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Research Article

Groundwater usage characterization in a tribal stretch infected with chronic kidney disease of unknown etiology (CKDu)

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ABSTRACT

This reconnaissance study was carried out in urgency as residents complained of groundwater contamination in a tribal stretch infected with chronic kidney disease of unknown etiology in central India where at least 100 people have already died and more than 300 hospitalized. Multi-indexing techniques were used to evaluate groundwater quality for drinking, irrigation, and industrial purposes. The comprehensive water quality index (CWQI) classifies ~52 % of the 27 collected samples suitable for drinking, and ~37 % partially suitable pending certain treatment. While the relative abundance of chemical parameters stands at $Ca^{2+} > Na^+ > Mg^{2+} > K^+$ for cations and $HCO_3^- > Cl^- > NO_3^- > SO_4^{2-} > F^-$ for anions, the groundwater in the area suffers from general hardness, nitrate, and fluoride contamination. It is hypothesized that fluoride ions possibly couple with excess alkaline earth elements and anions to form metal-complexes inviting Hofmeister phenomena to act in the human kidneys through ingested groundwater. For agricultural water quality assessment, historically developed 10 irrigation indices have been used that classify most groundwater samples suitable for agriculture. Corrosivity indices reveal that the groundwater has moderate to high corrosive affinity. Although the results of the irrigation and corrosivity indices are coherent with CWQI water classes, the use of so many indices based on certain chemical parameters to evaluate water samples for agricultural purposes delivers mixed results and confuses workers about the actual water quality in the field. This calls for the development of a new, robust, and comprehensive standard for appraisal of irrigation water quality that could be used uniformly worldwide.

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Introduction

Chronic kidney disease of unknown etiology (CKDu) is a recent discovery in this part of the world in central India in a tribal stretch. About 100 people have already died and more than 300 compulsively hospitalized from a single village, Supebeda, that consists of only 1200 people in the state of Chhattisgarh. Media reports since 2018 and public outcry nationally compelled many Government agencies to visit the area and investigate the malady to find a solution. Although medical teams ascribed the menace to CKDu (Chowdhary et al., 2020), common people still believe that groundwater is the real culprit (Rathore et al., 2022). The entire village historically relies on this precious resource for all their water use. Two of the present authors visited the area in 2020 and made a quick appraisal of its groundwater quality (Dewangan and Verma, 2022). Since no serious quality deterioration could be detected, Herojeet et al. (2023) made an in-depth analysis of the collected data and found that the area indeed suffers from nitrate (NO_3^-) and fluoride (F^-) contamination. They did make a deterministic and probabilistic modeling of the human health risk assessment due to these contaminants, but a wholesome picture of the groundwater quality from usage perspective could not be brought out. Hence the present investigation.

Literatures on CKDu reveal that agricultural workers are mostly the victims of this enigmatic disease throughout the world (Bradley et al., 2024; Fiseha et al., 2024). While Hettithanthri et al. (2021) define the characteristics of the affected population as low-income agricultural workers aged 30–60 years, Nayak et al. (2023a) directly link farming and water sources to the origin of CKDu based on 25 case studies from around the globe. This study was, therefore, extended from drinking water appraisal to deciphering groundwater quality for agricultural purposes so that some important evidences on the genesis of CKDu could be discerned. Besides, since the economy of this region depends on agriculture, it is imperative that the quality of groundwater is examined from its irrigational suitability perspective. Till date, researchers have mainly focused on studies related to several multifactorial features, such as hydrogeochemical investigations, source apportionment of chemicals, heat stress, agrochemicals, genetic predisposition, nonsteroidal anti-inflammatory drugs, infectious diseases (leptospirosis), and other nephrotoxic medications while working on CKDu (Gifford et al., 2017; Jolly and Thomas, 2022; Hettithanthri et al., 2021; Redmon et al., 2021). Very limited work has so far been done on the suitability of groundwater resources for various water uses, such as for drinking, agriculture, and industry, in a CKDu area. This work fulfils this gap in knowledge in the quest for finding a solution to the infection by CKDu.

Chhattisgarh State is rapidly implementing the Government of India's ambitious "National Jal Jeevan Mission" in which "Har Ghar Jal (water in every home)" is the popular slogan (Press Information Bureau, 2024). This scheme aims to provide every household in the country with access to piped water connections to ensure a clean drinking water supply, thus improving public health and sanitation (Sustainable Development Goal 6). To alleviate apprehension of CKDu infection due to water usage in Supebeda, the State Government is in the process of prioritizing implementation of this scheme in this region. But then since the modus operandi of the scheme shall involve pipelines and many other fixtures made up of metals for storing and transporting groundwater from high-yielding borewells, it is essential that the corrosiveness of the water is examined to ensure safety and efficient performance of these materials. Moreover, because this study area lies in a 'naxal-prone' zone affected by the Left Wing Extremism (Press Information Bureau, 2019), the Indian Government has a long-term plan to industrialize the region to enhance employability of the people and engage them in the rightful way. Since industrialization shall involve heavy machinery and use of various kinds of materials, it is vitally important that groundwater is evaluated adequately for its corrosiveness and affinity to scaling.

Supebeda has been constantly drawing the Government's attention recently because of the public sufferings due to CKDu, and it is likely that this area shall be prioritized for early implementation of all Government's schemes. Therefore, the primary objective of this study is to characterize the groundwater resources of this village from various usage perspectives, such as for drinking, agricultural and industrial purposes, using multi-indexing techniques and statistical analyses, keeping an eye on any possible breakthrough on the genesis of CKDu for the greater good of humanity. The study answers the following five essential hypothetical questions: (1) Whether groundwater is potable? (2) Whether there is a link between drinking water and CKDu? (3) Whether groundwater is suitable for agricultural purposes? (4) Whether groundwater quality will hinder the Government's endeavors for piped water supply to the villages? (5) How good groundwater is for industrial usage?

Chronic kidney disease (CKD) is the third fastest growing malady infecting about 850 million people globally (Nature, 2024). It's predicted to become the fifth highest cause of years of life lost by 2040 from a rank of sixteenth in 2016 (Foreman et al., 2018) and twelfth in 2017 (Global Burden of Disease – Chronic Kidney Disease Collaboration, 2020). It causes the highest economic burden of any disease group in the low-and lower-middle-income countries (Essue et al., 2017; Levin et al., 2023), such as Sri Lanka (Abeysekera et al., 1996), Central American nations (Trabanino et al., 2002), Tunisia (Abid et al., 2003), Egypt (Minshawy, 2011), and India (Rajapurkar et al., 2012). What is intriguing is its unknown etiology (CKDu) primarily affecting the economically weaker sections of society, such as farming communities (Hettithanthri et al., 2021; Bradley et al., 2024; Fiseha et al., 2024). While groundwater is considered the root cause of CKDu in Sri Lanka (Imbulana and Oguma, 2021; Zeng et al., 2022; Shi et al., 2023; Chandrajith et al., 2024), this hypothesis is supported by many other workers worldwide, such as by Khandare et al. (2015), Lal et al. (2020), Tatapudi et al. (2019), and Mascarenhas et al. (2017) in India, Campese (2017) in central America and most recently by Nayak et al. (2023a) globally. In India, it is reported in the States of Andhra Pradesh (Ramesh et al., 2011; Ganguli, 2016), Goa (Mascarenhas et al., 2017), Delhi (Ghosh et al., 2017), Tamil Nadu (Parameswaran et al., 2020), Odisha (Mohanty et al., 2020), Maharashtra (Mogal, 2020), and

Chhattisgarh (Chowdhary et al., 2020), a part of which forms the present study area of Supebeda. The fact that about one-fourth of the Supebeda's population suffers from CKDu, the economic turmoil on the families of this village can very well be visualized.

The village Supebeda is important because it is for the first time that CKDu infection of such a greater magnitude (100+ deaths and 300+ hospitalizations) has occurred in India. And it is the second time in the history of CKDu investigations that groundwater is being studied in detail from a utilization perspective. The first such study was carried by Hu et al. (2024) in Sri Lanka for drinking and industrial purposes, but their appraisal in terms of groundwater potability is of limited scope due to adoption of three indices that give contrasting results. Moreover, they do not identify any violating parameter(s) that could possibly be playing a role in the etiology of CKDu. The present analysis is unique in the sense that it evaluates the groundwater resources of a CKDu region not only for drinking but also for agricultural and industrial purposes by using all conventional techniques prevalent in literature. It answers many pertinent questions the public in such areas have been asking the medical professionals and authorities for quite some time. Besides, it identifies many violating parameters that are members of the Hofmeinster ion series, strongly hypothesized as a dominant factor for the onset of CKDu (Rajkumar et al., 2025a). The outcome of this study will, therefore, not only help the people of Supebeda but also the millions of people suffering from CKDu around the globe.

1. Materials and methods

1.1. Study area

Village Supebeda, with a population of 1200 people, occupies a geographical area of 3 km^2 in the administrative district of Gariabandh, Chhattisgarh State, India (Fig. 1). It is situated beside the river Tel that demarcates its border with the Indian State of Odisha in the east. Agriculture is the primary occupation of the villagers, and rice is their staple food. Farm workers mostly spend their time in the field with limited access to clean drinking water. The village has nearly equal male-female ratio and a literacy rate of 50.51 %. Climatologically, the area is characterized by subtropical monsoon conditions. The area receives moderate annual rainfall (1200 mm) with a winter temperature of 5 °C–25 °C and summer of 29 °C–46 °C.

1.2. Local hydrogeology

Three distinct lithological units, (i) migmatiticquartzo feldspathic gneiss, (ii) banded augen gneiss and (iii) hornblende granite, characterize the area (Gupta et al., 2000; Neogi and Das, 2000). Herojeet et al. (2023) give a detailed account of the mineralogical composition of these geological formations (Fig. 1). Groundwater occurs in both unconfined and confined conditions in the aquifers. The weathered portion at shallower level (< 20 m) define the unconfined conditions with the occurrence of semi-confined to confined conditions at depth in the charnockite and khondalite. The surface topography controls the movement of groundwater toward the

low-lying areas, and regionally toward the Tel River, in unconfined aquifers, as depicted by the water table elevation contours (240–260 m). Large-diameter wells (dugwells) with a depth range of 7–16 m and a yield range of 25–40 m^3/day tap the shallower unconfined aquifers, while 50–80 m deep borewells withdraw groundwater from depth with a yield of 85–430 m^3/day. Borehole records identify major fracture zones at three distinct depth zones: 40–45, 60–65, 75–80 m. Transmissivity of the aquifers varies between 15 and 45 m^2/day that occasionally goes up to 100 m^2/day depending on site conditions.

1.3. Groundwater sampling and analysis

Groundwater samples were strategically collected from 27 active wells (26 borewells of about 60 m depth and one dugwell (G9) of about 10 m depth) around the village Supebeda in the premonsoon season of May 2020. Attempt was made to collect a sample from each borewell location inside the village or at least from one borewell if the two borewells are in closer proximity. One pair of groundwater samples was collected from each location with 1000 mL size High-Density Polyethylene (HDPE) plastic bottles that were prewashed with HNO_3 (10 %) and rinsed with double-deionized water. During field operation, borewells were pumped out for 10–15 min to get fresh groundwater and the sampling bottles were thoroughly rinsed 2–3 times with this water before sampling to retain its naturality. Essential field parameters (pH, electrical conductivity (EC), and total dissolved solids (TDS)) were measured onsite with the help of portable instruments, such as pH/EC/TDS meters (Hanna HI 9811–5). Whatman filter paper (0.45 μm) was used to filter the groundwater samples to remove the suspended particulate matters. The samples were acidified with HNO_3 (pH ~2) and kept at 4 °C to preserve their original character. The internationally accepted American Public Health Association (2005) protocols were adopted for analyzing the major cations (Ca^{2+}, Mg^{2+}, Na^+, and K^+) and anions (HCO_3^-, Cl^-, SO_4^{2-}, F^-, and NO_3^-). Using double-deionized water, Merck-GR grade chemicals and reagents were used to prepare the chemical solutions. All glassware and apparatus were rinsed with 10 % hydrochloric acid for one full day and re-cleaned with double-deionized water. For instrumental calibration, blank samples were prepared from the stock solutions of each chemical parameter. Charge balance error (CBE) equation was used to examine the analytical accuracy with an acceptable limit of ± 5 % (Hounslow, 2018) (Eq. (1)).

$$\text{CBE \%} = \frac{\sum (\text{Cations})\text{meq/L} - \sum (\text{Anions})\text{meq/L}}{\sum (\text{Cations})\text{meq/L} + \sum (\text{Anions})\text{meq/L}} \times 100 \qquad (1)$$

