQI was calculated using eqn. 5, wherein each parameter was assigned a specific weight (w_i) based on its relative significance to human health [22]. This weighting approach reflects the contribution of individual parameters to overall water quality assessment. The relative weight W_i of each parameter was determined using eqn. 6, while the quality rating (sub-index) Q_i for all location was evaluated by using eqn. 7.

$$WQI = \frac{\sum_{i=1}^{n} W_i Q_i}{\sum_{i=1}^{n} W_i} \quad (5)$$

$$W_i = \frac{W_i}{\sum_{i=1}^{n} W_i} \quad (6)$$

$$Q_i = \frac{V_n - V_o}{S_n - V_o} \times 100 \quad (7)$$

where n = number of parameters; w_i = weight for each parameter; W_i = weightage of each water quality parameters; Q_i = quality rating of each water quality parameter; S_n = maximum allows standard permissible limit (PL) value for individual parameters according to BIS-2012, 2015 and WHO-2017; V_n = analysed value of respective parameter for individual sampling site and V_o = standard value for each parameter; taken as 7.0 for pH and 0 for all rest of the other parameters [12-14,31].

Hydrogeochemical evolution: Hydrochemical facies denote the chemical composition of surface water, indicative of its interaction with rocks and geochemical processes. The Piper diagram illustrate ionic composition and clarify surface water dynamics and quality fluctuations that underpin thorough and sustainable water quality evaluation. The Piper trilinear diagram was used to classify the water types and identify the corresponding hydrochemical facies [32]. There are two triangular field first one for cations (Ca^{2+}, Mg^{2+}, $Na^+ + K^+$) and another for anions ($HCO_3^- + CO_3^{2-}$, Cl^-, SO_4^{2-}), which project into a central diamond-shaped field representing overall water type. All the ions are expressed in meq/L % for graphical representation. The Gibbs diagram help to identify which mechanisms are controlling surface water hydrochemistry from rock-water interaction, evaporation and atmospheric precipitation [33]. Rock dominance involves mineral weathering; evaporation dominance shows high salinity; precipitation dominance indicates low mineral content. Eqns. 8 and 9 are used to calculate ionic ratios for Gibbs ratio-I and Gibbs ratio-II. The units of measurement for TDS and all other ions are mg/L.

$$GIBBS\text{-}I = \frac{Cl^-}{Cl^- + HCO_3^-} \quad (8)$$

$$GIBBS\text{-}II = \frac{Na^+ + K^+}{Na^+ + K^+ + Ca^{2+}} \quad (9)$$

RESULTS AND DISCUSSION

Physico-chemical parameters exploration: Ion dominance has a chemistry trend like $Cl^- > HCO_3^- > SO_4^{2-} > CO_3^{2-} > NO_3^- > F^-$ for major anions, while major cations follow the order $Mg^{2+} > Na^+ > Ca^{2+} > K^+$. Box-whisker plots (Fig. 3) illustrate the range, distribution and variability of the 16 anal-

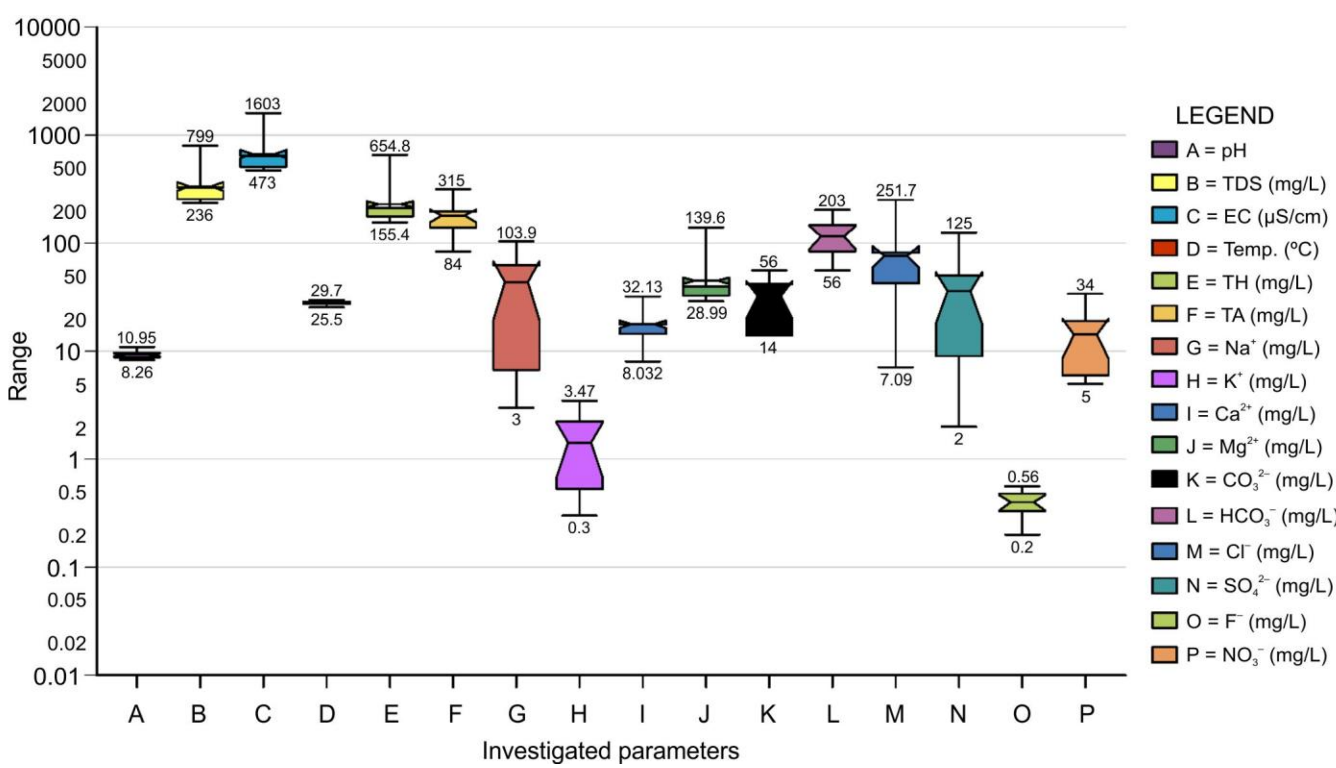

Fig. 3. Box-Whisker plots with range and variability of physico-chemical parameters in the study area (Junagadh district of Saurashtra peninsula, India)

ysed physico-chemical parameters in reservoir surface water across the Junagadh district, Gujarat (JND), India [15,34]. Stiff diagrams constructed from the major cation and anion concentrations illustrate the ionic composition and loading characteristics of surface water at each sampling site [35]. As shown in Fig. 4, the Stiff diagram facilitates comparison of water chemistry among different reservoirs and provides insight into the dominant ionic constituents and potential salt combinations formed through geochemical processes [36].

