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Groundwater quality of Arattupuzha coastal region of Kerala, India: A study based on pollution index

Balamuralikrishna, V S Achari* & M Mohanadas

Environmental Chemistry Laboratory, School of Environmental Studies, Cochin University of Science and Technology, Kochi, Kerala – 682 022, India

*[E-mail: vsachari@cusat.ac.in]

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The hydrogeochemical profile of groundwater in the southern Kerala coast - Arattupuzha, in Alappuzha, Kerala, India is reported for drinking and domestic suitability. People at Arattupuzha mostly depend on public water supply for their domestic and drinking requirements due to limited freshwater availability. In this context, the palatability of coastal groundwater sources was evaluated and presented based on the weighted arithmetic mean Water Quality Index (WQI) and Pollution Index of Groundwater (PIG) methods. Groundwater was collected from 6 shallow (Dug wells) and 5 deep (Bore wells) sources during pre-monsoon (PRM), monsoon (MON) and post-monsoon (POM) seasons in 2019. Water was analysed for various physical and chemical parameters *viz.* pH, Eh, Electrical Conductivity (EC), Total Dissolved Solids (TDS), Total Alkalinity (TA), Total Hardness (TH), Cl^-, SO_4^{2-}, HCO_3^-, total iron, Dissolved Oxygen (DO), Biochemical Oxygen Demand (BOD), NO_3^-, Na^+, K^+, Ca^{2+} and Mg^{2+}. The results were compared with the WHO and BIS standards for drinking water quality. The WQI showed that most of the groundwater sources are unsuitable (WQI > 100) for direct drinking purposes. This is attributed to the total iron, TH and TA; hence, it requires pre-treatment prior to use. In the PRM season, the WQI values were 74.5±95.5 (Shallow Groundwater - SG) and 315.1±151.4 (Deep Groundwater - DG), indicating poor water quality, while in MON and POM, these were 181.9±125.4 (SG), 413.8±296.7 (DG) and 225.2±97.9 (SG), 406.4±132.6 (DG), respectively showing non-suitability for drinking purpose. Hill-Piper Trilinear diagram revealed Ca-Mg-HCO_3 as the dominant hydrochemical facies. PIG results revealed insignificant pollution (PIG < 1) in water with 0.5±0.3 (SG) and 0.6±0.3 (DG) values in PRM. Additionally, the Durov, Stiff and radial diagrams were used to represent the prominent ionic composition of water sources. Overall, the groundwater quality of Arattupuzha coastal area revealed that groundwater in pre-monsoon was much safer than in the monsoon and post-monsoon seasons.

[**Keywords**: Coastal aquifers, Hill-Piper Trilinear diagram, Hydrogeochemistry, Pollution, Water quality]

Introduction

Drinking water availability is a problem in many regions of the world due to over-exploitation and groundwater contamination[1-3]. Accessibility to safe drinking water is a fundamental human right[2]. This groundwater is an essential resource for ensuring a better livelihood and sustainable living. Access to safe and clean drinking water and sanitation is one of the targets of the UN sustainable development goals (Goal 6). Studies have shown that the global population is experiencing severe water scarcity and is increasing from 32 million people in 1900 to a projected 3.1 billion people by 2050. The global groundwater crisis is exacerbated by water quality degradation, with a direct adverse impact on human health[4]. The fast-growing population has a significant influence on up keeping the quantity and quality of groundwater[5]. India has a coastline of 7516.6 km, where coastal dug wells are threatened by frequently occurring high tide and saltwater intrusion. Arattupuzha coast (Alappuzha, Kerala) was inundated by 26th December 2004 Indian Ocean tsunami with severe damages. Widespread inundation by giant waves spoiled the region's inherent biodiversity and geochemistry. It is difficult to restore the pristine quality of groundwater once it is contaminated even by natural hazards. Hence, it is important to monitor and assess the groundwater quality at regular intervals to infer the variability.

The Water Quality Index (WQI) is a commonly used model for differentiating the fineness of water for drinking and domestic purposes[6-8]. Numerous other computational methods such as entropy-weighted water quality index and fuzzy logic methods are also commonly applied[8]. Additionally, various hazard indices are also used to evaluate the risk of heavy metal content in groundwater and the associated environmental/human health issues[9].