1.4. Drinking water quality parameters

1.4.1. Comprehensive water quality index (CWQI)
Besides the drinking water quality standards defined by the Bureau of Indian Standards (BIS, 2012) and the World Health Organization (WHO, 2022), an indexing technique called 'comprehensive water quality index (CWQI) (Rajkumar et al., 2022) based on the relaxable and non-relaxable physicochemical parameters has been used to appraise the suitability of Supebeda's groundwater for drinking purposes. Relaxable pa-
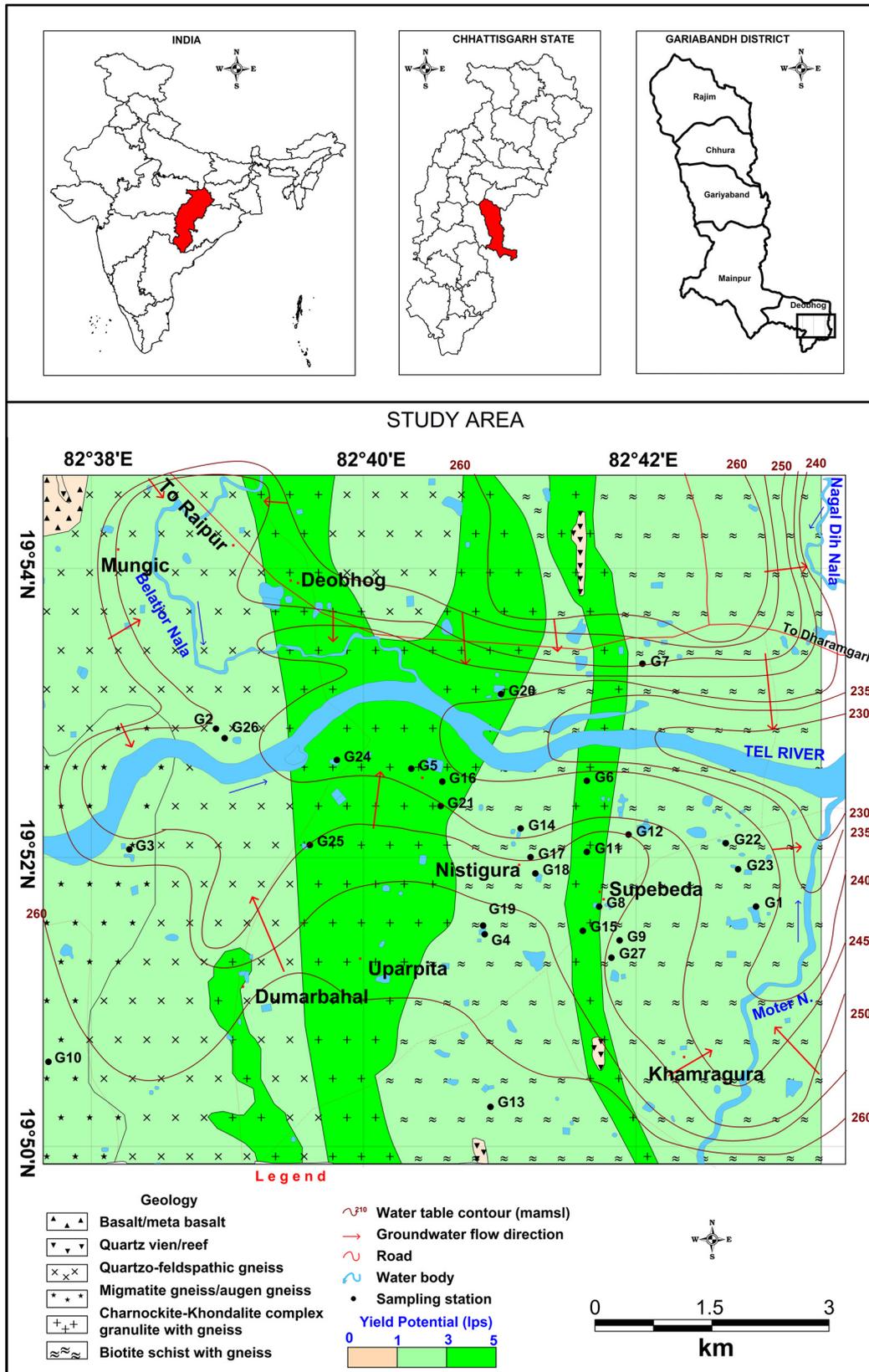
Fig. 1 – Sampling locations and hydrogeology in village Supebeda, district Gariabandh, Chhattisgarh state, India.

rameters are those that have acceptable and permissible limits (in the absence of an alternative source of water) as per the BIS (2012), and non-relaxable parameters are those that have only one permissible limit (BIS, 2012) or guideline value (WHO, 2022). In the present study, pH, TDS, TH, Ca^{2+}, Mg^{2+}, Cl^-, and F^- are relaxable parameters, while EC, Na^+, K^+, HCO_3^-, and NO_3^- are non-relaxable parameters.

The quality rating (q_i) of a parameter in a water sample(x) is computed by the numerical difference between its acceptable limit (AL) and measured value in the sample divided by its AL, as shown in Eq. (2).

$$q_i = \frac{AL_i - V_i}{AL_i} \qquad (2)$$

where, V_i = the actual concentration of the measured parameter (i^{th}) and AL = acceptable limit of this (i^{th}) parameter as per the BIS (2012).

In this calculation, if the AL of a parameter is not given by the BIS (2012), its WHO (2022) guideline value is considered for evaluation, viz., for EC, Na^+, K^+, and HCO_3. If the water sample(x) consists of m number of parameters (i.e., m_a, m_b, m_c, , m_z), two segments of quality rating (q_i) calculation, as given below, is possible depending on the concentration of each parameter and their q_i values.

(i) When the concentration of a parameter (for example, $i_{m_a}{}^{th}$ parameter) is less than or equal to its acceptable limit ($V_{i_{m_a}} \leq AL_{i_{m_a}}$) or guideline value ($V_{i_{m_a}} \leq GV_{i_{m_a}}$): In this case, the impact of $i_{m_a}{}^{th}$ parameter shall have negligible or no health implication and its quality rating value ($q_{i_{m_a}}$) will bear a positive value.

$$q_{i_{m_a}} = \frac{AL_{i_{m_a}} - V_{i_{m_a}}}{AL_{i_{m_a}}} \text{ or } q_{i_{m_a}} = \frac{GV_{i_{m_a}} - V_{i_{m_a}}}{GV_{i_{m_a}}} \qquad (3)$$

where, $V_{i_{m_a}}$ = the actual concentration of the measured parameter ($i_{m_a}{}^{th}$) in the water sample(x), $AL_{i_{m_a}}$ = acceptable limit of the $i_{m_a}{}^{th}$ parameter, and $GV_{i_{m_a}}$ = guideline value of the $i_{m_a}{}^{th}$ parameter.

(ii) When the measured concentration of a parameter (for example, $i_{m_b}{}^{th}$ parameter) exceeds its acceptable limit ($V_{i_{m_b}} > AL_{i_{m_b}}$) or guideline value ($V_{i_{m_b}} > GV_{i_{m_b}}$): In this case, the $i_{m_b}{}^{th}$ parameter of the water sample(x) may have an immediate or long-term health effect and its quality rating value ($q_{i_{m_b}}$) will be a negative value.

$$q_{i_{m_b}} = \frac{AL_{i_{m_b}} - V_{i_{m_b}}}{AL_{i_{m_b}}} \text{ or } q_{i_{m_b}} = \frac{GV_{i_{m_b}} - V_{i_{m_b}}}{GV_{i_{m_b}}} \qquad (4)$$

where, $V_{i_{m_b}}$ = the actual concentration of the measured parameter ($i_{m_b}{}^{th}$) in the sample(x), $AL_{i_{m_b}}$ = acceptable limit of the $i_{m_b}{}^{th}$ parameter as per the BIS (2012), and $GV_{i_{m_b}}$ = guideline value of the $i_{m_b}{}^{th}$ parameter.

Further, the quality rating (q_i) of a chemical parameter in the water sample(x) is multiplied by its corresponding relative weight (W_i) to generate a sub-index (SI_i) value:

$$SI_i = q_i \times W_i \qquad (5)$$

where, W_i is the relative weight of the ith parameter, which is, in fact, the normalized unit weight of this parameter. The SI value of a parameter can have a positive (SI_{pi}) or negative (SI_{ni}) value depending on its quality rating (q_i) calculated as per Eqs. (3) and (4) above. Rajkumar et al. (2022) generated the normalized unit weight (W_i) of selected parameters based on the analytical hierarchy process (AHP) (Appendix A Table S1).

Based on SI values, the CWQI in a water sample may be defined as follows:

$$CWQI = \sum_{i=1}^{m} SI_i \qquad (6)$$

But, since in a water sample, two segments (positive or negative) of q_i, and therefore SI, values are possible, CWQI too shall have two components, i.e., positive CWQI (P_{CWQI}) and negative CWQI (N_{CWQI}), as follows:

$$P_{CWQI} = \sum_{i=1}^{m_1} SI_{pi} \qquad (7)$$

$$N_{CWQI} = \sum_{i=1}^{m_2} SI_{ni} \qquad (8)$$

where, with the total number of chemical parameters in the water sample being m (i.e., $m = m_1 + m_2$), m_1 = number of parameters that have positive SI values (SI_{pi}) in the water sample and m_2 = number of parameters that have negative SI values (SI_{ni}) in the same water sample.

A N_{CWQI} score shall always be represented by a negative (-) symbol since this score is based on the cumulative value of the negative quality ratings (q_i) of a set of parameters that shall have negative sub-index (SI_{ni}) values (since they exceed their acceptable/guideline limits). The overall classification of a water sample is based on its cumulative N_{CWQI} value, as explained in Table 1.

Unlike other water quality indices, CWQI does not average out the quality rating (q_i) values of the chemical parameters in a water sample to obtain a cumulative figure to characterize the water sample, but considers the cumulative scores of both positive CWQI (P_{CWQI}) and negative CWQI (N_{CWQI}) values separately to classify the water sample for a specific usage. Therefore, the water classification based on CWQI is more reliable than those of the conventional water quality indices available in the literature.

1.5. Irrigation water quality indices

Besides using the irrigation quality criteria prescribed by the Food and Agriculture Organization (FAO, 1994), various historically developed irrigation water quality indices have been used, such as Kelly ratio (KR) (Kelly, 1940), residual sodium carbonate (RSC) (Eaton, 1950), sodium adsorption ratio (SAR) (Richards, 1954), percent sodium (%Na) (Wilcox, 1955), permeability index (PI) (Doneen, 1961), potential salinity (PS) (Doneen, 1961), magnesium hazard (MH) (Szabolcs and Darab, 1964), and synthetic harmful coefficient (K) (Zhou et al., 2009). The following equations define these

Table 1 – Classification of groundwater samples based on Comprehensive Water Quality Index (CWQI) in village Supebeda, district Gariabandh, Chhattisgarh state, India.

CQWI ranges			Classes	No. of samples
P_{CWQI} score	N_{CWQI} score	N_{CWQI} numerical score		Premonsoon
$0 \leq P_{CWQI} \leq 1.0$	$N_{CWQI}=0$	$N_{CWQI}=0$	Excellent	6
$0 \leq P_{CWQI} \leq 1.0$	$0 > N_{CWQI} \geq \frac{ML}{4}$	$0 > N_{CWQI} \geq -0.21$	Good	15
$0 < P_{CWQI} \leq 1.0$	$\frac{ML}{4} > N_{CWQI} \geq \frac{2ML}{4}$	$-0.21 > N_{CWQI} \geq -0.42$	Marginal	3
$0 < P_{CWQI} \leq 1.0$	$\frac{2ML}{4} > N_{CWQI} \geq \frac{3ML}{4}$	$-0.42 > N_{CWQI} \geq -0.63$	Poor	NIL
$0 < P_{CWQI} \leq 1.0$	$\frac{3ML}{4} > N_{CWQI} \geq ML$	$-0.63 > N_{CWQI} \geq -0.84$	Very poor	3
$0 < P_{CWQI} \leq 1.0$	$N_{CWQI} < ML$	$N_{CWQI} < -0.84$	Unacceptable	NIL

P_{CWQI}: positive comprehensive water quality index; N_{CWQI}: negative comprehensive water quality index; ML: maximum limit.

indices numerically.

$$KR = \frac{Na^+}{(Ca^{2+} + Mg^{2+})} \times 100 \quad \text{(Kelly, 1940)} \quad (9)$$

$$RSC = (HCO_3^-) - (Ca^{2+} + Mg^{2+}) \quad \text{(Eaton, 1950)} \quad (10)$$

$$SAR = \frac{Na^+}{\sqrt{\frac{Ca^{2+}+Mg^{2+}}{2}}} \quad \text{(Richards, 1954)} \quad (11)$$

$$\%Na = \frac{(Na^+ + K^+)}{(Ca^{2+} + Mg^{2+} + Na^+ + K^+)} \times 100 \quad \text{(Wilcox, 1955)} \quad (12)$$

$$PI = \frac{\left(Na^+ + \sqrt{HCO_3^-}\right)}{(Ca^{2+} + Mg^{2+} + Na^+ + K^+)} \times 100 \quad \text{(Doneen, 1961)} \quad (13)$$

$$PS = Cl^- + \sqrt{SO_4^{2-}} \quad \text{(Doneen, 1961)} \quad (14)$$

$$MH = \frac{Mg^{2+}}{(Ca^{2+} + Mg^{2+})} \times 100 \quad \text{(Szabolcs and Darab, 1964)} \quad (15)$$

$$K = 12.4\,mol/L + SAR \quad \text{(Zhou et al., 2009)} \quad (16)$$

where, all ion concentrations are expressed in the meq/L and mol/L in Eq. (16) indicates the total dissolved ions in g/L.

1.6. *Industrial water quality indices*

The corrosion and scaling processes affect the efficiency of industrial equipment, machinery, pipelines, and even their byproducts in water, and therefore, are obvious health concerns (Hoseinzadeh et al., 2013). The industrial water must be corrosion and scaling free (Singh et al., 2012; Mokif et al., 2018). A systematic evaluation of water quality by multiple corrosive indices is, therefore, more advantageous than any single index approach in the decision-making process (Mirzabeygi et al., 2016; Davil et al., 2009). Accordingly, in this study, five different indices developed historically, such as Langelier saturation index (LSI) (Langelier, 1936), Ryznar stability index (RSI) (Ryznar, 1944), Larson-Skold index (L-SI) (Larson and Skold, 1958), Aggressive index (AI) (AWWA, 1975), and Puckorius scaling index (PSI) (Puckorius and Brooke, 1991), have been used. These indices (Eqs. (17)-(22)) predict that the water will

dissolve, precipitate, or be in equilibrium with the calcium carbonate.

$$LSI = pH_w - pH_s \quad \text{(Langelier, 1936)} \quad (17)$$

$$RSI = 2pH_s - pH \quad \text{(Ryznar, 1944)} \quad (18)$$

where pH_w is the measured pH in water and pH_s is the water saturation pH with respect to $CaCO_3$ calculated as follows (Eq. (19)).

$$pH_s = (9.3 + A + B) - (C + D) \quad (19)$$

where, constant $A = \frac{(\log_{10}[TDS] - 1)}{10}$, $B = -13.12\log_{10}$ (Temperature in $°C + 273) + 34.55$, and $C = \log_{10}(Ca$ as $CaCO_3$ mg/L$) - 0.4$, and $D = \log_{10}(\text{alkalinity as } CaCO_3$ mg/L$)$.

$$L - SI = \frac{\left(SO_4^{2-} + Cl^-\right)}{\left(HCO_3^- + CO_3^{2-}\right)} \quad \text{(Larson and Skold, 1958)} \quad (20)$$

where, the parameter concentration unit is meq/L.

$$AI = pH + \log_{10}\left(Alk \times Ca^{2+}\right) \quad \text{(AWWA, 1975)} \quad (21)$$

where, pH is the measured pH, Ca^{2+} is the calcium hardness of $CaCO_3$ (mg/L), and Alk is the total alkalinity (mg/L).

$$PSI = 2pH_s - pH_{eq} \quad \text{(Puckorius and Brooke, 1991)} \quad (22)$$

where, $pH_{eq} = 1.465 \times \log_{10}[\text{total alkalinity}] + 4.54$ and pH_s is the water saturation pH with respect to $CaCO_3$ (Eq. (19)).