Physiological characteristics and surface water ionic chemistry: The pH values of the surface water samples range from 8.26 to 10.95 (mean = 9.33 ± 0.74), exceeding the WHO (7-8) and BIS (6.5-8.5) allowable permissible limit (PL). The surface water in the study area is highly alkaline in nature. Limestone and carbonate rock weathering can increase the pH value of water [37]. More than 8.5 pH, tastes bitter and can also cause digestive problems, skin irritation and lower disinfection efficiency in water, making it not safe for long-term human consumption [15,22,38]. Electrical conductivity (EC) is a measurement of the capacity of a solution to allow the flow of electric current. The electrical conductivity (EC) exhibits moderate ranges from 473 to 1603 μS/cm (mean = 671.08 ± 298.68 μS/cm), lying within the BIS limit of 750-3000 μS/cm. Total dissolved solids (TDS) is a measurement of solid residue left after evaporation due to the dryness of the solution. TDS ranges from 236 to 799 mg/L (mean = 336.15 ± 148.91 mg/L), which is below the BIS (500-2000 mg/L) and WHO (600-1000 mg/L) limits. Table-2 shows that the total alkalinity (TA) value ranges from 84 to 315 mg/L (mean = 180.38 ± 60.50 mg/L) and the total hardness (TH) value ranges from 155.37 to 654.78 mg/L (mean = 229.64 ± 130.24 mg/L). Both of these values are mostly within acceptable limits set by BIS (2012, 2015) and WHO (2017). According to Table-2, major cations such as Na^+ (3-103.91 mg/L; mean 43.71 ± 35.99), K^+ (0.30-3.47 mg/L; mean 1.43 ± 1.03), Ca^{2+} (8.03-32.13 mg/L; mean 17.79 ± 6.64) and Mg^{2+} (28.99-139.63 mg/L; mean 45.01 ± 28.98). All cations fall within the permissible range except Mg^{2+}, whereas two sites exceed permissible limit [31,39]. Two sites (R1 and R4) have higher sodium, which shows the implementation of seawater impact on surface water quality in the dry season.

Major anions such as carbonate (CO_3^{2-}) range from 14.00 to 56.00 mg/L (mean 32.31 ± 15.53), ± 15.53), bicarbonate (HCO_3^-) varies from 56.00 to 203.00 (mean 115.77 ± 47.70), chloride (Cl^-) (7.09-251.7 mg/L; mean 76.63 ± 65.01 mg/L), sulfate (SO_4^{2-}) (2-125 mg/L; mean 35.92 ± 36.04 mg/L), nitrate (NO_3^-) (5-34 mg/L; mean 14.23 ± 9.84 mg/L) and fluoride (F^-) (0.20–0.56 mg/L; mean 0.40 ± 0.10 mg/L) all remain well below permissible limit except chloride for one site.