The Pollution Index of Groundwater (PIG) is used for evaluating the pollution level in groundwater sources[3]. Water quality monitoring helps to know the effectiveness of the existing pollution control measures. Efforts are required to control the pollutants by adopting purification procedures[9,10]. Water containing TDS of more than 500 mg/L is undesirable and affects human kidney functioning[8]. Drinking water containing high Cl^- (> 250 mg/L) leads to health situations of diarrhoea, vomiting, fatigue, dehydration, weakness and difficulty in berating.

The WQI is the most effective tool to evaluate and share information on the quality of water to concerned citizens and policymakers[11]. Hydrogeochemistry reveals the distribution of the ions in water, which can be used to determine the type and quality of water. An understanding of the geochemical components in water and their physical existence are important to determine origin and suitability for drinking and other purposes[12-14]. Some of the reported studies on the groundwater quality of the Kerala state are known[6,8,15-20]. The 26th December 2004 Indian Ocean Tsunami impacted coastal groundwater sources to a situation of severe saline inundation and quality deterioration. This disaster opened up a new avenue of research on hydrogeochemistry of groundwater in a post-tsunami disastrous scenario. Achari[1] studied the water quality in the tsunami-affected coastal areas of Kerala and compared the results with those of pre-tsunami situations. Additionally, Krishna & Achari[6] studied groundwater for drinking and industrial purposes from the black sand mineral-rich coastal region of Kerala, India and revealed that water quality in the post-monsoon (POM) season is excellent for drinking. Nickel (Ni) exhibited carcinogenic risk in children and adult populations in the Alappad coastal region. Further, Krishna & Achari[8] studied the seasonal variation of groundwater chemistry in tsunami-affected Alappad coastal regions of Kerala using the entropy weighted method. Some more research works, like Mohanadas *et al.*[17] studied the impact of seafood processing industries in the coastal region of Alappuzha, Kerala; Viswanath *et al.*[18] studied the physico-chemical properties of groundwater of the Kozhikode district (Kerala) by applying multivariate statistical methods; Prasanth *et al.*[19] studied the groundwater quality and its suitability for drinking and agriculture use in coastal stretch of Alappuzha; and Manjusree *et al.*[20] studied the factors controlling the shallow groundwater quality in two coastal panchayats in the Alappuzha district of Kerala.

Arattupuzha (Alappuzha) is a barrier islet that lies between the Trivandrum – Shoranur (TS) canal in the east and the Arabian Sea in the west in the coastal region of Kerala, India. Most people there depend on groundwater for their domestic and irrigational uses. Arattupuzha coast, in Kerala, has economically valuable black sand deposits. It comprises minerals like ilmenite, rutile, zircon, and sillimanite. The rapid urbanisation and industrialisation has been accompanied by enhanced public awareness and concern regarding groundwater protection[21-22]. In the above context, the present study is focused on an objective to highlight seasonal variation of WQI and PIG in shallow groundwater sources of Arattupuzha coast. This study aims to report the groundwater chemistry and hydrogeochemical mechanisms as a drive for safe drinking water and sanitation in a highly vulnerable coastal community.

Materials and Methods

Study area

The study area for the present investigation includes Arattupuzha coastal village, located north latitudes between 09°07'41" to 09°11'26" N and east longitudes between 76°26'25" to 76°28'23" E. Geographic location of each sampling well and descriptions are presented in Table 1. The coast is under continuous threat of frequently occurring high tides and erosion, as reported by the residents. Arattupuzha village is located in Karthikappally Taluk of Alappuzha District and the western portion of the Kerala State (Fig. 1). Alappuzha District has 82 km of coastline, which is 14 % of the total coastal land of Kerala state[23].