2. Results and discussion

2.1. *Groundwater suitability for drinking purposes*

2.1.1. *Based on BIS (2012) and WHO (2022)*

Suitability appraisal of Supebeda's groundwater for drinking purposes has been carried out based on the criteria defined by the BIS (2012) and WHO (2022). The Indian standards give both acceptable and permissible limits of most chemical parameters, while WHO give only the guideline values. In this study, BIS (2012) standards have been followed, and in case

Table 2 – Drinking water standards of selected countries and descriptive statistics of analysed chemical parameters in groundwater samples collected in village Supebeda, district Gariabandh, Chhattisgarh state, India during premonsoon season (2020).

	Drinking water quality standards						Agricultural water quality standards	Range	Mean ± SD (standard deviation)	Mean ± SE (standard error)	Relative percentage of SE	% of sample above BIS (2012) and WHO (2022) standards			% of sample above FAO (1994)
	India (BIS, 2012)		WHO (2022)	European Union (2023)	Australian (NHMRC, 2017)	USEPA (2024a, 2024b)	FAO (1994)								
	AL	PL	GV	Parametric value	GV	MCL						> AL	> AL < PL	≥ PL	
Physical parameters															
pH	6.5–8.5		6.5–8.5	—-	6.5–8.5	6.5- 8.5[c]	6.5–8.4	7.2–8.3	7.9 ± 0.3	7.9 ± 0.1	0.7 %	NIL			NIL
EC	—-		1500[a]	2500	—-	—-	0–3000	313.0–3446.0	941 ± 795	941 ± 153	16.3 %	11.11 % (3)			7.4 % (2)
TDS	500	2000	600	—-	600	500[c]	0–2000	200.32–2205.44	602.2 ± 509.0	602.2 ± 97.9	16.3 %	37.04 % (10)	29.63 % (8)	7.41 % (2)	7.4 % (2)
TH	200	600	500	—-	200	—-	—-	65.0–755.0	257 ± 178	257 ± 34.3	13.4 %	44.44 % (12)	33.33 % (9)	11.11 % (3)	——
Major cations															
Ca^{2+}	75	200	300	—-	—-	—-	0–400	20.0–214.0	67 ± 53	67 ± 10.2	15.0 %	33.33 % (9)	29.6 % (8)	3.7 % (1)	NIL
Mg^{2+}	30	100	100	—-	—-	—-	0–60	3.6–52.8	21 ± 13.2	21 ± 2.5	12.1 %	14.81 % (4)	14.81 % (4)	NIL	NIL
Na^+	—-		200[a]	200	180	—-	0–920	16.4–185.5	65 ± 43.9	65 ± 8.5	13.0 %	NIL			NIL
K^+	—-		12[a]	—-	—-	—-	—-	0.6–11.4	2.2 ± 2.1	2.2 ± 0.4	18.0 %	NIL			——
Major anions															
HCO_3^-	—-		500[a]	—-	—-	—-	0–610	85.0–519.0	297 ± 109	297 ± 21	7.1 %	3.7 % (1)	3.7 % (1)	NIL	NIL
Cl^-	250	1000	250	250[c]	250	250[c]	0–1063	7.1–408.3	73.8 ± 109.2	73.8 ± 21	28.5 %	11.11 % (3)	11.11 % (3)	NIL	NIL
SO_4^{2-}	200	400	250	250[c]	500	250[c]	0–960	4.8–105.5	29 ± 30.6	29 ± 5.9	20.3 %	NIL	NIL	NIL	NIL
NO_3^-	45		50	50	50	10[b]	0–45	0–128.3	39 ± 40	39 ± 7.7	19.7 %	37.04 % (10)			37.0 % (10)
F^-	1	1.5	1.5	1.5	1.5	2[c] 4[b]	0–20	0–1.9	0.9 ± 0.6	0.9 ± 0.1	12.1 %	37.04 % (10)	11.11 % (3)	25.93 % (7)	NIL

AL: acceptable limit; PL: permissible limit in the absence of alternative source of water by BIS (2012); GV: guideline value; MCL: maximum contaminant levels.

[a] indicates guideline value of the parameter as per WHO (2022) (adopted when BIS Bureau of Indian Standards 2012 does not provide any standard limit for a parameter).

[b] stands for the National Primary Drinking Water Regulations, and [c] refers to the Secondary Drinking Water Standards. Note: All the chemical parameters are expressed in mg/L, except for EC (µS/cm) and pH (unitless).

it does not give any upper limit for a specific parameter, the WHO guideline value has been adopted. Table 2 lists the BIS (2012) and WHO (2022) drinking water quality standards besides that of few other countries (Australia, the European Union, and the USA), for comparison purposes. As one can see, the Indian standards are as stricter as that of other developed countries.

Table 2 also summarizes the analyzed physicochemical parameters of all groundwater samples collected from Supebeda, and the detailed analytical results per each sampling location are given in Appendix A Table S2. These tables show that the pH value in the study area varies from 7.2 to 8.3 with a mean $\pm$ SD of 7.9 $\pm$ 0.3. This depicts the near neutral to slightly alkaline nature of water. There is a wide variation of EC from 313.0 to 3446.0 µS/cm (mean $\pm$ SD $= 941 \pm 795$); 11.11 % of the samples exceed the EC guideline value of 1500 µS/cm (WHO, 2022). Few locations are prone to groundwater salinity due to excessive mineralization from the leaching of agrochemicals (Ako et al., 2011; Rajkumar et al., 2020). In 37.04 % and 7.41 % of the samples, TDS values are above the acceptable limit of 500 mg/L and permissible limit of 2000 mg/L of BIS (2012), respectively.

The total hardness (TH) concentrations range from 65.0–755.0 mg/L, with 44.44 % and 11.11 % of the samples above the acceptable and permissible limits of 200 and 600 mg/L, respectively (BIS, 2012). The excess TH is attributed to the elevated concentrations of alkaline earths (Ca^{2+} and Mg^{2+}) and weak acid (HCO_3^-) in groundwater (Herojeet et al., 2016; Singh et al., 2020a; Rajkumar et al., 2025a). Direct ingestion of untreated hardwater for a prolonged duration poses a threat to human health, namely calcification of arteries, gastrointestinal ulceration, urolithiasis, and pulmonary disorder (WHO, 2011; Sidhu et al., 2013; Rajkumar et al., 2025b).

Further, the box-whisker plot (Appendix A Fig. S1) identifies the relative dominance of cations and anions in groundwater as $Ca^{2+} > Na^+ > Mg^{2+} > K^+$ and $HCO_3^- > Cl^- > NO_3^- > SO_4^{2-} > F^-$. The concentration of Ca^{2+} varies from 20.0 to 214.0 mg/L (mean $\pm$ SD $= 67 \pm 53$) with about 33.33 % of the samples exceeding the acceptable limit of 75 mg/L and about 3.7 % the permissible limit of 200 mg/L (BIS, 2012). Magnesium (Mg^{2+}) concentration varies from 3.6 to 52.8 mg/L, with 14.81 % of the samples above the BIS (2012) acceptable limit of 30 mg/L. The high content of alkaline earths (Ca^{2+}, Mg^{2+}) may be due to the weathering of silicate, carbonate, dolomite, and sandstone minerals, as well as ion exchange processes and the leaching of agrochemicals (Liu et al., 2021; Zhou et al., 2020; Singh et al., 2020b; Rajkumar et al., 2023). The concentrations of alkali metals (Na^+, K^+) are within their respective guideline values of 200 mg/L and 12 mg/L, respectively (WHO, 2022).

The minimum and maximum values of bicarbonate (HCO_3^-) ions are 85 mg/L and 519 mg/L with a mean $\pm$ SD of 297 $\pm$ 109; only a meagre 3.7 % of the samples show above the guideline value of 500 mg/L (WHO, 2022). These ions are possibly derived from geogenic sources, such as the dissolution of silicate, calcite, gypsum, and dolomite (Marghade et al., 2020; Nematollahi et al., 2018). The Cl^- content varies between 7.1–408.3 mg/L, with 11.11 % of the samples above the acceptable limit of 250 mg/L (BIS, 2012). High concentration of Cl^- ions in groundwater may be due to anthropogenic factors, such as seepage of domestic and sewage wastewater, and ap-

plication of Cl^- fertilizers, such as ammonium chloride and potash (Zhou et al., 2014). Singh et al. (2020b) report that the elevated concentrations of ions like Ca^{2+}, Mg^{2+}, HCO_3^- and Cl^- in groundwater are indicative of total hardness. The concentration of SO_4^{2-} ion ranges from 4.8 to 105.5 mg/L and is within the BIS (2012) acceptable limit of 200 mg/L.

Direct consumption of drinking water containing excess concentrations of nitrate and fluoride ions are known to have numerous health effects (Rajkumar et al., 2023; Adimalla and Qian, 2019). The range of nitrate content in groundwater in the study area is 0–128.3 mg/L with a mean $\pm$ SD of 39 $\pm$ 40, and 37.04 % of the samples exceed their guideline value of 45 mg/L (BIS, 2012). Anthropogenic activities, such as excreta from livestock farms, runoff from agricultural land, leaching from waste dumping sites, and discharge of untreated sewerage, possibly enrich the nitrate contamination in groundwater. The prolonged exposure to high nitrate content through direct ingestion shows numerous clinical symptoms, namely methemoglobinemia (body dehydration and gastrointestinal infections), blue-baby syndrome (cyanosis), multiple sclerosis, and non-Hodgkin lymphoma (Fabro et al., 2015; Chang et al., 2009; Gao et al., 2012; Elisante and Muzuka, 2017; Herojeet et al., 2023).

The fluoride content varies from 0 mg/L to 1.9 mg/L with a mean $\pm$ SD of 0.9 $\pm$ 0.6, and 37.04 %, and 25.93 % of the samples show above the acceptable limit of 1.0 mg/L and permissible limit of 1.5 mg/L, respectively (BIS, 2012). High amount of fluoride ions in groundwater may be due to weathering of fluoride-bearing minerals, such as fluorite, amphiboles, biotite, and hornblende granite gneiss, etc., in rocks, sediments, and soils, evapotranspiration and atmospheric deposition (Li et al., 2014; Maitra et al., 2021; Herojeet et al., 2023; Rajkumar et al., 2025a,b).

2.1.2. Based on comprehensive water quality index (CWQI)

The scores of P_{CWQI} range from 0.14 to 0.61 and that of N_{CWQI} from $(-0.78)-0.00$ in the chemical parameters of the 27 groundwater samples (Table 3). As per the CWQI water classification, 6 (22.2 %) samples fall in the "excellent" class, 15 (55.56 %) samples in "good", and 3 (11.11 %) samples each in "marginal" and "very poor" classes (Table 1 and Fig. 2). The groundwater samples (G3, G6, G7, G10, G13, and G16) falling under the excellent water class are suitable for direct usage for drinking, domestic, and irrigation purposes. The samples (G2, G5, G9, G11, G12, G23, G24, and G27) belonging to the good water class may be conditionally used for drinking. They are, however, suitable for direct domestic uses. Thus, 14 samples (6 + 8 samples under excellent and good water classes, respectively) (i.e., 52 %) are suitable for potable use.

Some of the groundwater samples (G1, G4, G8, G14, G15, G20, and G21) falling under good category have fluoride as the single violator parameter (> 1.5 mg/L) (BIS, 2012). Groundwater from these locations is recommended for drinking purposes only after proper treatment, such as by the membrane defluorination method and ion exchange processes. Three samples (G19, G22, and G26) belonging to the marginal class may be considered for drinking only after treatment, but the water is still fit for direct use for domestic purposes. Finally, the samples (G17, G18, and G25) belonging to the very poor water class

Table 3 – Results of CWQI in the groundwater samples collected from village Supebeda, district Gariabandh, Chhattisgarh state, India.

Sample nos.	Village	P_{CWQI}	N_{CWQI}	Sample nos.	Village	P_{CWQI}	N_{CWQI}	Sample nos.	Village	P_{CWQI}	N_{CWQI}
G1	Sum Sagarpara	0.501	−0.13	G10	Sanjhakar para	0.581	0.00	G19	Fulimunda	0.388	−0.22
G2	Kumdi	0.515	−0.01	G11	Sanjhakar para	0.565	−0.05	G20	Chotibudi	0.576	−0.13
G3	Kumhadai	0.506	0.00	G12	Badh para	0.578	−0.04	G21	Dahigaon	0.521	−0.07
G4	Fulimunda	0.582	−0.08	G13	Satnami para	0.602	0.00	G22	Model para-I	0.275	−0.23
G5	Nishiguda	0.514	−0.01	G14	Almunyia	0.416	−0.10	G23	Model para-II	0.422	−0.11
G6	Supebeda	0.433	0.00	G15	Jai Thankur di ke	0.238	−0.15	G24	Dabnai	0.463	−0.07
G7	Sendmuda	0.613	0.00	G16	Nishiguda	0.537	0.00	G25	Navaguda	0.302	−0.69
G8	Sanjhakar para	0.599	−0.10	G17	Nishiguda	0.166	−0.78	G26	Kundai Kala	0.264	−0.28
G9	Sanjhakar para	0.557	−0.06	G18	Nishiguda	0.144	−0.75	G27	Bastipara	0.429	−0.19
Mean						P_{CWQI}	N_{CWQI}				
Maximum						0.46	−0.16				
Minimum						0.14	−0.78				
						0.61	0.00				

are unfit for drinking and domestic uses. They could, however, be used for irrigation of salt-tolerant crops.