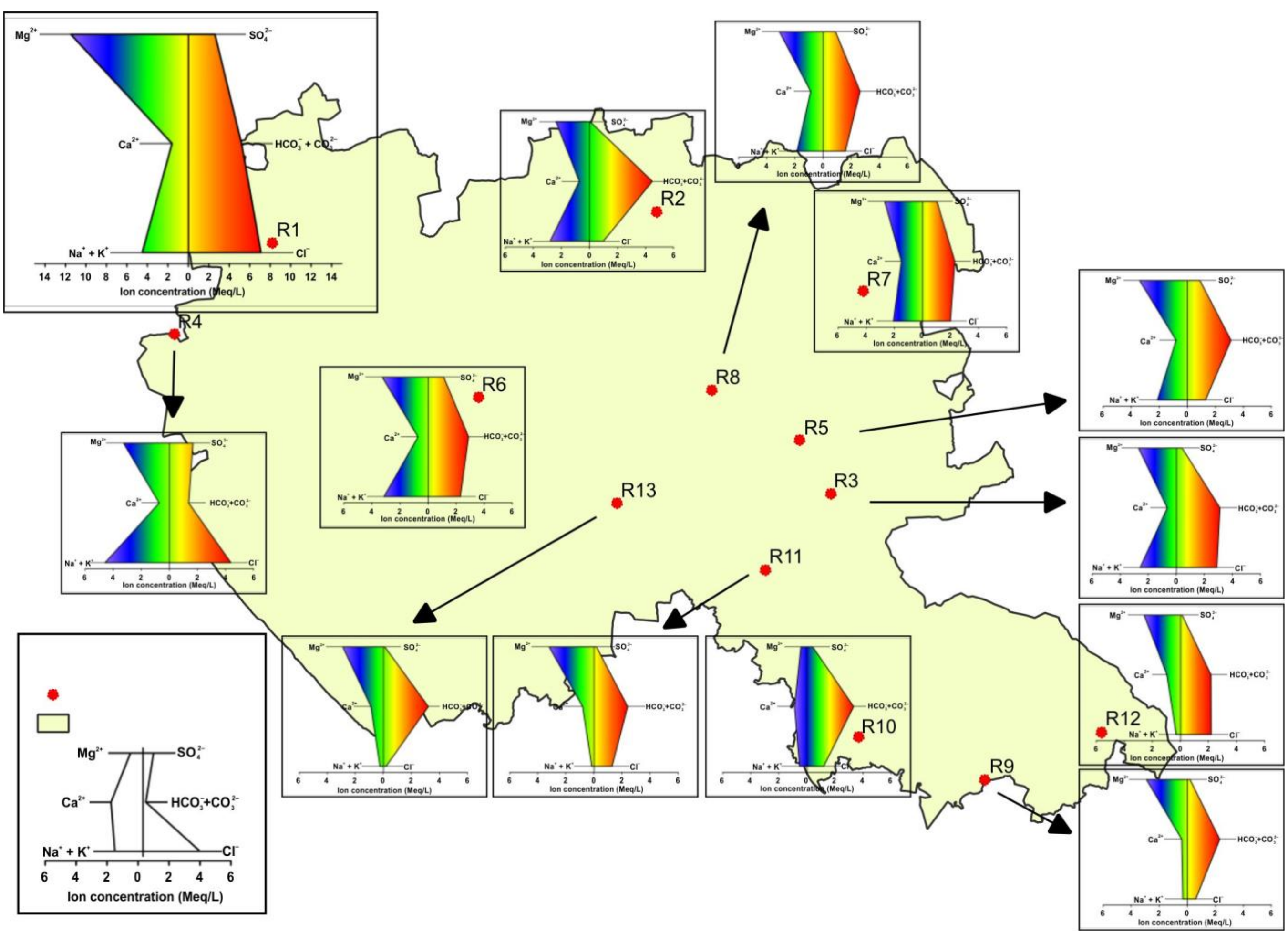

Fig. 4. Stiff plot for major ions of individual sample sites of Junagadh district (JND) of Saurashtra peninsula, India

TABLE-2
STATISTICAL DETAILS OF SURFACE AND GROUNDWATER PARAMETERS IN THE JND REGION WITH BIS (2012, 2015) AND WHO (2017) DRINKING WATER STANDARDS

Parameters	Max	Min	Mean	SD	BIS (2012, 2015)	WHO (2017)
pH	10.95	8.26	9.33	0.74	6.5-8.5	7-8
EC (µS/cm)	1603.00	473.00	671.08	298.68	750-3000	–
TDS (mg/L)	799.00	236.00	336.15	148.91	500-2000	600-1000
Temperature (ºC)	29.70	25.50	27.95	1.19	–	–
TA (mg/L)	315.00	84.00	180.38	60.50	200-600	–
TH (mg/L)	654.78	155.37	229.64	130.24	200-600	200
Na^+ (mg/L)	103.91	3.00	43.71	35.99	–	50-200
K^+ (mg/L)	3.47	0.30	1.43	1.03	–	12
Ca^{2+} (mg/L)	32.13	8.03	17.79	6.64	75-200	100-300
Mg^{2+} (mg/L)	139.63	28.99	45.01	28.98	30-100	-
Cl^- (mg/L)	251.70	7.09	76.63	65.01	250-1000	250
SO_4^{2-} (mg/L)	125.00	2.00	35.92	36.00	200-400	250
CO_3^{2-} (mg/L)	56.00	14.00	32.31	15.53	–	100
HCO_3^- (mg/L)	203.00	56.00	115.77	47.70	300-600	–
NO_3^- (mg/L)	34.00	5.00	14.23	9.84	45	50
F^- (mg/L)	0.56	0.20	0.40	0.10	1-1.5	1.5

Sites R1 and R4 exhibit seawater contamination effects caused by high evaporation and seawater-freshwater mixing near the coastal Ghed region of the Junagadh-Porbandar boundary. This indicates increasing chloride enrichment and salinity intrusion driven by climatic change, reduced freshwater inflow and rising sea levels [8,40].

Irrigation suitability indices: The evaluation irrigation by such indices provides insight into the hydrochemical behaviour of water and its potential impacts on soil and crop yield productivity [41]. Salinity hazard (SH), sodium adsorption ratio (SAR), residual sodium carbonate (RSC) and sodium percentage (Na%), provide an understanding of surface water compatibility with agricultural uses [15,23,42]. The salinity hazard (SH in µS/cm) values range from 477 to 1603 µS/cm shows in Fig. 5. According to Table-3 for SH, 84.62% of the sample sites lie in a good range, while 15.38% of the sample