Alappuzha coastal province of Kerala comprises the quaternary alluvium and tertiary sediments. The subsurface water occurrence, distribution, transportation, and composition are closely linked to the composition and structure of the underlying geological formations[16,23]. A unit of unconsolidated deposit called an aquifer yields a usable quantity of water. Groundwater recharged by precipitation, rivers and streams infiltration reaches the water table. The coastal plains have an elevation of less than 7.6 m from the mean sea level. The elevation of the midland region ranges from 7.6 to 76 m above mean sea level. Alleppey, vaikom, quilon, and warkalli are the four distinct layers that make up the tertiary sedimentary formations that are found along the western region of

Table 1 — Geographic locations of sampling stations at Arattupuzha coastal area

Station Id	Station description (Dug wells)	Well type	Latitude	Longitude	Remarks
DW 1	Valiyazheekal Mahadeva temple well	Dug well	09°08’33” N	76°27’43” E	Used for drinking
DW 2	Parvathy temple well	Dug well	09°08’49” N	76°27’49” E	Not used for drinking
DW 3	Kuriyappassery temple well	Dug well	09°09’40” N	76°27’49” E	Used for drinking
DW 4	Panakkal temple well	Dug well	09°09’53” N	76°27’10” E	Not used for drinking
DW 5	Bhaskaran- house owner	Dug well	09°10’51” N	76°26’35” E	Used for drinking
DW 6	Mohanan- house owner	Dug well	09°11’03” N	76°11’03” E	Used for drinking
BW 1	Thara – House owner	Bore well	09°08’26” N	76°27’41” E	Used for drinking
BW 2	Valiyazheekkal pump	Bore well	09°08’32” N	76°28’01” E	Used for drinking
BW 3	Prawn shed- Bore well	Bore well	09°08’43” N	76°27’35” E	Used for drinking
BW 4	Biju- house owner	Bore well	09°09’21” N	76°27’35” E	Used for drinking
BW 5	Kuriyappassery Pump	Bore well	09°09’40” N	76°27’16” E	Used for drinking

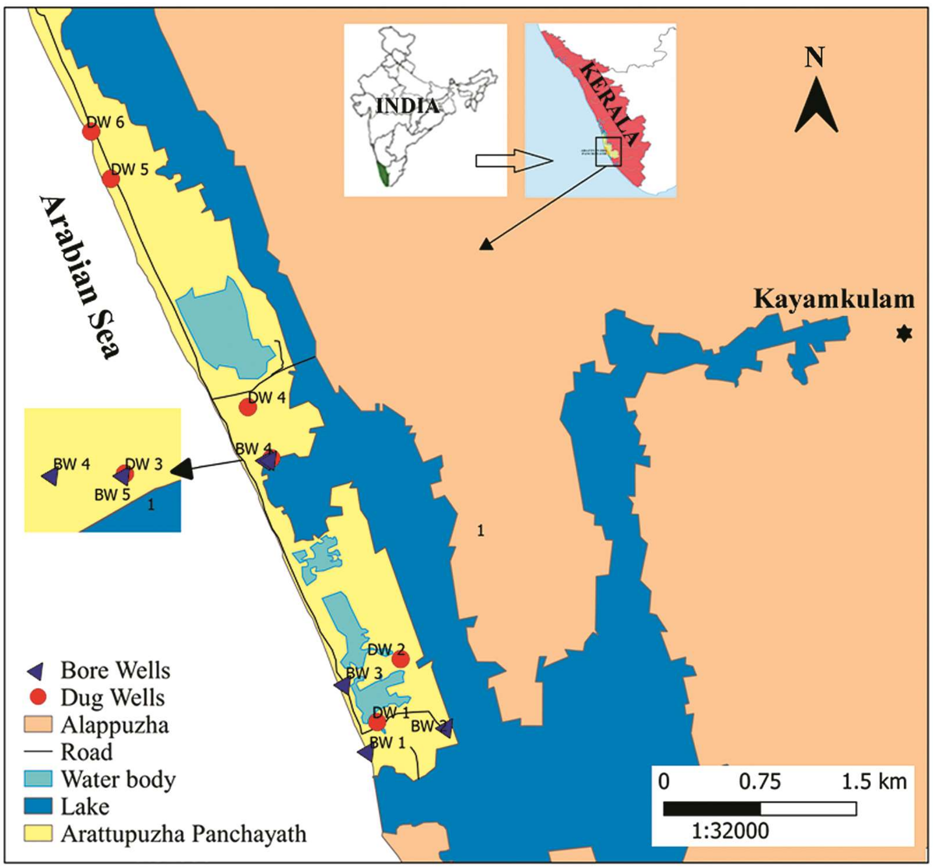

Fig. 1 — Groundwater sampling locations at Arattupuzha coastal region, Kerala, India