The advantages of CWQI are that it generates six distinct water classes for various uses, i.e., for drinking, domestic, irrigation, and industrial consumption (Table 1), and none of the water sources is rejected from usage perspective. The water classification is entirely based on the quality ratings and unit weights of the physicochemical parameters.

2.2. Groundwater suitability for irrigation purposes

2.2.1. Based on FAO (1994)
Groundwater has always been the preferred source of irrigation in this region. With respect to EC and TDS, their measured concentrations indicate exceedance of their permissible limits (3000 mg/L for EC and 2000 mg/L for TDS) in 7.4 % of the samples (Table 2). Most parameters, such as pH, TH, major cations (Ca^{2+}, Mg^{2+}, Na^+, K^+) and anions (HCO_3^-, Cl^-, SO_4^{2-}, F^-), are within their usual standard ranges for irrigational use (FAO, 1994). Among anions, 37 % of the samples show excess concentrations of nitrate (> 45 mg/L) (Table 2).

Further, FAO (1994) suggests that when the ratio of Ca^{2+}/Mg^{2+} is less than 1, the potential effect of exchangeable sodium and magnesium increases in the soil. In the study area, the Ca^{2+}/Mg^{2+} ratio values range from 0.93 to 8.17 (mean = 3.55), and a meagre 3.70 % of the samples may have magnesium effect. Presently, there is no such report of magnesium hazard affecting soil salinity in the study area (Appendix A Table S3).

2.2.2. Based on irrigation water quality indices
As many as 10 irrigation indices have been used to evaluate the groundwater quality (Appendix A Table S3).

1) Total dissolved solids (TDS)

As the primary indicator of the total mineral content in groundwater, it appraises the chemical equilibrium between water and the solute (salts) in the aquifer system. Irrigation water containing a higher amount of TDS accumulates excess amount of dissolved ions as salts around the root zone of the plants, thereby affecting normal plant growth, development, and crop production (Singh et al., 2020a). The classification of TDS values by Ayers and Westcot (1994) and University of California Committee of Consultants (UCCC, 1974) in groundwater depicts that the majority of the samples in Supebeda area fall under "suitable" (55.56 %) and "moderate" (37.04 %) water classes. Only a small number of the samples (7.41 %) is not fully fit for the irrigational use (Table 4 and Appendix A Fig. S2).

2) Salinity hazard (EC)

Electrical conductivity determines the degree of salinity in a water sample due to the presence of excessive amount of ionic species in it. The semi-arid climatic conditions in the region cause a high evaporation rate of soil moisture resulting in the increased salt deposition in the upper soil horizon (Chacha et al., 2018; Wagh et al., 2018; Rajkumar et al., 2025a). Further, high EC in irrigation water accelerates soil salinity and reduces drainage capacity, affecting the capillary water content in soil (Li et al., 2016a; Amiri et al., 2015). The salinity hazard classification of groundwater as per Richards (1954) is provided in Table 4 and Appendix A Fig. S3. Most of the samples (62.96 %) in Supebeda are good enough for irrigational purposes. The remaining samples fall under doubtful (29.63 %) and unsuitable (7.41 %) categories. None of the samples fall under 'excellent' water class for irrigation, however.

3) Kelley's Ratio (KR)

Kelley's ratio (KR), developed by Kelly (1940), is defined by the ratio of Na^+ ion concentration and the alkaline earths (Ca^{2+} and Mg^{2+}) content in water. The value of KR varies from 0.16 to 3.05 meq/L in the study area (Appendix A Table S3). According to the classification of the KR water classes (Table 4 and Appendix A Fig. S4), about 77.78 % of the samples having KR values of < 1 meq/L are fit for irrigational uses. The remaining samples (22.22 %) have values greater than unity depicting that the enrichment of Na^+ ions over the combined concentrations of Ca^{2+} and Mg^{2+} ions may have sodium toxicity in the soil, a condition not favourable for irrigation.
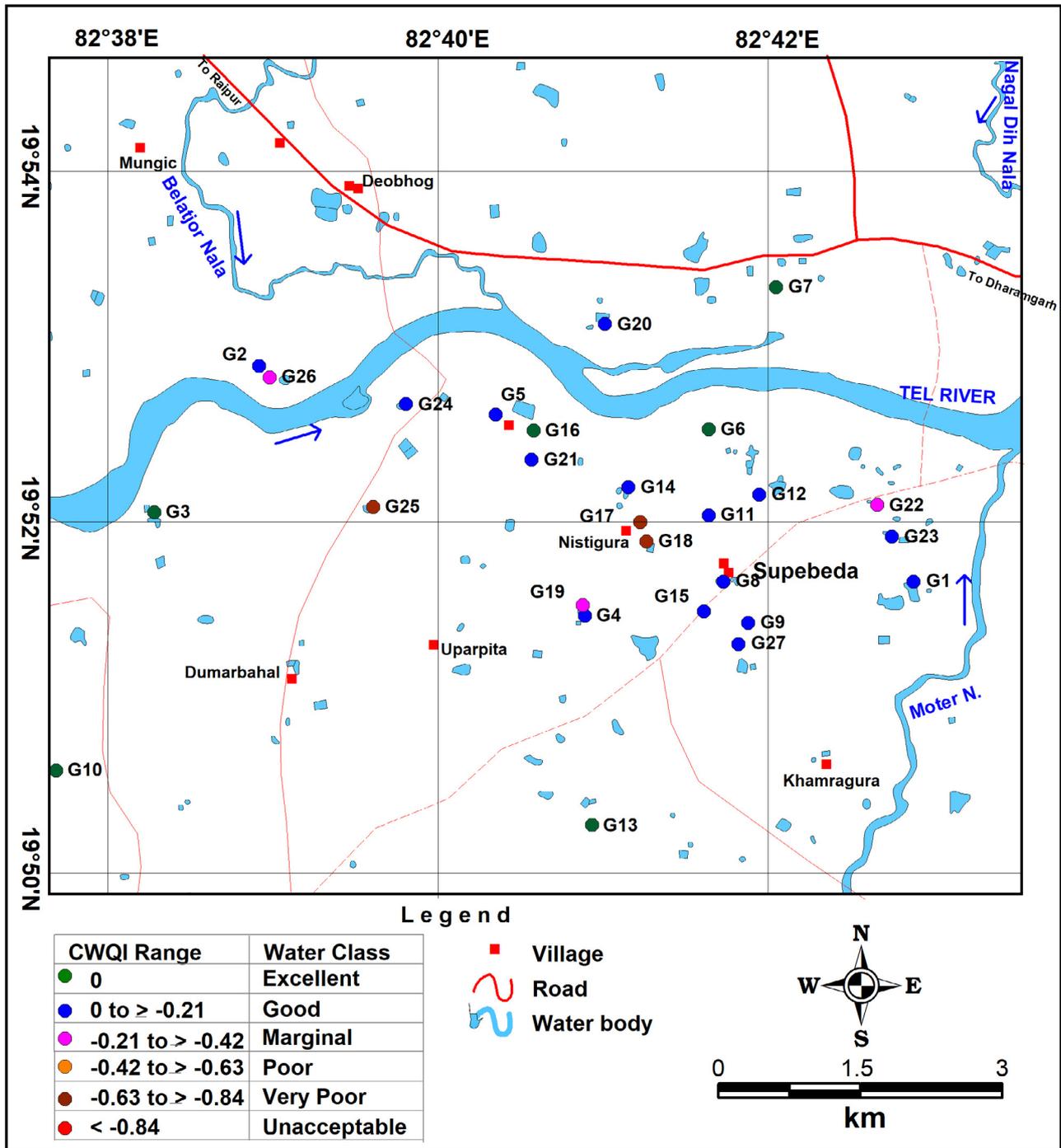
Fig. 2 – Classification of groundwater samples based on comprehensive water quality index (CWQI) in village Supebeda, district Gariabandh, Chhattisgarh state, India.

4) Residual Sodium Carbonate (RSC)

Eaton (1950) developed the residual sodium carbonate (RSC) concept to determine the hazardous effects of CO_3^- and HCO_3^- with respect to the alkaline earth metals (Ca^{2+} and Mg^{2+}) in irrigation water. The relative abundance of CO_3^- and HCO_3^- over the alkaline earth metals in water precipitates the Ca^{2+} and Mg^{2+} ions, thereby increasing the deposition of sodium carbonate in the soil matrix (Purushothaman et al., 2014; Ahamed et al., 2015). HCO_3^- ions are the predominant anions in Supebeda, leading to high pH and alkalinity in groundwater. Marghade et al. (2020) and Agoubi et al. (2011) divulge that high RSC values increase sodium toxicity and make it infertile; thus, RSC values less than 1.25 meq/L are desirable for irrigation.

The RSC values in the study area range from −9.63 to 4.93, with −0.23 as the mean value, which indicates that the low concentration of Na^+ ions and a significantly higher concen-

Table 4 – Classification of groundwater samples based on irrigation indices in village Supebeda, district Gariabandh, Chhattisgarh state, India.

Parameters	Range	Water class	No. of samples	% of samples
TDS	< 450	Suitable	15	55.56 %
(Ayers and Westcot, 1994; UCCC, 1974)	450–2000	Moderate	10	37.04 %
	> 2000	Unsuitable	2	7.41 %
Salinity hazard (EC values in µS/cm)	< 250	Excellent (C1)	NIL	NIL
(Richards, 1954)	250–750	Good (C2)	17	62.96 %
	750–2250	Doubtful (C3)	8	29.63 %
	> 2250	Unsuitable (C4)	2	7.41 %
Kelly's ratio (KR) (Kelly, 1940)	< 1	Suitable	21	77.78 %
	> 1	Unsuitable	6	22.22 %
Residual sodium carbonate (RSC)	< 1.25	Good	17	62.96 %
(Eaton, 1950)	1.25–2.5	Doubtful	4	14.81 %
	> 2.5	Unsuitable	6	22.22 %
Sodium adsorption ratio (SAR)	< 10	Excellent (S1)	27	100 %
(Richards, 1954)	10–18	Good (S2)	NIL	NIL
	18 – 26	Doubtful (S3)	NIL	NIL
	> 26	Unsuitable (S4)	NIL	NIL
%Na	< 20	Excellent	5	18.52 %
(Wilcox, 1955)	20–40	Good	12	44.44 %
	40–60	Permissible	8	29.63 %
	60–80	Doubtful	2	7.41 %
	> 80	Unsuitable	NIL	NIL
Permeability index (PI)	Class I	Max. permeability	6	22.22 %
(Doneen, 1961)	Class II	75 % of Max. permeability	14	51.85 %
	Class III	25 % of Max. permeability	7	25.93 %
Potential salinity (PS)	< 5	Excellent to Good	23	85.19 %
(Doneen, 1961)	5–10	Good to Injurious	2	7.41 %
	> 10	Injurious to Unsatisfactory	2	7.41 %
Magnesium ratio (MR)	< 50	Suitable	23	85.19 %
(Szabolcs and Darab, 1964)	> 50	Unsuitable	4	14.81 %
Synthetic harmful coefficient (K) (Zhou et al., 2009)	< 25	Excellent	25	92.59 %

tration of HCO_3^- ions in some of the groundwater samples may be due to the dissolution of silicate and carbonate minerals (Appendix A Table S3). Eaton (1950) classified the RSC values into three water classes for irrigation purposes (Table 4 and Appendix A Fig. S5). Majority of the groundwater samples (62.96 %) fall under the "good" water class for irrigation. Within the good water class, 13 samples show negative RSC values signalling elevated concentrations of Ca^{2+} and Mg^{2+} ions favouring carbonate precipitation and low Na^+ content in groundwater (Appendix A Table S3). The remaining samples, 14.81 % and 22.22 %, respectively, belong to the "doubtful" and "unsuitable" water classes that have RSC values above the safe limit of 1.25 meq/L for irrigation (Table 4). These samples may accelerate the Na-induced Ca^{2+} and Mg^{2+} deficiency affecting soil salinity and stunt plant growth (Zhang et al., 2019; Adimalla and Wu, 2019). The Na^+ ions present in the irrigation water binds to clay minerals releasing Ca^{2+} and Mg^{2+} ions in the percolating water (Rajkumar et al., 2025a), causing high Na^+ content in the plant root zone in soil, especially in the upper layer of soil, and creating salt burn effects in the soft tissues of the plant roots.

5) Sodium adsorption ratio (SAR)

The potential alkali or sodicity hazard is quantitatively determined by SAR (Eq. (11)) (Richards, 1954). Sodicity hazard is more detrimental in alkaline soil because the exchangeable

Ca^{2+} and Mg^{2+} ions are readily replaced by Na^+ ions, causing soil compaction, deflocculation, and decreased permeability (Ahamed et al., 2015). In the study area, the SAR values vary from 0.52 to 4.20 with a mean of 1.85 (Appendix A Table S3). Since all groundwater samples have SAR values of < 10, they are excellent for irrigational use in different soil types and for a variety of crops (Table 4 and Appendix A Fig. S6).

The US Salinity Laboratory diagram (USSL, 1954) (Fig. 3a) that plots SAR vs. EC values depicts that 62.96 % of the analyzed water samples have medium salinity with low sodium hazard (C2-S1), indicating that the groundwater could be used for agricultural purposes in all types of soil (Rao, 2017a). The remaining samples show high salinity with low sodium hazard (C3-S1) (29.63 %) and very high salinity with low sodium hazard (C4-S1) (7.41 %). Notably, 37.04 % of the samples may be considered for irrigation in soils with high drainage potential to minimize the salinity effect (Bauder et al., 2011; Marghade et al., 2020). Singh et al. (2020a) report that high salinity in irrigating groundwater may damage the soil texture and nutrient imbalance, affecting the metabolic activities in crops.