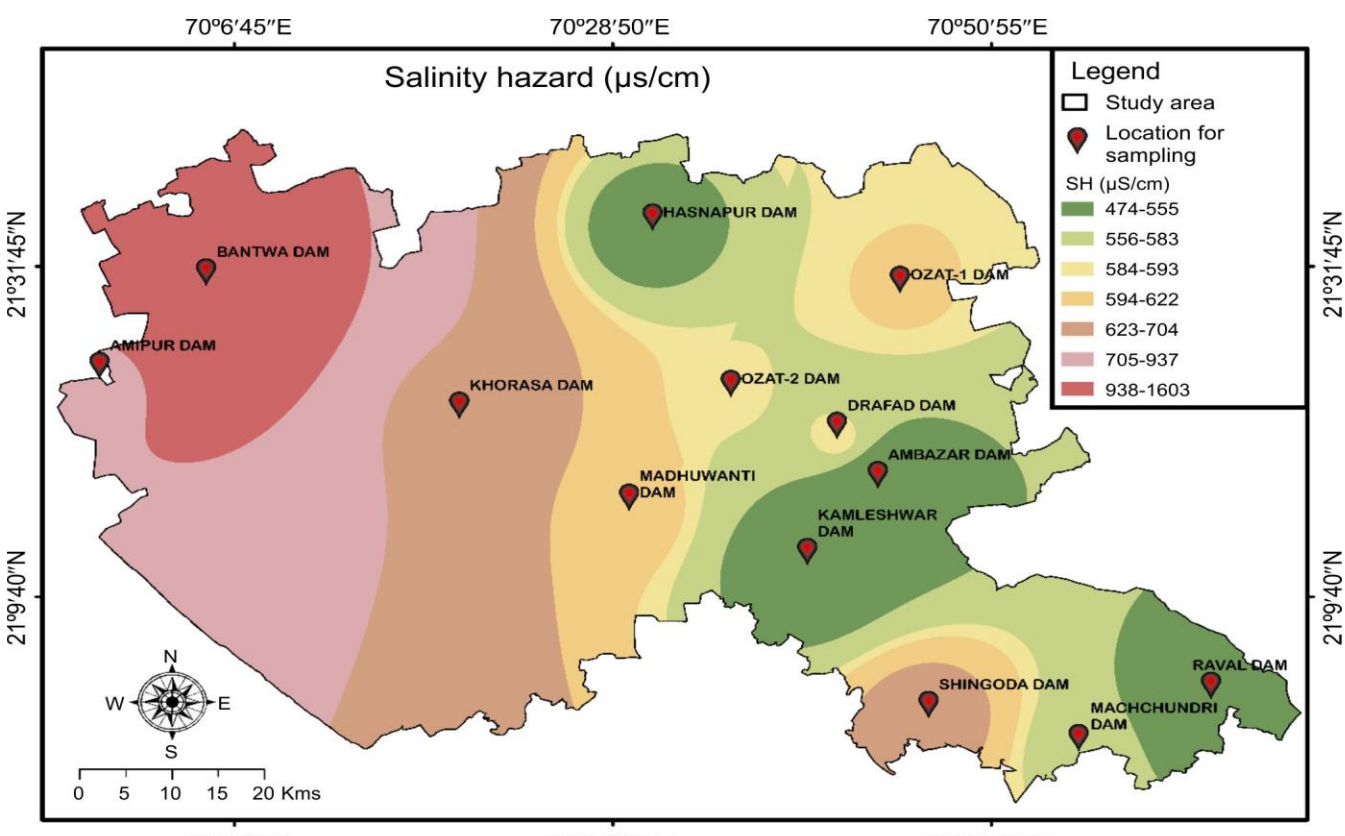

Fig. 5. Spatial distribution map of salinity hazard (SH) in study area JND of Saurashtra peninsula, India

TABLE-3
IRRIGATION SUITABILITY INDICES (SH, SAR, RSC AND Na %) AND WQI STATUS OF STUDY AREA (JND OF SAURASHTRA PENINSULA, INDIA)

Indices	Ranges	Status	Sample (%)
Salinity hazard (SH, µS/cm)	<250	Excellent	0
	250-750	Good	84.62
	750-2000	Permissible	15.38
	2000-3000	Doubtful	0
	>3000	Unsuitable	0
Sodium adsorption ratio (SAR, meq/L)	<10	Excellent	100
	10-18	Good	0
	18-26	Doubtful	0
	>26	Unsuitable	0
Residual sodium carbonate (RSC, meq/L)	<1.25	Excellent	100
	1.25-2.5	Doubtful	0
	>2.5	Unsuitable	0
Sodium percentage (Na %)	<20	Excellent	38.46
	20-40	Good	30.77
	40-60	Permissible	30.77
	60-80	Doubtful	0
	>80	Unsuitable	0
Water quality index (WQI)	<50	Excellent	15.38
	50.1-100	Good	84.62
	100.1-200	Poor	0
	200.1-300	Very poor	0
	>300	Unsuitable	0

have a permissible range. Higher EC value leads to increases in salinity. Here, in terms of SH, water is suitable for irrigation. The sodium adsorption ratio (SAR) has value ranges from 0.093 to 3.198 surrounding the district as shown in Fig. 6. All the sample sites lie in a good range, which indicates good water quality for agricultural applications. Higher sodium can impact the health of soil, which affects crop development [43]. According to Fig. 7, the value of residual sodium carbonate (RSC) ranged from -7.89 to 1.39, whereas the value of RSC has a good range of water quality for irrigation in the JND region. According to Fig. 8, the sodium percentage (Na%) value ranges from 3.3 to 52.6. The sodium percentage (Na%) shows that 38.46% of samples lie in the excellent range, 30.77% are in the good range and 30.77% are permissible, indicating low sodium hazard and generally safe irrigation water in the study area (Table-3). High sodium concentrations in irrigation water can adversely affect soil structure by reducing permeability and impairing root development, ultimately leading to decreased crop productivity [44,45]. Therefore, water with high sodium content is unsuitable for sustainable agricultural use. Based on the evaluated irrigation indices, the surface water in the JND region generally falls within excellent to moderate quality categories for agricultural irrigation. The U.S. Salinity Laboratory (USSL) diagram has a total of all 16 classes, providing deeper insight into the suitability of surface water for irrigation in the JND [46]. According to Fig. 9,