the state[23]. Along the midland area, the tertiary and crystalline formations are lateritized. The coastal lowlands are covered in recent alluvial deposits. The Indian coastal tract is highly prone to cyclones. The onset of the southwest monsoon from June brings high waves closer to the southwest coast till September.

Sample collection and analysis

Groundwater samples were collected from the shallow (dug wells, depth 3.0 – 4.5 m) and deep (bore wells, mean depth 40 m) groundwater sources during pre-monsoon (PRM), monsoon (MON), and post-monsoon (POM) seasons of the year 2019. Samples were collected in pre-washed 2.5 litre polyethylene containers. Water samples from bore wells were collected only after allowing 5 min of free flow to remove any stagnant water in the tube. Samples collected for the determination of iron was acidified with concentrated HCl. The sample water was also used to rinse the collection bottles to prevent any contamination. The sample name and date of the collection were labelled on the bottles and kept in the ice box and sealed to carry to the laboratory (not later than 3 hrs), and were analysed immediately within 24 hrs. Analytical grade chemicals and reagents were used to prepare reagents and standard solutions (Merck). Standard Methods (APHA)[24] were followed for the collection and analysis of each sample. pH, Eh, Electrical Conductivity (EC) and Total Dissolved Solids (TDS) were analysed on site using multiparameter probe (Eutech PCD, 650). The analysed water parameters namely EC, TDS, Dissolved Oxygen (DO) and Biochemical Oxygen Demand (BOD) by Azide modification method, Total hardness (EDTA titration), Total alkalinity (Titrimetric method), Chloride (Argentometric titration), Total iron (1,10-Phenanthroline method), Sulphate (Turbidimetric method), Nitrate (UV screening method), Sodium and Potassium (Flame photometry), Calcium, and Magnesium (Titrimetry) were considered for the computation of the WQI. For the present study, 6 representative shallow groundwater sources (dug wells) and 5 deep groundwater (bore well) were selected. Hill-Piper Trilinear diagram, Durov, Stiff and radial diagrams were prepared in Aquachem 2014.2 (Waterloo, Canada) software. Water quality parameters, analytical methods, and instruments adopted for the study are shown in Table S1. The instruments were calibrated according to the manufacturer's guidelines and standard operating procedures described.

Water Quality Index (WQI)

The WQI is a mathematical model to determine the water quality for drinking and domestic purposes[25-26]. A numerical representation of groundwater quality can be done using the WQI[27]. In this study, 15 water quality parameters were considered for the calculation of WQI. In this method, the weighing factor (W_i) is determined. These factors were multiplied by all the quality ratings (q_i) of each parameter, and an aggregate was taken to the final result (Eq. 1).

$$WQI = \frac{\sum W_i q_i}{\sum W_i} \quad \ldots (1)$$

Where, $q_i = 100*[V_o - V_i] / [S_i - V_i]$ ... (2)

and $W_i = K/S_i$ … (3)

Here, K is the proportionality constant for the weights,

$$K = \frac{1}{\sum_{i=1}^{n} \frac{1}{Si}} \quad \ldots (4)$$

The q_i is quality rating for the i^{th} water quality parameters $(i = 1, 2, 3, 4 \ldots n)$; V_o is the observed value or estimated concentration of any parameter; V_i is the ideal value of that particular parameter (zero for all parameter except pH and DO). V_i for pH is 7, and for DO, it is 14.6 mg/L. Si is the standard permissible value of particular parameter, based on the guidelines of World Health Organisation (WHO)[28]. The standard permissible value (S_i) and weighing factor (W_i) calculated for each parameter for the calculation of WQI are presented in Table 2. These values are used to compute quality rating (q_i) for each parameter.