6) Percent Sodium (%Na)

Wilcox (1955) developed a concept of sodium (%Na) to indicate sodium hazard in soil. Sodium occurs in substantial proportion with carbonate in alkali soil or sulphate and chlo-
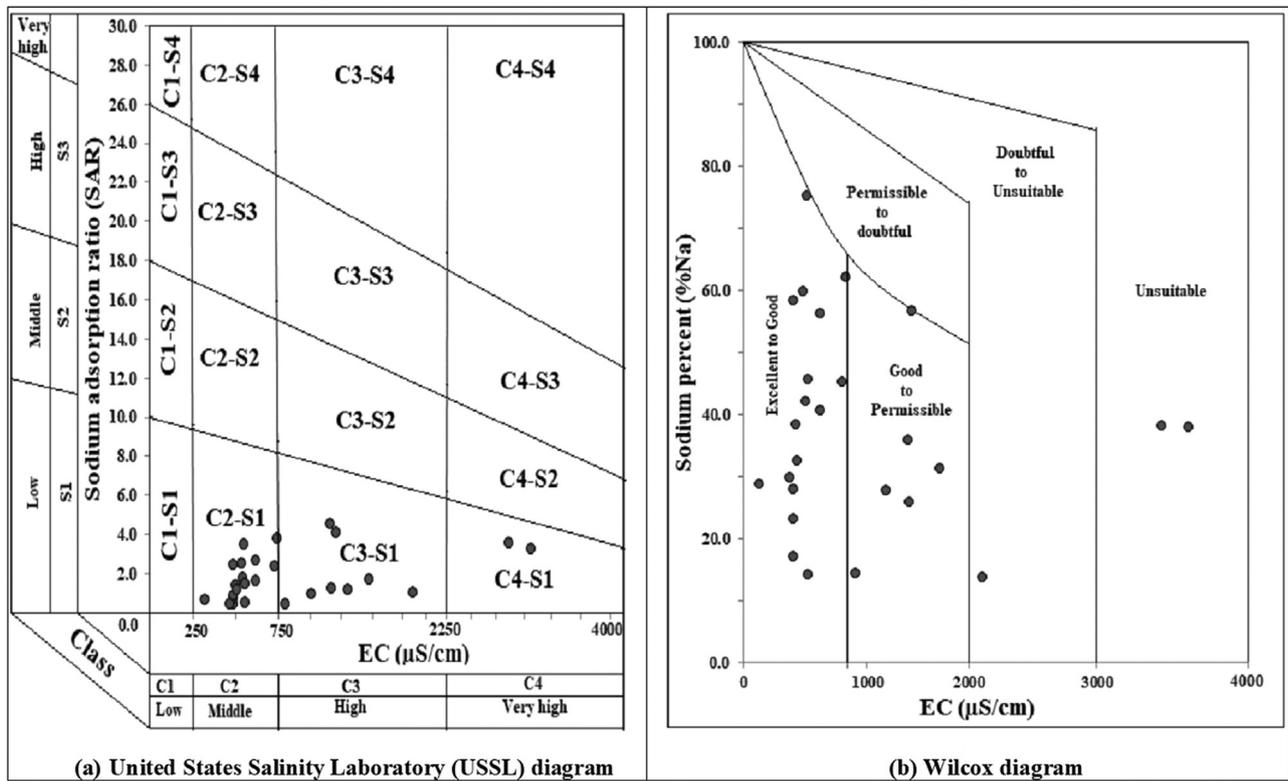
Fig. 3 – (a) United States Salinity Laboratory (USSL), and (b) Wilcox diagrams for groundwater samples from village Supebeda, district Gariabandh, Chhattisgarh State, India. EC: electrical conductivity.

ride in saline soil. Therefore, the irrigation water enriched with soluble sodium accelerates the reaction in the soil matrix to diffuse the exchangeable cations that affect the soil structure and reduce permeability (Khan and Abbassi, 2013; Chacha et al., 2018; Wagh et al., 2018). Bashir et al. (2017) report that the %Na value above 60 % in irrigation water deteriorates the internal soil pore spaces, reducing the aeration and drainage capacity. These effects are aggravated in water with high EC and elevated concentration of Na^+ in soil, inhibiting plant growth (Islam et al., 2017).

The %Na value varies from 14.04 % to 75.42 %, with a mean of 37.15 % in the study area (Appendix A Table S3). Wilcox (1955) devised five water classes based on the %Na for irrigation suitability. According to this classification, the groundwater samples falling under excellent, good, permissible, and doubtful categories are 18.52 %, 44.44 %, 29.63 %, and 7.41 %, respectively, in Supebeda (Table 4 and Appendix A Fig. S7); none are unsuitable for irrigational use.

Further, the Wilcox diagram is essentially based on EC concentrations and %Na values of the groundwater samples. Fig. 3b shows that 62.96 % of the samples in Supebeda fall under "excellent to good" category, 25.93 % of the samples in "good to permissible", 3.70 % of the samples in "doubtful to unsuitable", and 7.41 % of the samples in "unsuitable" water classes for irrigation purposes. Li et al. (2016b) report that groundwater samples with a %Na value of less than 60 % are ideal for irrigation. Accordingly, out of the 27 samples collected, two samples, such as (G1 and G20) falling under "excellent to good" category, are not fully fit for irrigational use

for having >60 % of %Na value, even if their EC values are less than 750 µS/cm. Similarly, one sample (G25) under "doubtful to unsuitable" category and two of the samples (G17 and G18) under "unsuitable" water class have %Na values of less than 60 %, but their EC values are more than 2000 µS/cm, and therefore, are not suitable for irrigating crops as they may cause sodicity or salinity hazard in the soil. Therefore, it is ideal to consider both EC and %Na values in combination in characterizing a water sample rather than treating them independently for appraisal of irrigation water quality.

7) Permeability Index (PI)

Doneen (1961) developed the permeability index (PI) as an indicator to determine if the water quality is suitable for irrigational uses. Water permeability is chiefly affected by the enriched content of Na^+ ions, but the problem is further aggravated by the elevated concentrations of HCO_3^-, Ca^{2+}, and Mg^{2+} ions that precipitate in the soil (Brindha and Kavitha, 2015). Thus, prolonged irrigation in agricultural land often leads to accumulation of these residual chemicals inhibiting the movement of water in the upper horizon of soil and limiting the gravitational and capillary water formation and normal seed germination.

The permeability index is calculated using Eq. (13) and the water classes it forms are shown in Table 4. The PI values diverge from 26.93 to 113.29 meq/L in the study area (Appendix A Table S3). Appendix A Fig. S8a and b depict that about 22.22 % and 51.85 % of the samples fall under "Class I (maximum permeability)" and "Class II (above or 75 % of max-

imum permeability)" water types, respectively, and, therefore, are suitable for irrigation. At the same time, the remaining 25.93 % of the samples belonging to "Class III (below or 25 % of maximum permeability)" water type, are unfit for agricultural purposes. The groundwater samples with high PI values imply that the elevated concentrations of Na^+ and HCO_3^- ions may be attributed to cation exchange processes and the dissolution of silicate and carbonate minerals (Xu et al., 2019; Rajkumar et al., 2025b).

8) Potential Salinity (PS)

Potential salinity (PS), proposed by Doneen (1961), is defined as the summation of the Cl^- ions with half the SO_4^{2-} concentrations in water. It is one of the important irrigation water indicators computed using Eq. (14). Generally, the excess concentration of Cl^- ions in groundwater is linked to anthropogenic factors (Singh et al., 2020a; Herojeet et al., 2016; Rajkumar et al., 2025b). On the other hand, numerous geogenic and anthropogenic inputs influence the SO_4^{2-} content in the aquifers (Rao et al., 2017b; Rajkumar et al., 2023).

The PS values diverge from 0.25 to 13.00 meq/L with a mean of 2.76 meq/L in the study area (Appendix A Table S3). According to PS water categorization (Table 4), 85.19 % and 7.41 % of the samples belong to "excellent to good (< 5 meq/L)" and "good to injurious (5–10 meq/L)" water classes, respectively. Conversely, the rest of the samples (7.41 %) fall under "injurious to unsatisfactory (> 10 meq/L)" category, indicating their unsuitability for irrigation. Appendix A Fig. S9 shows the spatial distribution of PS water classes in the Supebeda area.

9) Magnesium Hazard (MH)

The alkaline earth metals are the elements that show relative dominance among the cations. Further, Ca^{2+} and Mg^{2+} ions maintain the state of equilibrium in the natural freshwater ecosystem (Raju et al., 2011). Optimum levels of Ca^{2+} and Mg^{2+} concentrations are necessary for irrigation water as these ions function as the vital macronutrients in soil solution that support the aggregation of mineral matter and germination of plants (Nayak et al., 2023b). The effects of excess Mg^{2+} content can be catalyzed by the elevated amount of Na^+ ions that disturb the soil stoichiometry, thereby reducing drainage capacity and crop yield (Rao et al., 2012).

Szabolcs and Darab (1964) developed the magnesium hazard index and its water classification for agricultural purposes. In the study area, MH values in the groundwater samples range from 16.80 to 64.04 meq/L (Appendix A Table S3). Based on the MH water classes, most of the samples (85.19 %) have less than 50 meq/L of MH value, and, therefore, are suitable for agricultural uses (Table 4). The remaining groundwater samples (14.81 %) exceed 50 meq/L value, indicating that these samples carry potential threat to increase the soil alkalinity adversely affecting the crop productivity. Appendix A Fig. S10 shows the spatial distribution of MH water classes in the Supebeda area.

10) Synthetic Harmful Coefficient (K)

Zhou et al. (2009) developed the synthetic harmful coefficient (K) to determine the possible combined effect of salinity and alkali hazards from the irrigation water. It is computed

based on the concentrations of the TDS and the SAR values (Eq. (16)) and the resulting classifications are excellent (K < 25), permissible (25 < K < 36), doubtful (36 < K < 44), and unsuitable (K > 44) water types.

In the study area, K value varies from 3.21 to 30.66 with a mean of 9.41, and, therefore, none of the samples is classified under the "doubtful" and "unsuitable" categories for irrigation purposes (Table 4 and Appendix A Table S3). Most of the groundwater samples, ∼92.59 %, fall under the "excellent" water class, and the rest ∼7.41 % of the samples belong to "permissible" water class for agricultural purposes (Appendix A Fig. S11).

2.3. Groundwater suitability for industrial purposes

The groundwater samples of the study area are evaluated for industrial purposes using various historically developed corrosion and scaling indices (Appendix A Table S4). Corrosion is caused when water reacts with or dissolves metal plumbing, while scaling occurs when water has high levels of minerals like calcium carbonate, which can build-up on surfaces (Vendrell and Atiles, 2003). Corrosion and scaling data are essential prior to laying of pipelines and establishment of industries that require stringent water quality standards (United States Geological Survey, 2019; Mankikar, 2021).

2.3.1. Langelier saturation index (LSI)
Langelier saturation index (LSI) is developed by Langelier (1936) to qualitatively measure the tendency of water to dissolve or precipitate calcium carbonate, and is calculated using Eq. (17) (Langelier, 1936). This index gives three water classes, as described in Table 5. In the present study, all groundwater samples have negative LSI values (LSI < 0), divulging corrosive tendencies. In fact, the LSI values between −2.71 and −1.64 (Appendix A Table S4) signal excess content of free CO_2. Low alkalinity enhances the $CaCO_3$ dissolution in water, thus raising its corrosive affinity (Mirzabeygi et al., 2016).

2.3.2. Ryznar stability index (RSI)
Ryznar (1944) modified LSI and developed a quantitative index, RSI, in search of a superior index for estimating water's vulnerability to scale formation. This index is often used in combination with LSI to predict the corrosion or scaling tendencies of water toward mild steel (Ravikumar and Somashekar, 2012). Eq. (18) shows the calculation for the RSI values that are always positive. Table 5 gives the resulting water classes. In the Supebeda study area, RSI value varies from 11.48 to 13.01 (Appendix A Table S4), which divulges that all the groundwater samples are categorized as having aggressive corrosivity potential with RSI of > 8.5.

2.3.3. Larson-Skold index (L-SI)
The Larson-Skold index is used as an indicator to estimate the water corrosivity towards mild steel (Larson and Skold, 1958). This index is computed as the ratio of chloride and sulphate concentrations with respect to that of bicarbonate and carbonate in a water sample (Eq. (20)). The increased concentrations of chloride and sulphate ions in water enhance the corrosivity effect in water (Choi et al., 2015). The L-SI result varies

Table 5 – Classification of groundwater samples based on corrosion and scaling indices in village Supebeda, district Gariabandh, Chhattisgarh state, India.

Name of indices	Water class	Specification	No. of samples	% of samples
Langelier saturation index (LSI)	LSI < 0	Water is under-saturated with $CaCO_3$ and shows corrosive affinity	27	100 %
	LSI=0	Water is saturated with $CaCO_3$ (equilibrium) and neither show corrosive nor scaling tendency	NIL	NIL
	LSI > 0	Water is super-saturated with $CaCO_3$ having scaling tendency	NIL	NIL
Ryznar stability index (RSI)	RSI < 5.5	High scaling tendency	NIL	NIL
	5.5 < RSI < 6.2	Moderate scaling tendency	NIL	NIL
	6.2 < RSI < 6.8	Low corrosive tendency	NIL	NIL
	6.8 < RSI < 8.5	Moderate corrosive affinity	NIL	NIL
	RSI > 8.5	Rigorous corrosive behaviour	27	100 %
Larson-Skold index (L-SI)	L-SI < 0.8	Scaling tendency	NIL	NIL
	0.8 < L-SI < 1.2	Higher corrosion rates can be obtained	22	81.48 %
	L- SI > 1.2	High rates of localized corrosion can be expected	5	18.52 %
Aggressive index (AI)	AI < 10	Extremely aggressive (corrosive) conditions	NIL	NIL
	10 < AI < 12	Moderately aggressive	3	11.11 %
	AI > 12	Nonaggressive (not corrosive) tendency and scaling affinity	24	88.89 %
Puckorius scaling index (PSI)	PSI < 6	Scaling tendency	NIL	NIL
	6 < PSI < 7	Little affinity for scaling and corrosion	NIL	NIL
	PSI > 7	Significant corrosive tendency	27	100 %

from 0.05 to 2.85, with a mean of 0.36 (Appendix A Table S4). Table 5 gives the three L-SI water classes. As per this table, 81.48 % of the groundwater samples fall under 0.8 < L-SI < 1.2 range, indicating a higher corrosion tendency (Aminiyan and Aminiyan, 2020). The remaining 18.52 % of the samples have L-SI value of > 1.2, depicting that higher rate of localized corrosion can be expected due to excess concentrations of chloride and sulphate catalysts.