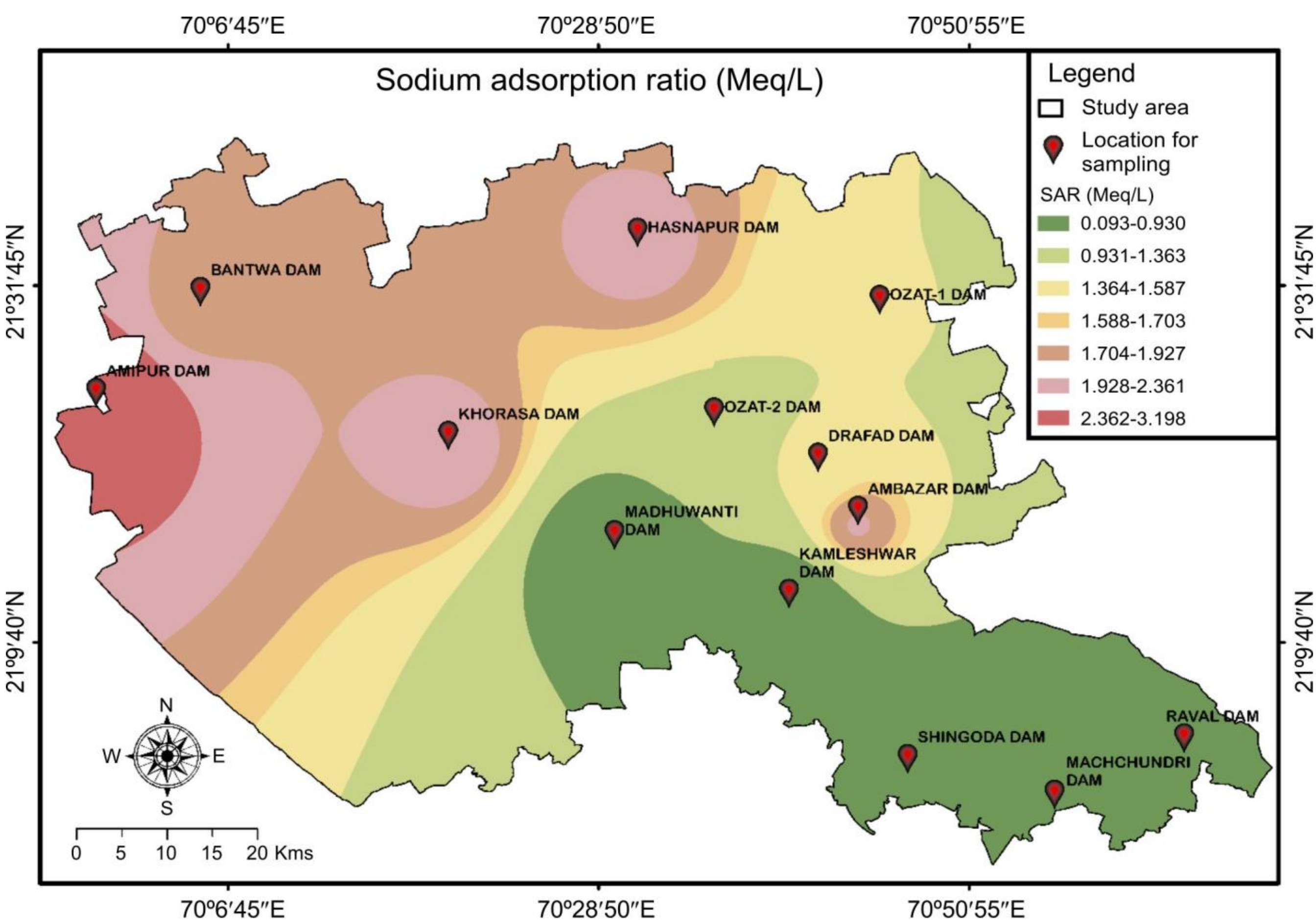

Fig. 6. Spatial distribution map of sodium adsorption ratio (SAR) in study area JND of Saurashtra peninsula, India

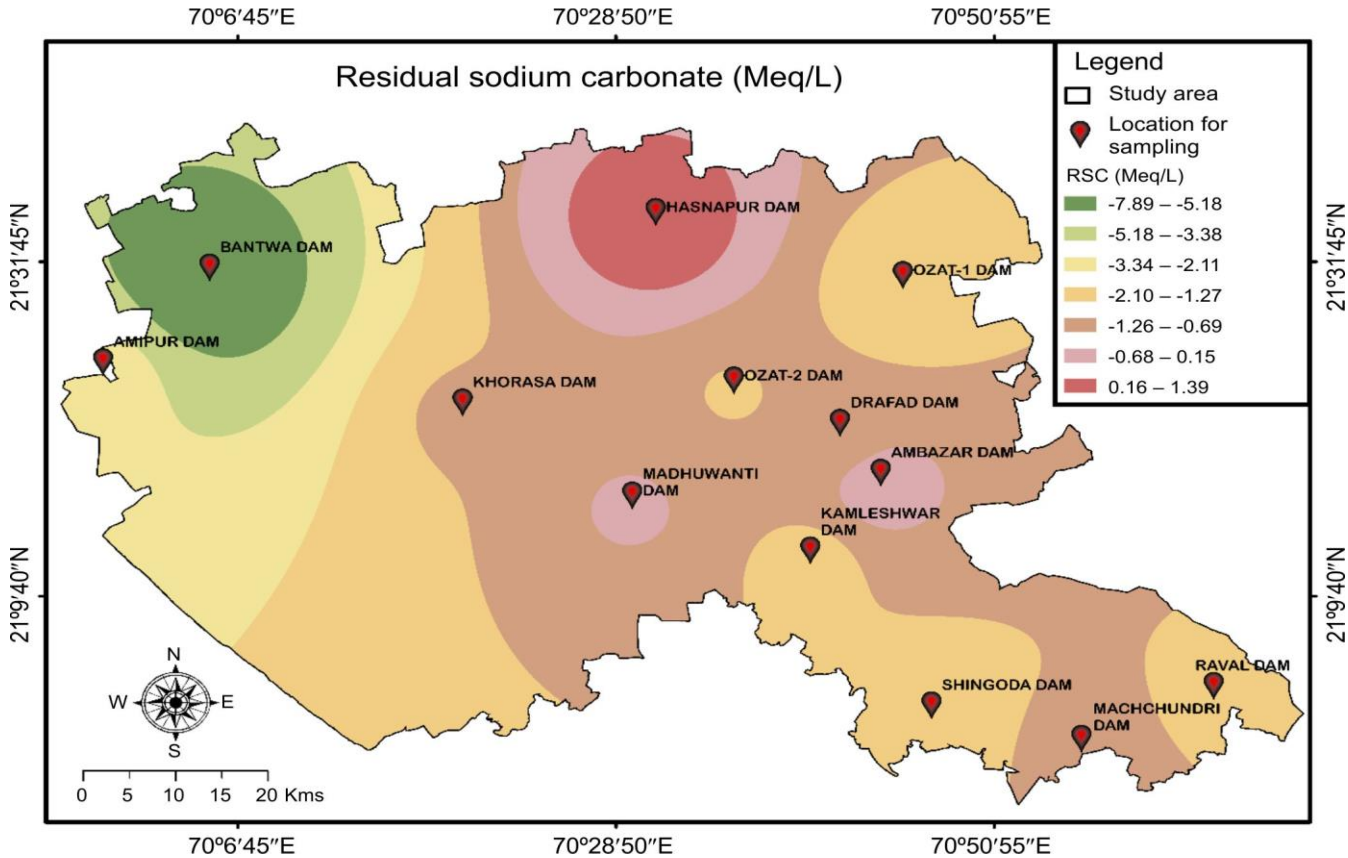

Fig. 7. Spatial distribution map of residual sodium carbonate (RSC) in study area JND of Saurashtra peninsula, India