According to WQI, water is classified into five categories[27]. They are 'Excellent' (WQI = 0 – 25) water quality with 'A' grade, 'Good' (WQI = 25 – 70) with 'B' grade water, 'Poor' (WQI = 51 – 75) 'C' grade water, 'Very Poor' (WQI = 76 – 100) 'D' grade water, and 'Unfit for Drinking Purposes' (WQI > 100) 'E' grade water.

Pollution Index of Groundwater (PIG) analysis

Pollution index of groundwater is commonly applied for the evaluation of drinking water quality. It's computation process has five steps. First step (I) is to find the relative unit weight *(Rw)* on a scale of 1 – 5. The weightage of each parameter is assigned based on their direct impact on human health. The

Table 2 — Physico-chemical parameters used for the calculation of WQI

Parameters	Standard permissible value[28,29] (Si)	Ideal value[9] (V_i)	Weighing factor (Wi)
pH	8.5	7	0.028
DO	5.0	14.6	0.048
EC (µS)	1500.0	0	0.000
TDS	500.0	0	0.000
BOD	3.0	0	0.080
Alkalinity	200.0	0	0.001
Total hardness	300.0	0	0.001
Chloride	250.0	0	0.001
Iron	0.3	0	0.801
SO_4^-	200.0	0	0.001
NO_3^-	45.0	0	0.005
Na^+	200.0	0	0.001
K^+	12.0	0	0.020
Ca^{2+}	75.0	0	0.003
Mg^{2+}	30.0	0	0.008
			$\sum W_i = 1.000$

unit weight of water quality parameters and corresponding standard (BIS)[29] values are given in Table 3. Second step (II) is to evaluate the weight parameter *(Wp)* of each parameter to assess their relative contribution to the groundwater quality. It is the ratio of *Rw* and ∑*Rw*, as shown in the Eq. (5).

$$Wp = \frac{Rw}{\sum Rw} \quad \text{… (5)}$$

In the third step (III), the status of concentration *(Sc)* was estimated. *C* is the water quality parameter in each of the water samples by their respective standard limits (D_S) (Eq. 6).

$$Sc = \frac{C}{Ds} \quad \text{… (6)}$$

In this study, permissible limits of the WHO[28] and BIS[29] were used as the standard limits for the PIG assessment. In the fourth step (IV), the overall quality of the groundwater *(Ow)* was computed by multiplying the *Wp* with the *Sc*, as shown in Eq. (7).

$$Ow = Wp \times Sc \quad \text{… (7)}$$

The final step (V) is to find out the *Ow* values per sample (Eq. 8).

$$PIG = \sum Ow \quad \text{… (8)}$$

The final PIG values are classified into five groups[3] namely 'Insignificant pollution' (PIG < 1), Low pollution (1.0 < PIG < 1.5), Moderate pollution (1.5 < PIG < 2.0), High pollution (2.0 < PIG < 2.5), and Very high pollution (PIG > 2.5).

Table 3 — Water quality parameters and components used for PIG computation

Parameters (*C*)	Unit	Relative weight (*Rw*)[3]	Weight parameter (*Wp*)[3]	Standard value (*Ds*)[29]
pH	-	3	0.081	8.5
TDS	mg/L	5	0.135	500
Cl^-	mg/L	4	0.108	250
Iron	mg/L	4	0.108	0.3
SO_4^{2-}	mg/L	5	0.135	200
NO_3^-	mg/L	5	0.135	45
Na^+	mg/L	4	0.108	200
K^+	mg/L	1	0.027	12
Ca^{2+}	mg/L	2	0.054	75
Mg^{2+}	mg/L	2	0.054	30
		$\sum R_W = 35$	$\sum W_P = 1.00$	

Results and Discussion

Hydrogeochemical characteristics

The physicochemical parameters analysed from groundwater samples revealed that the samples exhibit much variation in the concentration of several parameters seasonally (PRM, MON, and POM, 2019). The results were evaluated in accordance with the standard drinking water specifications of WHO[28] and BIS[29]. The parameters exceeding the BIS acceptable limits along with their permissible limits, are presented in Table 4. Higher values in Electrical Conductivity (EC) are due to the result of a high level of mineralisation[30] that occurred in the coastal phreatic aquifers of the study area due to leaching of Ca^{2+}, Mg^{2+}, Na^+, K^+, Cl^-, SO_4^{2-}, NO_3^- and Fe.