2.3.4. *Aggressive index (AI)*

The aggressive index (AI) was specifically developed by the AWWA (1975) to monitor the corrosivity of water in asbestos pipes (Ahmed et al., 2021). It is calculated using the actual concentrations of pH, calcium hardness, and total alkalinity from a water sample, as outlined in Eq. (21). The AI value varies from 11.66 to 12.82, with a mean value of 12.34 in Supebeda's groundwater (Appendix A Table S4). Table 5 presents the AI water classes that shows that 11.11 % of the samples fall in **10 < AI < 12** category with a moderate corrosive tendency. The remaining 24 (88.89 %) samples have AI > 12, which depicts that such water types have scaling affinity but have nonaggressive potential toward corrosion (Ahmed et al., 2021).

2.3.5. *Puckorius scaling index (PSI)*

This index predicts water buffering potential and capacity to undergo precipitation (Puckorius and Brooke, 1991). Like RSI, the PSI value is always positive and is computed as the difference between the saturation pH of water as $CaCO_3$ and the equilibrium pH (pH_{eq}) to evaluate the buffering capacity (Eq. (22)). The PSI value ranges from 11.23 to 13.56 (Appendix A Table S4). Table 5 gives the PSI water classes, which state that all groundwater samples (100 %) belong to a significant corrosive water class for industrial purposes.

Similar study on the water stability indices have been conducted in the CKDu-infected North Central Province (NCP) of Sri Lanka (Hu et al. 2024) from piped water supply perspective, and it is found that groundwater in that region too is highly corrosive, but of lesser magnitude than that of Supebeda.

3.   Conclusions

This reconnaissance study undertaken on public demand satisfactorily characterizes the groundwater resources of the village Supebeda from various usage perspectives, such as for drinking, agricultural and industrial purposes, using multi-indexing techniques and statistical analyses. The answers to the five questions raised prior to starting the work are as follows.

Whether groundwater is potable?

Although the drinking water specifications by the BIS (2012) and WHO (2022) do not give a clear picture of the drinking water quality, many hotspots have been identified where one or more of the physicochemical parameters exceed their acceptable limits, and in many cases their permissible limits. However, CWQI has been successful in classifying ~52 % of the samples potable and ~37 % partially potable that need adequate treatment prior to use for drinking. High concentrations of alkaline earths (Ca^{2+} and Mg^{2+}) and weak acid (HCO_3^-) at places have led to groundwater hardness that have many health implications. Similar is the case with nitrate and fluoride that exceed their permissible limits in more than a quarter of the water samples.

Analysis shows that while the groundwater samples (G3, G6, G7, G10, G13, and G16) falling under the excellent water class are suitable for direct usage for drinking, domestic, and irrigation purposes, eight samples (G2, G5, G9, G11, G12, G23, G24, and G27) belonging to the good water class are most suitable for direct domestic uses with conditional us-

age for drinking in emergency. In seven samples (G1, G4, G8, G14, G15, G20, and G21), F^- is the single violator parameter, and groundwater at these locations may be used for drinking only after adequate treatment, such as by membrane defluorination methods (reverse osmosis, nanofiltration, electrodialysis, and membrane distillation) and ion exchange processes. These methods are good enough for removal of nitrate too from groundwater (Sewak et al., 2023). Other notable methods for fluoride removal include adsorption, coagulation, and precipitation processes (Ayala et al., 2018). Besides, people may consume nutritious food containing rich amounts of calcium and vitamin C for early mitigation of fluoride contamination. In fact, the Government has provided two fluoride treatment plants that use the electrolysis method, which is by far an excellent means for fluoride removal (Thamarai et al., 2024), but these facilities are poorly maintained and need immediate attention. While the three samples (G19, G22, and G26) classified under marginal category can be used for domestic purposes, the rest three samples (G17, G18, and G25) are unfit for both drinking and domestic uses and may be closed with immediate effect.

There is a public demand for treated surface water supply from the nearby Tel River, which may be examined from a feasibility perspective under the Government's National Jal Jeevan Mission (Har Ghar Jal - water in every home) program. But the process may take some time for implementation. What is immediately feasible is the supply of piped water from the high-yielding wells locally, and the installation of a greater number of fluoride treatment plants at strategic locations for public convenience.

Whether there is a link between drinking water and CKDu?

Many workers have hypothesized groundwater as the primary causative factor for CKDu. In Supebeda, although no specific etiological reasons could be deciphered in this preliminary study, it gives many important clues that need further investigation. Elevated concentrations of fluoride have been found in the urine samples of the CKDu patients from Supebeda. Many patients even show signs of skeletal fluorosis (Chowdhary et al., 2020). Studies elsewhere show that fluoride ions have an intrinsic relationship with CKDu (John et al., 2021). Therefore, whether the alkaline earth elements (Ca^{2+}, Mg^{2+}) controlling the total hardness couple with fluoride concentrations to play a role in the origin of CKDu in this study area is a subject of investigation. But then exceedance of these elements with respect to their permissible limits in groundwater, besides excess anions, introduces the topic of Hofmeister phenomena (Hofmeister, 1888) acting inside human kidneys through the ingestion of drinking water (Rajkumar et al., 2025a). Chronic kidney diseases are generally linked to 'salting-in' and 'salting-out' processes of proteins that are further interlinked with Hofmeister ion series. Therefore, understanding the role of this series in forming metal-complexes from water molecules, particularly coupling of fluoride ions with Ca^{2+}, Na^+, Mg^{2+}, K^+, HCO_3^-, Cl^-, NO_3^-, SO_4^{2-}, will help comprehend the paradox of protein denaturation inside the kidney, leading to the onset of CKDu. This study, therefore, is not conclusive about the link between drinking water and CKDu, but strongly hypothesizes the role of Hofmeister phenomena on the onset of CKDu.

Whether groundwater is suitable for agricultural purposes?

Besides the parameter-wise water quality standard by the FAO (1994) for irrigation, 10 other indices have been used in this study, each with a different chemical parameter/formula to examine the suitability of groundwater for agricultural purposes, but the outputs of the indices are in many ways contradictory. While some indices, namely KR, %Na, SAR, MH, and K give importance to the cationic parameters (Ca^{2+}, Mg^{2+}, Na^+, and K^+), PS classifies water based on anionic chemicals (Cl^-, and SO_4^{2-}), and few others, such as RSC and PI, depend on both cations and anions (Ca^{2+}, Mg^{2+}, Na^+, K^+, and HCO_3^-) for evaluating groundwater resources. Therefore, the existing irrigation indices are parameter centric and are restricted to certain specific cations and anions only without considering many other key physicochemical parameters, such as pH, EC, TH, NO_3^-, F^-, etc. in the groundwater quality appraisal. These omitted parameters may impart different significance level while maintaining the nutrient stoichiometry balance in different types of soil ecology. This calls for a new, robust, and comprehensive method of appraisal for water quality for agricultural purposes. With all these limitations, the present study does not leave any clue as to why the groundwater in the Supebeda area is not fit for agricultural use. Agricultural communities have somehow been linked to CKDu because they are constantly exposed to pesticides and agro-chemicals and work in the field for long hours under the sun without adequate food and water. Many workers attribute CKDu to heat stress, strenuous labor, and dehydration among many other reasons (Anupama et al., 2020; Stalin et al., 2020; Jolly and Thomas, 2022; Priyadarshani et al., 2023). According to this study, farming activities without adequate precautions or protections could contribute to the etiology of CKDu, but this does not apply to groundwater classified as suitable for agricultural uses.

Whether groundwater quality will hinder the Government's endeavors for piped water supply to the villages?

The groundwater in Supebeda region is characterized by hard water and is highly corrosive prone to scaling. Besides effecting frequent leakages, corrosion can add to toxic levels of metals like copper and lead to water causing its bitter taste and staining plumbing fixtures, while scaling can reduce water flow in pipes as well as heat transfer and damage the equipment used (Vendrell and Atiles, 2003). Therefore, utmost care needs to be taken while selecting the right quality of pipelines while using them for water supply purposes.

How good groundwater is for industrial usage?

Supebeda's groundwater is good enough for general usage purposes, but while utilizing it for industrial applications and piped water supply purposes, the hard, corrosive, and scaling nature of water must be considered before its actual use. Water softening as and when necessary could be a solution.

Finally, the disease CKDu is usually diagnosed late, and no data are available on factors predicting its progression (Pearce et al., 2019). Till date, many reasons are attributed to its etiology, such as groundwater contamination, overuse of pesticides, heat stress, strenuous labor, dehydration, overuse of non-steroidal anti-inflammatory drugs, mycotoxins, hypertension, infections, diabetes mellitus, herbal medication, fam-

ily history, tobacco use, etc. (Anupama et al., 2020; Stalin et al., 2020; Jolly and Thomas, 2022; Priyadarshani et al., 2023). While many of these factors apply to Supebeda area, where most patients are agricultural workers who are constantly exposed to pesticides and agro-chemicals and work long hours in the field under the sun without proper food and water, what is very clear is the significant lack of awareness among the people of the basic sense of self-care in terms of health and hygiene. There are many instances of social ostracization and a lack of employment opportunities for the people infected with CKDu (Rathore et al., 2022). This is because residents are unaware that any form of CKD is a non-communicable disease (Global Burden of Disease – Chronic Kidney Disease Collaboration, 2020; Levin et al., 2023). The literacy rate in the village is 50.51 %, indicating an urgent need for public awareness through various IEC (information, education, and communication) schemes not only about the disease but also regarding the maintenance of a healthier lifestyle and basic sanitation facilities to ensure a cleaner environment. What is at least expected of them is to refrain from drinking water from random sources and to consume groundwater only from designated wells or certified fluoride treatment plants. The State Government of Chhattisgarh has a robust machinery for community medicine. In addition to the village inhabitants, the local administration and health institutions across the State are taking the disease seriously. It is hoped that the disease will be controlled soon in this region.

Data availability

The datasets generated during and/or analyzed during the current study are already presented in the form of tables and figures in the manuscript. In case of any specific requirement, the corresponding author may please be contacted for the needful.

Ethics approval

The present study did not involve any human or animal experimentation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Herojeet Rajkumar: Writing – original draft, Visualization, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Rakesh K. Dewangan:** Project administration, Methodology, Investigation, Formal analysis, Data curation. **Pradeep K. Naik:** Writing – review & editing, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Data curation, Conceptualization. **Janak R. Verma:** Software, Project administration, Investigation, Formal analysis, Data curation. **Prabir K. Naik:** Resources, Project administration, Investigation.

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Appendix A Supplementary data

Supplementary material associated with this article can be found in the online version at doi:10.1016/j.jes.2025.02.037.

References

Abeysekera, D.T.D.J., Kaiyoom, S.A.A., Dissanayake, S.U., 1996. Place of peritoneal dialysis in the management of renal failure patients admitted to General Hospital Kandy. Kandy Soc. Med., 18th Annual Acad. Confer. (19).

Abid, S., Hassen, W., Achour, A., Skhiri, H., Maaroufi, K., Ellouz, F., et al., 2003. Ochratoxin A and human chronic nephropathy in Tunisia: is the situation endemic? Hum. Exp. Toxicol. 22 (2), 77–84.

Adimalla, N., Qian, H., 2019. Hydrogeochemistry and fluoride contamination in the hard rock terrain of Central Telangana, India: analyses of its spatial distribution and health risk. SN Appl. Sci. 1, 202.

Adimalla, N., Wu, J., 2019. Groundwater quality and associated health risks in a semi-arid region of South India: implication to sustainable groundwater management. Hum. Ecol. Risk Assess. 25, 191–216.

Agoubi, B., Kharroubi, A., Abida, H., 2011. Hydrochemistry of groundwater and its assessment for irrigation purpose in coastal Jeffara aquifer, southeastern Tunisia. Arab. J. Geosci. 6, 1163–1172.

Ahamed, A.J., Loganathan, K., Jayakumar, R., 2015. Hydrochemical characteristics and quality assessment of groundwater in Amaravathi River basin of Karur district, Tamil Nadu, South India. Sustain. Water Resour. Manag. 1, 273–291.

Ahmed, S., Sultan, M.W., Alam, M., Hussain, A., Qureshi, F., Khurshid, S., 2021. Evaluation of corrosive behaviour and scaling potential of shallow water aquifer using corrosion indices and geospatial approaches in regions of the Yamuna River basin. J. King Saud Univ. Sci. 33, 101237.

Ako, A.A., Shimada, J., Hosono, T., Ichiyanagi, K., Nkeng, G.E., Fantong, at al., 2011. Evaluation of groundwater quality and its suitability for drinking, domestic, and agricultural uses in the Banana plain (Mbanga, Njombe, Penja) of the Cameroon volcanic line. Environ. Geochem. Health 33, 559–575.

American Public Health Association, 2005. Standard Methods for the Examination of Water and Wastewater, 21st Ed. American Public Health Association, Washington, DC.

Aminiyan, M.M., Aminiyan, F.M., 2020. Comprehensive integrated index–based geochemistry and hydrochemical analyses of groundwater resources for multiple consumptions under coastal conditions. Environ. Sci. Pollut. Res. 27, 21386–21406.