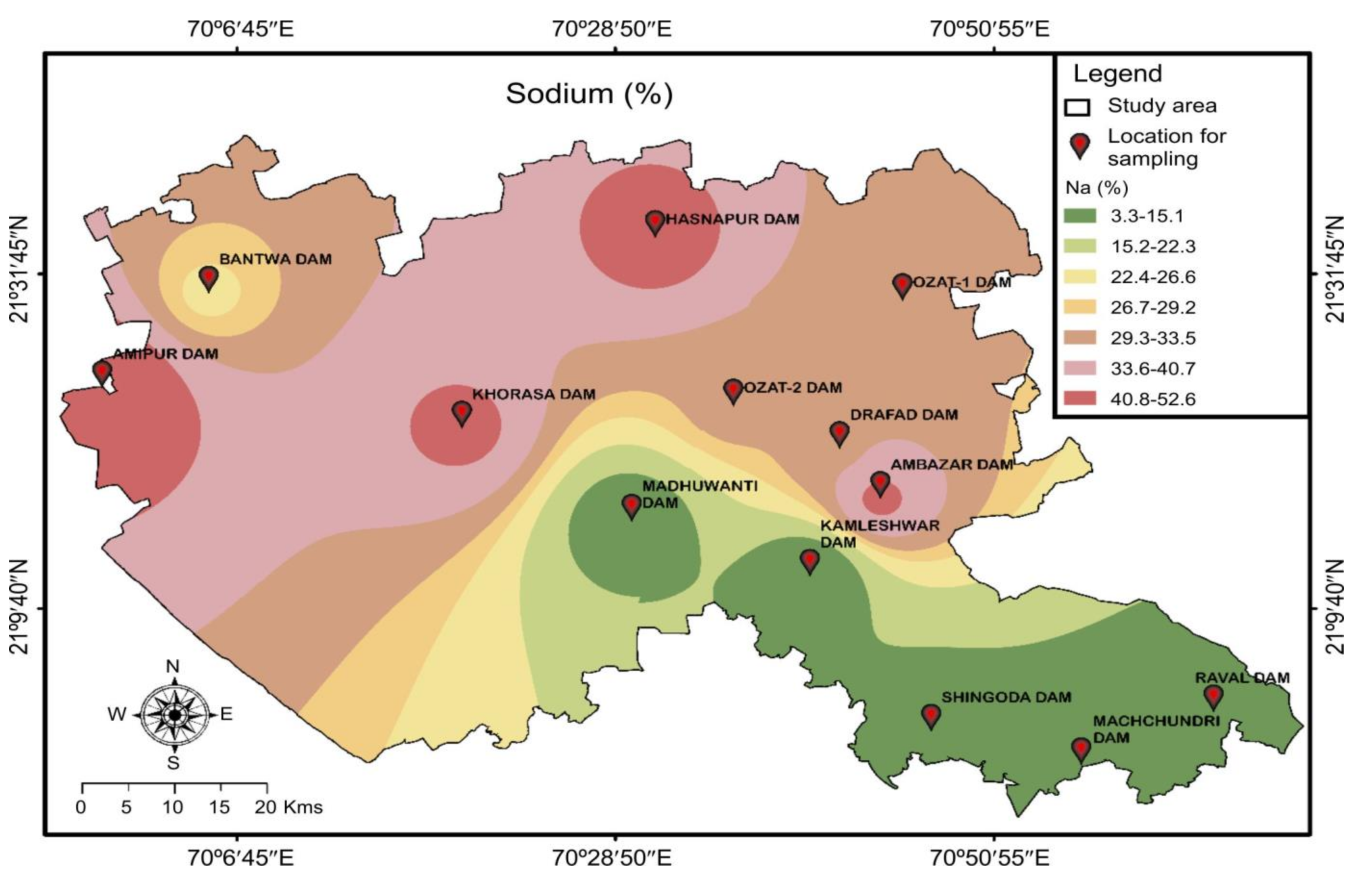

Fig. 8. Spatial distribution map of residual sodium percentage (Na%) in study area JND of Saurashtra peninsula, India

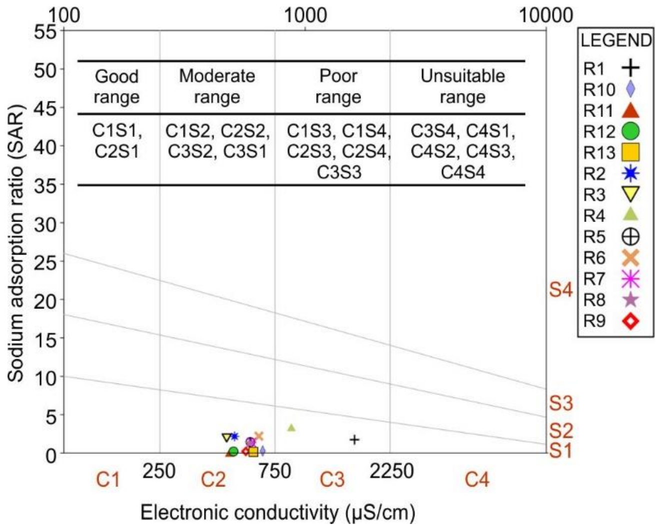

Fig. 9. USSL diagram (SAR *vs.* EC) shows surface water irrigation suitability of JND region of Saurashtra peninsula, India

TABLE-4
ASSIGNED WEIGHTS (w_i), WEIGHTAGE (W_i) AND PERMISSIBLE LIMITS (S_n) OF EACH PHYSICO-CHEMICAL PARAMETERS USED FOR WATER QUALITY INDEX (WQI) EVOLUTION

Parameters	w_i	W_i	WHO-2017 PL (S_n)
pH	2	0.049	8.5
TDS (mg/L)	5	0.122	1000
EC (μS/cm)	3	0.073	750 (BIS)
TH (mg/L)	2	0.049	200
Na^+ (mg/L)	3	0.073	200
K^+ (mg/L)	2	0.049	12
Ca^{2+} (mg/L)	2	0.049	300
Mg^{2+} mg/L)	2	0.049	100 (BIS)
Cl^- (mg/L)	4	0.098	250
SO_4^{2-} mg/L)	3	0.073	250
HCO_3 (mg/L)	3	0.073	600
NO_3^- (mg/L)	5	0.122	50
F^- (mg/L)	5	0.122	1.5
		$\sum W_i = 1.0$	

almost 11 sample sites lie in a good range (C2S1 zone) of water for irrigation. While 2 sample sites lie in moderate range (C3S1 zone) category of water quality.

Water quality index (WQI): According to Table-4, WQI is classified into five water quality categories. In Fig. 10, the WQI values range from 29.5 to 78.5. In JND, 84.62% of samples lie in the good water quality status of WQI and 15.38% of samples lie in the excellent water quality status [11,30]. This range reflecting JND reservoirs has a satisfying range for drinking and domestic purposes.

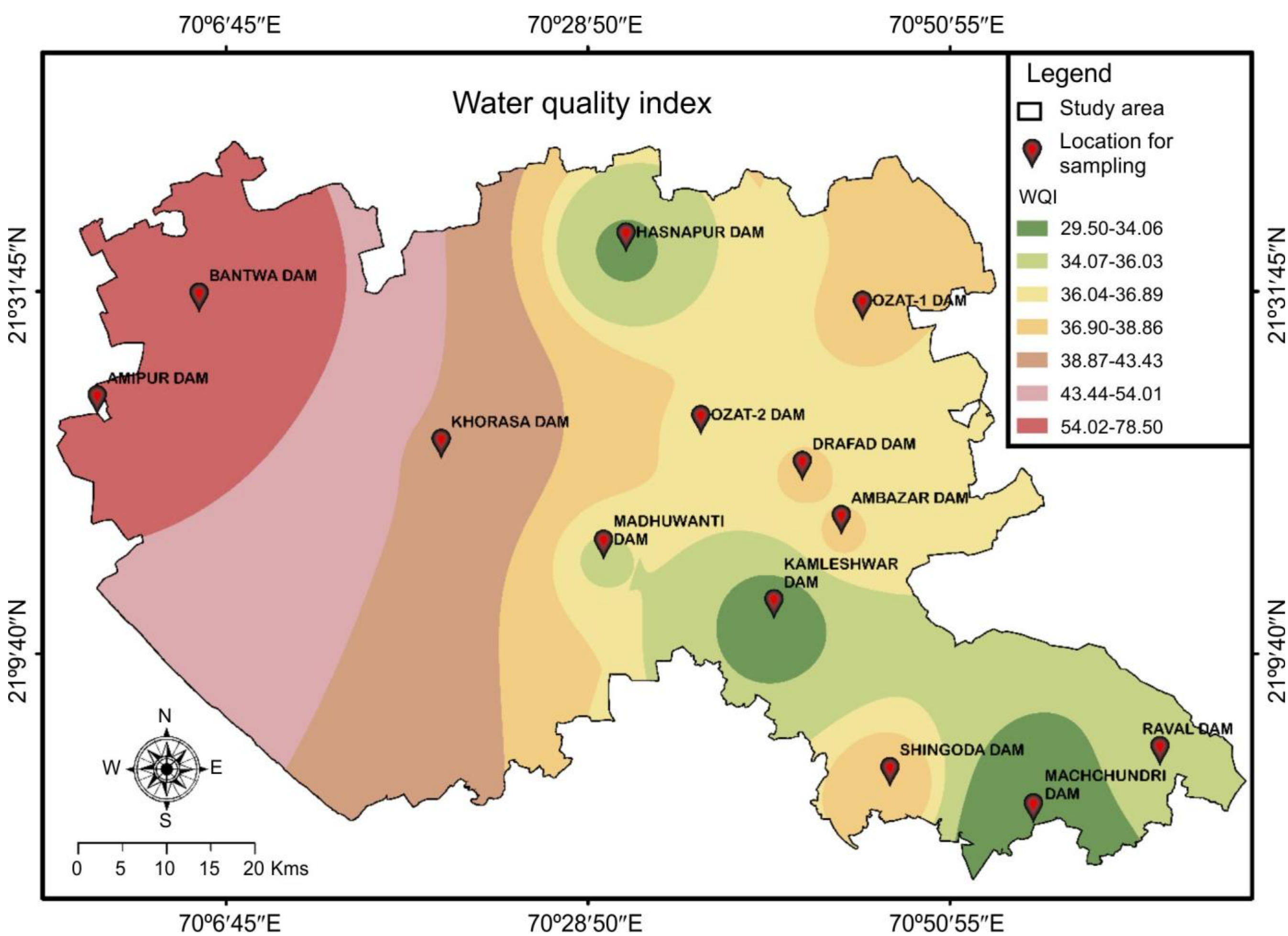

Fig. 10. Spatial distribution map of water quality index in JND region of Saurashtra peninsula, India

Hydrogeochemical characterisation

Hill piper trilinear diagram analysis: The Piper trilinear diagram (Fig. 11) illustrates the hydrochemical facies and water types of surface water in the JND region. From the diamond plot, alkaline earths (1→4→5) > alkalis (2→3→6) show Ca^{2+} + Mg^{2+} dominate over Na^+ + K^+ and weak acids (1→3→6) > strong acids (2→4→5) indicate that surface water is dominated by HCO_3^- [47]. Also, more than half of the samples plot in zones dominated by Ca^{2+}-Mg^{2+}-HCO_3^- type and other sample sites show mixed Ca^{2+}-Mg^{2+}-Cl^- type, while one site shows Na^+-K^+-Cl^- type. The observed patterns indicate the Na^+-K^+ enrichment, which is likely influenced by evaporation processes and/or anthropogenic inputs in the surface waters of the region. Interpretation of the Piper trilinear diagram shows Mg^{2+} as the dominant cation and HCO_3^- as the predominant anion [48]. Hence, based on the facts, the surface water was characterized by mixed hydrochemical facies, reflecting complex geochemical interactions and moderate mineralization within the study area.

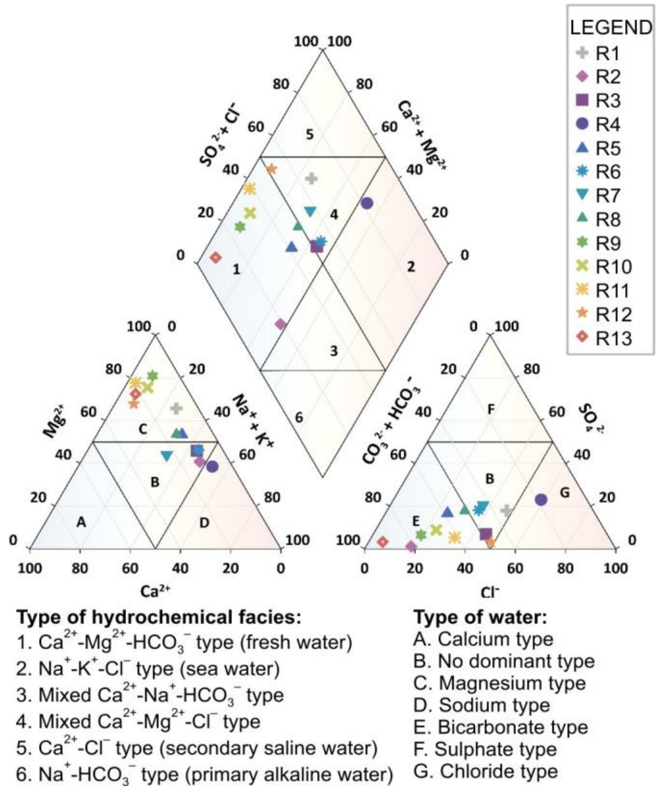

Fig. 11. Hill piper trilinear diagram of study area (Junagadh district of Gujarat, India)