Amiri, V., Sohrabi, N., Dadgar, M.A., 2015. Evaluation of groundwater chemistry and its suitability for drinking and agricultural uses in the Lenjanat plain, Central Iran. Environ. Earth Sci. 74, 6163–6176.

Anupama, Y.J., Sankarasubbaiyan, S., Taduri, G., 2020. Chronic kidney disease of unknown etiology: case definition for India–a perspective. Indian J. Nephrol. 30 (4), 236–240.

AWWA (American Water Works Association), 1975. Standards Committee on Asbestos-Cement Pressure Pipe. AWWA standard for asbestos-cement transmission pipe for water and other liquids. AWWA C402-75. J. Am. Water Works Assoc. 67 (8), 462–467.

Ayala, L.I.M., Paquet, M., Janowska, K., Jamard, P., Quist-Jensen, C.A., Bosio, G.N., et al., 2018. Water defluoridation: nanofiltration vs membrane distillation. Ind. Eng. Chem. Res. 57 (43), 14740–14748.

Ayers, R.S., Westcot, D.W., 1994. Water quality for agriculture. Irrigation and Drainage Paper. Food and Agriculture Organization, United Nations, Rome.

Bashir, E., Huda, S.N.U., Naseem, S., Hamza, S., Kaleem, M., 2017. Geochemistry and quality parameters of dug and tube well water of Khipro. District Sanghar, Sindh, Pakistan. Appl. Water Sci. 7, 1645–1655.

Bauder, T.A., Waskom, R.M., Sutherland, P.L., Davis, J.G., 2011. Irrigation Water Quality Criteria. Colorado State University Extension, Fort Collins, pp. 10–13.

BIS (Bureau of Indian Standards), 2012. Indian Standard Drinking Water - Specification (Second Revision) (IS 10500: 2012). Bureau of Indian Standards, New Delhi, pp. 1–16.

Bradley, M., Land, D., Thompson, D.A., Cwiertny, D.M., 2024. A critical review of a hidden epidemic: examining the occupational and environmental risk factors of chronic kidney disease of unknown etiology (CKDu). Environ. Sci. Adv. 4, 57–76.

Brindha, K., Kavitha, R., 2015. Hydrochemical assessment of surface water and groundwater quality along Uyyakondan channel, south India. Environ. Earth Sci. 73, 5383–5393.

Campese, V.M., 2017. Con: mesoamerican nephropathy: is the problem dehydration or rehydration? Nephrol. Dialysis Transpl. 32 (4), 603–606.

Chacha, N., Njau, K.N., Lugomela, G.V., Muzuka, A.N.N., 2018. Hydrogeochemical characteristics and spatial distribution of groundwater quality in Arusha well fields, Northern Tanzania. Appl. Water Sci. 8, 118.

Chandrajith, R., Nanayakkara, N., Zwiener, C., Daniel, C., Amann, K., Barth, J.A., 2024. Geochemical characteristics of groundwater consumed by patients with chronic kidney disease with unknown aetiology in the crystalline dry zone terrain of Sri Lanka. Expo. Health 16 (1), 183–195.

Chang, C.C., Tsai, S.S., Wu, T.N., Yang, C.Y., 2009. Nitrates in municipal drinking water and non-hodgkin lymphoma: an ecological cancer case-control study in Taiwan. J. Toxic Environ. Health A 73, 330–338.

Choi, J., Choi, B.G., Hong, S., 2015. Effects of NF treated water on corrosion of pipe distribution system and its implications to blending with conventionally treated water. Desalination 360, 138–145.

Chowdhary, P., Rathore, V., Jain, K., Galhotra, A., Verma, N., Kale, S.A., et al., 2020. CKD of unknown origin in Supebeda, Chhattisgarh, India. Kidney Int. Rep. 6, 210.

Davil, M.F., Mahvi, A.H., Norouzi, M., Mazloomi, S., Amarluie, A., Tardast, A., et al., 2009. Survey of corrosion and scaling potential produced water from Ilam water treatment plant. World Appl. Sci. 7, 11–24.

Dewangan, R., Verma, J.R., 2022. Groundwater quality in Supebeda area of Gariabandh district, Chhattisgarh. Central Ground Water Board, North Central Chhattisgarh Region, Raipur. Department of Water Resources, River Development and Ganga Rejuvenation, Ministry of Jal Shakti. Government of India, pp. 1–21.

Doneen, I.D., 1961. The influence of crop and soil on percolating water. In: Proceedings of biannual conference on groundwater recharge 1961, pp. 156–163.

Eaton, F.M., 1950. Significance of carbonates in irrigation waters. Soil Sci. 69, 123–133.

Elisante, E., Muzuka, A.N.N., 2017. Occurrence of nitrate in Tanzanian groundwater aquifers: a review. Appl. Water Sci. 7 (1), 71–87.

Essue, B., Laba, T.L., Knaul, F., Chu, A., Minh, H., Nguyen, T.K.P., et al., 2017. Economic burden of chronic ill health and injuries for households in low- and middle-income countries. In: Jamison, D.T., Gelband, H., Horton, S., Jha, P., Laxminarayan, R., Mock, C.N., et al. (Eds.), Disease Control Priorities: Improving Health and Reducing Poverty. The International Bank for Reconstruction and Development/The World Bank, Washington, pp. 121–143.

Fabro, A.Y.R., Ávila, J.G.P., Alberich, M.V.E., Sansores, S.A.C., Camargo-Valero, M.A., 2015. Spatial distribution of nitrate health risk associated with groundwater use as drinking water in Merida. Mexico. Appl. Geogr. 6, 49–57.

FAO (Food and Agriculture Organization), 1994. Water quality for agriculture, FAO Irrigation and Drainage Paper. Food Agricul Organiz United Nations Rome.

Fiseha, T., Ekong, N.E., Osborne, N.J., 2024. Chronic kidney disease of unknown aetiology in Africa: a review of the literature. Nephrology 29 (4), 177–187.

Foreman, K.J., Marquez, N., Dolgert, A., Fukutaki, K., Fullman, N., McGaughey, M., et al., 2018. Forecasting life expectancy, years of life lost, and all-cause and cause-specific mortality for 250 causes of death: reference and alternative scenarios for 2016–40 for 195 countries and territories. The Lancet 392 (10159), 2052–2090.

Ganguli, A., 2016. Uddanam nephropathy/regional nephropathy in India: preliminary findings and a plea for further research. AJKD 68 (3), 344–348.

Gao, Y., Yu, G., Luo, C., Zhou, P., 2012. Groundwater nitrogen pollution and assessment of its health risks: a case study of a typical village in rural-urban continuum, China. PLoS One 7 (4), e33982.

Ghosh, R., Siddarth, M., Singh, N., Tyagi, V., Kare, P.K., Banerjee, B.D., et al., 2017. Organochlorine pesticide level in patients with chronic kidney disease of unknown etiology and its association with renal function. EHPM 22, 1–8.

Gifford, F.J., Gifford, R.M., Eddleston, M., Dhaun, N., 2017. Endemic nephropathy around the world. Kidney Int. Rep. 2 (2), 282–292.

Global Burden of Disease – Chronic Kidney Disease Collaboration, 2020. Global, regional, and national burden of chronic kidney disease, 1990–2017: a systematic analysis for the Global Burden of Disease Study 2017. Lancet 395 (10225), 709–733.

Gupta, S., Bhattacharya, A., Raith, M., Nanda, J.K., 2000. Contrasting pressure–temperature–deformation history across a vestigial craton–mobile belt boundary: the western margin of the Eastern Ghats Belt at Deobhog, India. J. Metamorph. Geol. 18 (6), 683–697.

Herojeet, R., Dewangan, R.K., Naik, P.K., Verma, J.R., 2023. Probabilistic modelling is superior to deterministic approaches in the human health risk assessment: an example from a tribal stretch in central India. Sci. Rep. 13, 19351.

Herojeet, R.K., Madhuri, S.R., Renu, L., Ranjna, G., 2016. Application of environmetrics statistical models and water quality index for groundwater quality characterization of alluvial aquifer of Nalagarh Valley, Himachal Pradesh, India. Sustain. Water Resour. Manag. 2, 39–53.

Hettithanthri, O., Sandanayake, S., Magana-Arachchi, D., Wanigatunge, R., Rajapaksha, A.U., Zeng, X., et al., 2021. Risk factors for endemic chronic kidney disease of unknown etiology in Sri Lanka: retrospect of water security in the dry zone. Sci. Total Environ. 795, 148839.

Hofmeister, F., 1888. On the understanding of the effects of salts. Naunyn-Schmiedeberg's Arch. Pharmacol. 24, 247–260.

Hoseinzadeh, E., Yusefzadeh, A., Rahimi, N., Khorsandi, H., 2013. Evaluation of corrosion and scaling potential of a water treatment plant. Arch. Hyg. Sci. 2 (2), 41–47.

Hounslow, A., 2018. Water Quality data: Analysis and Interpretation. CRC Press, Boca Raton.

Hu, D., Indika, S., Makehelwala, M., Titus, C., Zhu, L., Pang, Z., et al., 2024. Chemical characteristics and water stability evaluation of groundwater in the CKDu Zone of Sri Lanka. J. Environ. Sci. 146, 67–80.

Imbulana, S., Oguma, K., 2021. Groundwater as a potential cause of Chronic Kidney Disease of unknown etiology (CKDu) in Sri Lanka: a review. J. Water Health 19 (3), 393–410.

Islam, M.A., Zahid, A., Rahman, M.M., Rahman, M.S., Islam, M.J., Akter, Y., et al., 2017. Investigation of groundwater quality and its suitability for drinking and agricultural use in the south central part of the coastal region in Bangladesh. Expo. Health 9, 27–41.

John, O., Gummudi, B., Jha, A., Gopalakrishnan, N., Kalra, O.P., Kaur, P., et al., 2021. Chronic kidney disease of unknown etiology in India: what do we know and where we need to go. Kidney Int. Rep. 6 (11), 2743–2751.

Jolly, A.M., Thomas, J., 2022. Chronic kidney disease of unknown etiology in India: a comparative study with Mesoamerican and Sri Lankan nephropathy. Environ. Sci. Pollut. Res. 29 (11), 15303–15317.

Kelly, W.P., 1940. Permissible composition and concentration of irrigated waters. Proceed. ASCF 66, 1-607.

Khan, T.A., Abbasi, M.A., 2013. Synthesis of parameters used to check the suitability of water for irrigation purposes. Int. J. Environ. Sci. 3 (6), 2031–2038.

Khandare, A.L., Reddy, Y.S., Balakrishna, N., Rao, G.S., Gangadhar, T., Arlappa, N., 2015. Role of drinking water with high silica and strontium in chronic kidney disease: an exploratory community-based study in an Indian Village. Indian J. Commun. Health 27 (1), 95–102.

Lal, K., Sehgal, M., Gupta, V., Sharma, A., John, O., Gummidi, B., et al., 2020. Assessment of groundwater quality of CKDu affected Uddanam region in Srikakulam district and across Andhra Pradesh, India. Groundw. Sustain. Dev. 11, 100432.

Langelier, W.F., 1936. The analytical control of anti-corrosion water treatment. J. Am. Water Works Assoc. 28, 1500–1521.

Larson, T.E., Skold, R.V., 1958. Laboratory studies relating mineral quality of water to corrosion of steel and cast iron*. Corrosion 14 (6), 43–46.

Levin, A., Okpechi, I.G., Caskey, F.J., Yang, C.W., Tonelli, M., Jha, V., 2023. Perspectives on early detection of chronic kidney disease: the facts, the questions, and a proposed framework for 2023 and beyond. Kidney Intl. 103 (6), 1004–1008.

Li, P., Li, X., Meng, X., Li, M., Zhang, Y., 2016a. Appraising groundwater quality and health risks from contamination in a semiarid region of northwest China. Expo. Health 8 (3), 361–379.

Li, P., Qian, H., Wu, J., Chen, J., Zhang, Y., Zhang, H., 2014. Occurrence and hydrogeochemistry of fluoride in shallow alluvial aquifer of Weihe River, China. Environ. Earth Sci. 71 (7), 3133–3145.

Li, P., Wu, J., Qian, H., 2016b. Hydrochemical appraisal of groundwater quality for drinking and irrigation purposes and the major influencing factors: a case study in and around Hua Country. China. Arab. J. Geosci. 9, 15.

Liu, J., Peng, Y., Li, C., Gao, Z., Chen, S., 2021. An investigation into the hydrochemistry, quality, and risk to human health of groundwater in the central region of Shandong Province, North China. J. Cleaner Product. 282, 125416.

Maitra, A., Keesari, T., Roy, A., Gupta, S., 2021. Fluoride contamination in and around selected geothermal sites in Odisha, Eastern India: assessment of ionic relations, fluoride exposure and remediation. Environ. Sci. Pollut. Res. 28, 1853–1856.

Mankikar, T.Y., 2021. Comparison of indices for scaling and corrosion tendency of groundwater: case study of unconfined aquifer from Mahoba District. UP State. Appl. Water Sci. 11 (6), 94.

Marghade, D., Malpe, D.B., Duraisamy, K., Patil, P.D., Li, P., 2020. Hydrogeochemical evaluation, suitability, and health risk assessment of groundwater in the watershed of Godavari basin, Maharashtra, Central India. Environ. Sci. Pollut. Res. 28, 18471–18494.

Mascarenhas, S., Mutnuri, S., Ganguly, A., 2017. Deleterious role of trace elements–silica and lead in the development of chronic kidney disease. Chemosphere 177, 239–249.

Minshawy, O., 2011. End stage renal disease in El-Minia Governorate, Egypt: data of the year 2007. Nephrourol. Mon. 3 (2), 118–121.

Mirzabeygi, M., Naji, M., Yousefi, N., Shams, M., Biglari, H., Mahvi, A.H., 2016. Evaluation of corrosion and scaling tendency indices in water distribution system: a case study of Torbat Heydariye, Iran. Desalin. Water Treat. 57, 25918–25926.