Mechanism controlling by Gibbs diagram: The Gibbs diagram identifies the mechanisms controlling surface water chemistry and provides a strong framework for understanding the geochemical relationships [16,41]. In Fig. 12a, the Gibbs-I diagram reveals that most samples fall between rock weathering and that surface water chemistry is primarily controlled by rock-water interaction. In Fig. 12b, the Gibbs-II diagram shows most samples in rock weathering, indicating

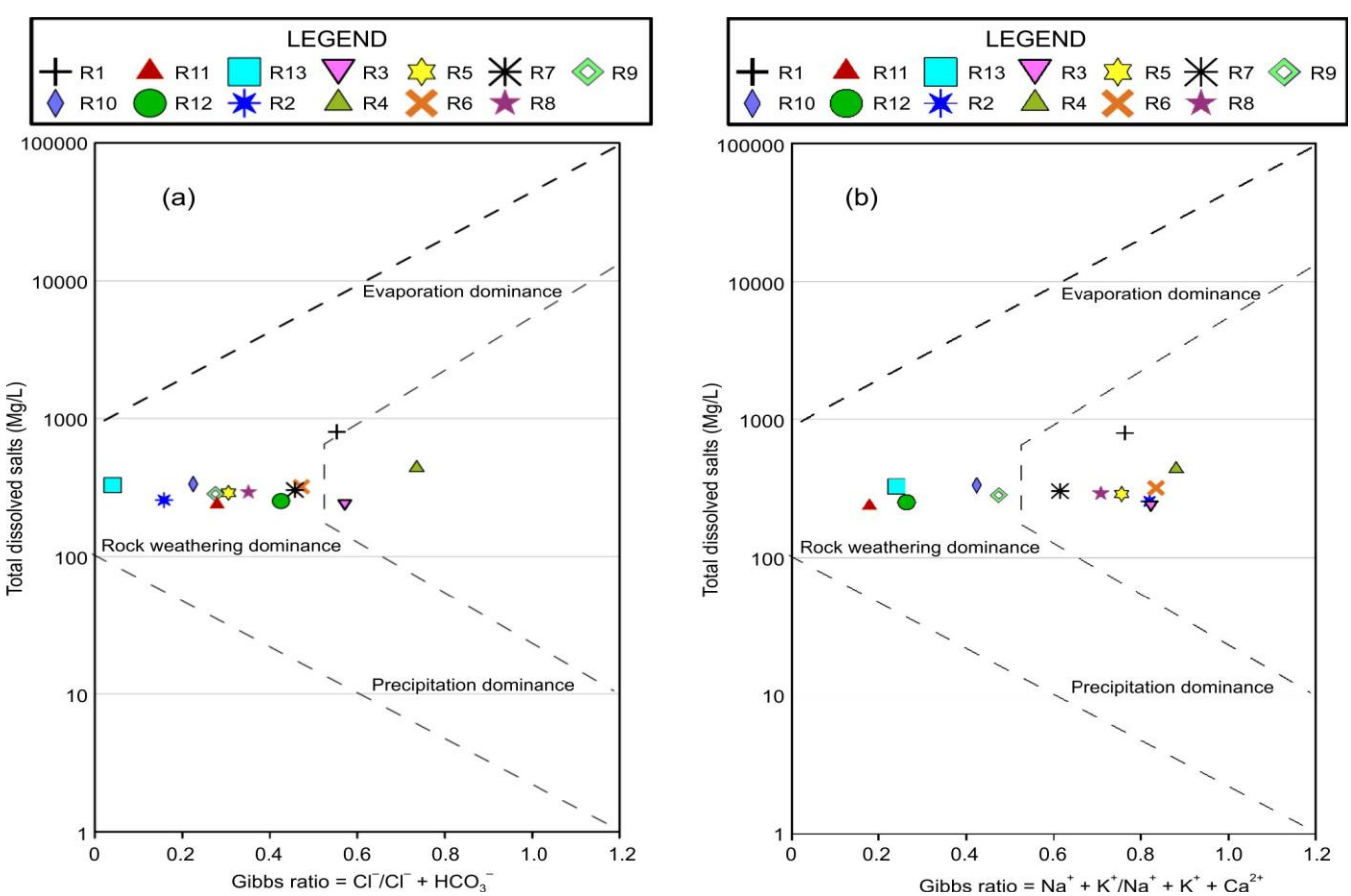

Fig. 12. Gibbs diagrams (a) anion and (b) cation of study area of JND of Saurashtra peninsula, India)

that surface water chemistry is mainly governed by rock-water interaction. The higher values of Gibbs ratios and TDS indicate strong evaporative effects influence [49].

Conclusion

In this investigation, the hydrochemical properties of 13 surface-water reservoirs in the Junagadh district (JND) of Saurashtra Peninsula, Gujarat state of India were evaluated by utilizing 16 physico-chemical parameters by following protocols of APHA (2017) standards. Reservoir waters are mostly alkaline, but two coastal sites near the Porbandar–Junagadh border have higher sodium and magnesium levels than desirable because of the influence of marine or evaporation effects. The spatial distribution of water quality variations showed clear spatial trends in the ionic concentration and suitability indices. The USSL diagram and the irrigation suitability indices show that most sites are good to moderate, which means that the salinity and sodicity levels are good for irrigation. The WQI results show that most of the surface waters in JND are in the excellent to good range, which means that there is no involvement of natural or anthropogenic factors. The most common hydrochemical facies are Ca^{2+}–Mg^{2+}–HCO_3^- and mixed Ca^{2+}–Mg^{2+}–Cl^- types. Gibbs diagrams indicate that rock weathering is the main geochemical process that controls water chemistry. Thus, based on the results, the surface waters in Junagadh district are suitable for drinking and irrigation, but targeted monitoring and management are essential to control salinisation and high alkalinity for the sustainability of water quality.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interests regarding the publication of this article.

DECLARATION OF AI-ASSISTED TECHNOLOGIES

During the preparation of this manuscript, the authors used an AI-assisted tool(s) to improve the language. The authors reviewed and edited the content and take full responsibility for the published work.

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