Mogal, V., 2020. Study of incidence & clinical profile of chronic kidney disease of unknown etiology (Ckdu) in a tertiary referral center. Kidney Meet, 5th World Kidney Congress; Webinar- June 22-23, 2020.

Mohanty, N.K., Sahoo, K.C., Pati, S., Sahu, A.K., Mohanty, R., 2020. Prevalence of chronic kidney disease in Cuttack District of Odisha, India. Int. J. Environ. Res. Public Health 17 (2), 456.

Mokif, L.A., Abbas, Z.H., Abdulhusain, N.A., 2018. Investigation of the corrosion and scaling potentials of raw and treated water and its effect on concrete tanks at Al-Tayyaraa Water Treatment Plant. JUBES 26 (2), 135–140.

Nature, 2024. Time to sound the alarm about the hidden epidemic of kidney disease. Nature 628, 7–8.

Nayak, A., Matta, G., Uniyal, D.P., 2023b. Hydrochemical characterization of groundwater quality using chemometric analysis and water quality indices in the foothills of Himalayas. Environ. Dev. Sustain. 25, 14229–14260.

Nayak, S., Rehman, T., Patel, K., Dash, P., Alice, A., Kanungo, S., et al., 2023a. Factors associated with chronic kidney disease of unknown etiology (CKDu): a systematic review. Healthcare 11 (4), 551.

Nematollahi, M.J., Clark, M.J.R., Ebrahimi, P., Ebrahimi, M., 2018. Preliminary assessment of groundwater hydrogeochemistry within Gilan, a northern province of Iran. Environ. Monit. Assess. 190 (4), 242.

Neogi, S., Das, N., 2000. Lithotectonic domains and metamorphic history of the boundary zone of the Eastern Ghats mobile belt and the Bastar craton, Deobhog area, Central India. Geol. Surv. India. Spec. Publ. 57, 180–204.

European Union, 2023. European Union (Drinking Water) Regulations 2023, Statutory Instruments (S.I. No. 99 of 2023), pp. 1–79.

NHMRC (National Health and Medical Research Council), 2017. Australian Drinking Water Guidelines Paper 6 National Water Quality Management Strategy. NHMRC, NRMMC (National Resource Management Ministerial Council), Commonwealth of Australia, Canberra (Version 3.4 Updated October 2017). pp. 176–189.

Parameswaran, S., Rinu, P.K., Kar, S.S., Harichandrakumar, K.T., James, T.D., Priyamvada, P.S., et al., 2020. A newly recognized endemic region of CKD of undetermined etiology (CKDu) in South India—"Tondaimandalam nephropathy". Kidney Int. Rep. 5 (11), 2066–2073.

Press Information Bureau, 2019, Naxal affected districts, PIB, Government of India. Available at: https://pib.gov.in/newsite/PrintRelease.aspx?relid=188075.

Pearce, N., Caplin, B., Gunawardena, N., Kaur, P., O'Callaghan-Gordo, C., Ruwanpathirana, T., 2019. CKD of unknown cause: a global epidemic? Kidney Int. Rep. 4 (3), 367–369.

Press Information Bureau, 2024. Jal Jeevan Mission: A Milestone in India's Rural Water Revolution, PIB, Government of India Available at:. https://pib.gov.in/PressNoteDetails.aspx?NoteId=152025&ModuleId=3.

Priyadarshani, W.V.D., de Namor, A.F.D., Silva, S.R.P., 2023. Rising of a global silent killer: critical analysis of chronic kidney disease of uncertain aetiology (CKDu) worldwide and mitigation steps. Environ. Geochem. Health 45 (6), 2647–2662.

Puckorius, P.R., Brooke, J.M., 1991. A new practical index for calcium carbonate scale prediction in cooling tower systems. Corrosion 47 (4), 280–284.

Purushothaman, P., Someshwar Rao, M., Rawat, Y.S., Kumar, C.P., Krishan, G., Parveen, T., 2014. Evaluation of hydrogeochemistry and water quality in Bist-Doab region, Punjab, India. Environ. Earth Sci. 72, 693–706.

Rajapurkar, M.M., John, G.T., Kirpalani, A.L., Abraham, G., Agarwal, S.K., Almeida, A.F., et al., 2012. What do we know about chronic kidney disease in India: first report of the Indian CKD registry. BMC Nephrol. 13, 1–8.

Rajkumar, H., Naik, P.K., Dewangan, R.K., Verma, J.R., Naik, P.K., 2025a. Hydrogeochemical forecasting in a tribal stretch infected with chronic kidney disease of unknown etiology. Sci. Total Environ. 969, 178906.

Rajkumar, H., Naik, P.K., Rishi, M., 2022. A comprehensive water quality index based on analytical hierarchy process. Ecol. Indic. 145, 109582.

Rajkumar, H., Naik, P.K., Rishi, M.S., 2020. A new indexing approach for evaluating heavymetal contamination in groundwater. Chemosphere 245, 125598.

Rajkumar, H., Naik, P.K., Singh, G., Rishi, M., 2023. Hydrogeochemical characterization, multi-exposure deterministic and probabilistic health hazard evaluation in groundwater in parts of Northern India. Toxin Rev. 42 (1), 204–227.

Rajkumar, K., Naik, P.K., Dewangan, R.K., Verma, J.R., Naik, P.K., 2025b. Geochemical characterization of groundwater and source apportionment of potential pollutants in a tribal stretch infected with chronic kidney disease of unknown etiology (CKDu). Chemosphere (Accepted) 376, 144272.

Raju, N.J., Shukla, U.K., Ram, P., 2011. Hydrogeochemistry for the assessment of groundwater quality in Varanasi: a fast-urbanizing center in Uttar Pradesh, India. Environ. Monit. Assess 173, 279–300.

Ramesh, K.V., Sasibhushan, B., Gouru Naidu, K., Mohan Kumar, S., 2011. The renal failure in Uddanam Region of Srikakulam district, Andhra Pradesh: areas identified for further investigations. IUP J. Chem. Eng. 3 (2), 68–71.

Rao, N.S., Rao, P.S., Dinakar, A., Nageswara, Rao, P.V., D, Marghade, 2017b. Fluoride occurrence in the groundwater in a coastal region of Andhra Pradesh. India. Appl. Water Sci. 7, 1467–1478.

Rao, N.S., Rao, P.S., Reddy, G.V., Nagamani, M., Vidyasagar, G., Satyanarayana, N.L.V.V., 2012. Chemical characteristics of groundwater and assessment of groundwater quality in Varaha River Basin, Visakhapatnam District, Andhra Pradesh, India. Environ. Monit. Assess. 184, 5189–5214.

Rao, N.S., Vidyasagar, G., Surya Rao, P., Bhanumurthy, P., 2017a. Chemistry and quality of groundwater in a coastal region of Andhra Pradesh. India. Appl. Water Sci. 7, 285–294.

Rathore, V., Pal, R., Galhotra, A., Nayak, S., Snehalata, Jha, V, et al., 2022. Community perception of chronic kidney disease in Supebeda, Chhattisgarh. Int. J. Curr. Res. Rev. 14 (2), 23–28.

Ravikumar, P., Somashekar, R., 2012. Assessment and modelling of groundwater quality data and evaluation of their corrosiveness and scaling potential using environmetric methods in Bangalore south Taluk, Karnataka State, India. Water Res. 39, 446–473.

Redmon, J.H., Levine, K.E., Lebov, J., Harrington, J., Kondash, A.J., 2021. A comparative review: chronic kidney disease of unknown etiology (CKDu) research conducted in Latin America versus Asia. Environ. Res. 192, 110270.

Richards, L.A., 1954. Diagnosis and Improvement of Saline and Alkali Soils. Agriculture Handbook, pp. 210–220 60.

Ryznar, J.W., 1944. A new index for determining amount of calcium scale formed by water. J. Am. Water Works Assoc. 36, 472.

Sewak, R., Sewak, P., Singh, P.S., 2023. Nitrate contamination in groundwater and preferred treatment technology in rural India. Water Secur. 20, 100149.

Shi, Q., Gao, Z., Guo, H., Zeng, X., Sandanayake, S., Vithanage, M., 2023. Hydrogeochemical factors controlling the occurrence of chronic kidney disease of unknown etiology (CKDu). Environ. Geochem. Health 45 (5), 2611–2627.

Sidhu, N., Rishi, M.S., Herojeet, R.K., 2013. Groundwater quality variation with respect to aquifer dispositioning in urbanized watershed of Chandigarh, India. Int. J. Environ Ecol. Family Urban Stud. 3 (2), 87–98.

Singh, G., Rishi, M.S., Herojeet, R., Kaur, L., Sharma, K., 2020a. Multivariate analysis and geochemical signatures of groundwater in the agricultural dominated taluks of Jalandhar district, Punjab, India. J. Geochem. Explorat. 208, 106395.

Singh, G., Rishi, M.S., Herojeet, R., Kaur, L., Sharma, K., 2020b. Evaluation of groundwater quality and human health risks from fluoride and nitrate in semi-arid region of northern India. Environ. Geochem. Health 42, 1833–1862.

Singh, V.K., Bikundia, D.S., Sarswat, A., Mohan, D., 2012. Groundwater quality assessment in the village of Lutfullapur Nawada, Loni, District Ghaziabad, Uttar Pradesh, India. Environ. Monit. Assess. 184, 4473–4488.

Stalin, P., Purty, A.J., Abraham, G., 2020. Distribution and determinants of chronic kidney disease of unknown etiology: a brief overview. Indian J. Nephrol. 30 (4), 241–244.

Szabolcs, I., Darab, C., 1964. The influence of irrigation water on high sodium carbonate content of soils. In: Proceedings of 8th international congress of ISSS, Trans, II, pp. 803–812.

Tatapudi, R.R., Rentala, S., Gullipalli, P., Komarraju, A.L., Singh, A.K., Tatapudi, V.S., et al., 2019. High prevalence of CKD of unknown etiology in Uddanam, India. Kidney Int. Rep. 4 (3), 380–389.

Thamarai, P., Deivayanai, V.C., Karishma, S., Yaashikaa, P.R., Saravanan, A., 2024. Effective removal of fluoride ions from contaminated water using electrochemical techniques: a critical review on recent developments and environmental perspective. J. Hazard. Mater. Adv. 16, 100483.

Trabanino, R.G., Aguilar, R., Silva, C.R., Mercado, M.O., Merino, R.L., 2002. End-stage renal disease among patients in a referral hospital in El Salvador. Revista panamericana de salud publica= Pan Am. J. Public Health 12 (3), 202–206.

UCCC (University of California Committee of Consultants), 1974. Guidelines For Interpretations of Water Quality For Irrigation. University of California Committee of Consultants, Berkeley.

United States Geological Survey, 2019. Corrosivity. Water resources mission area. USGS. https://www.usgs.gov/mission-areas/water-resources/science/corrosivity.

US Salinity Laboratory diagram (USSL), 1954. Diagnosis and Improvement of Saline and Alkaline Soils. United States Salinity Laboratory, US Department of Agriculture, Washington, DC.

USEPA (U.S. Environmental Protection Agency), 2024a. Secondary drinking water standards: guidance for nuisance chemicals (Last updated on June 14, 2024). Available at: https://www.epa.gov/sdwa/secondary-drinking-water-standards-guidance-nuisance-chemicals. Assessed November 15, 2024.

USEPA (U.S. Environmental Protection Agency), 2024b. National primary drinking water regulations (last updated on october 9, 2024). Available at: https://www.epa.gov/ground-water-and-drinking-water/national-primary-drinking-water-regulations. Assessed November 15, 2024.

Vendrell, P.F., Atiles, J.H., 2003. Your household water quality: corrosice or scaling water, housing and environment, Secondary Drinking Water Standards: Guidance for Nuisance Chemicals (Last updated on June 14, 2024).

Wagh, V., Panaskar, D., Aamalawar, M., Lolage, Y., Mukate, S., Adimalla, N., 2018. Hydrochemical characterisation and groundwater suitability for drinking and irrigation uses in semiarid region of Nashik, Maharashtra, India. Hydrospatial. Anal. 2, 43–60.

WHO (World Health Organization), 2011. Guidelines For Drinking-Water quality, 4th Edn. World Health Organization, Geneva.

WHO (World Health Organization), 2022. WHO guidelines for drinking water quality, fourth ed. In: Incorporating the First and Second Addenda. World Health Organization, Geneva, pp. 1–614.

Wilcox, L.V., 1955. Classification and use of irrigation waters. Washington, DC, pp. 1–19.

Xu, P., Feng, W., Qian, H., Zhang, Q., 2019. Hydrogeochemical characterization and irrigation quality assessment of shallow groundwater in the Central-Western Guanzhong Basin, China. Int. J. Environ. Res. Public Health 16 (9), 1492.

Zeng, X., He, W., Guo, H., Shi, Q., Zheng, Y., Vithanage, M., et al., 2022. Recognizing the groundwater related to chronic kidney disease of unknown etiology by humic-like organic matter. Npj Clean Water 5 (1), 8.

Zhang, W., Ma, L., Abuduwaili, J., Ge, Y., Issanova, G., Saparov, G., 2019. Hydrochemical characteristics and irrigation suitability of surface water in the Syr Darya River, Kazakhstan. Environ. Monit. Assess. 191, 572.

Zhou, J.L., Wu, B., Wang, Y.P., Guo, X.J., 2009. Distribution and quality assessment of medium salinity groundwater in plain areas in Tarim Basin, Xinjiang. China Rural Water Hydrop. 9, 32–36.

Zhou, Y., Li, P., Xue, L., Dong, Z., Li, D., 2020. Solute geochemistry and groundwater quality for drinking and irrigation purposes: a case study in Xinle City, North China. Geochem 80 (4), 125609.

Zhou, Z., Shi, X., Zheng, Y., Qin, Z., Xie, D., Li, Z., Guo, T., 2014. Abundance and community structure of ammonia-oxidizing bacteria and archaea in purple soil under long-term fertilization. Eur. J. Soil Biol. 60, 24–33.