The pH of all the stations is well within the acceptable limit set by BIS and WHO for all the seasons and no relaxation is permissible in the pH of drinking water beyond 6.5 – 8.5. According to reports from the Food and Agriculture Organization of the United Nations (FAO-UN)[31], the acceptable range of pH for irrigation water is 6.5 – 8.5. In the current study, none of the water samples or stations are found with undesirable pH ranges. The higher amount of TDS and EC reflected the number of dissolved salts in groundwater. However, the PRM season has exceeded the permissible limit for EC (1500 µS/cm) of WHO[28] compared to MON and POM season while comparing the total number and percentage of samples.

The EC, TH, and TA are the factors that contribute to undesirable changes in the region's groundwater. In SG sources 67 % of the samples in PRM (3160±4077 µS/cm), 50 % in MON (2050±2313 µS/cm), and 66 % in POM (2128±1538 µS/cm) season showed EC above the permissible limit. In contrast, the bore wells showed EC within the permissible limits (1500 µS/cm) with average values of 810±226 (PRM), 790±202 (MON) and 660±375 (POM). TDS and TH are expressed in calcium carbonate present in water. In SG sources, 67 % in PRM (60 % in DG), 50 % in MON (20 % in DG), and 50 % in POM (20 % in DG) seasons observed very hard water (Table 5). The desirable limit of TH is 200 mg/L for drinking water[29]. Dug well groundwater sources showed the average total iron concentration of 0.2±0.4 mg/L (PRM), 0.6±0.5 mg/L (MON) and 0.8±0.4 mg/L (POM). In contrast, the bore well sources showed elevated total iron content of 1.0±0.7 mg/L (PRM), 1.5±1.1 mg/L (MON) and 1.5±0.5 mg/L (POM). Higher amount of iron in groundwater is expected to

Table 4 — Physico-chemical parameters recorded in three seasons and their comparison with WHO[22] and BIS[23] standards

Parameters	(Acceptable limit) BIS IS:10500	WHO (2017) guideline value	Pre-monsoon		Monsoon		Post-monsoon	
			Dug wells	Bore wells	Dug wells	Bore wells	Dug wells	Bore wells
pH	6.5 – 8.5	6.5 – 8.5	7.7±0.5	7.1±0.3	0.8±0.8	7.1±0.2	7.9±0.3	7.2±0.3
Eh (mV)	-	-	-41.0±28.9	-4.6±14.9	-60.2±48.0	-7.2±9.9	-53.2±16.7	-14.8±11.1
EC (µS/cm)	-	1500	3160±4077	810±226	2050±2313	790±202	2128±1538	660±374.9
TDS (mg/L)	500	600	324.7±212.3	185.0±52.7	764.9±0.8	312.4±82.8	947.9±707.0	285.6±168.4
DO (mg/L)	-	-	5.5±2.5	3.3±2.2	7.4±2.9	4.5±3.0	4.3±1.9	4.4±3.2
BOD (mg/L)	-	-	2.5±1.0	10.8±19.3	2.4±2.9	1.9±1.1	2.8±1.2	2.0±1.2
Alkalinity (mg/L)	200	-	228.9±114.4	211.5±60.8	210.6±91.2	198.0±59.6	245.0±118.7	147.0±84.3
TH (mg/L)	200	100	246.8±154.5	156.8±49.3	166.3±93.2	152.5±36.3	201.1±102.8	115.2±72.4
HCO_3^- (mg/L)	-	-	279.2±139.6	258.0±74.2	256.9±111.2	241.6±72.8	298.9±144.9	179.3±102.8
Cl^- (mg/L)	250	250	132.5±121.3	13.6±8.8	79.5±142.5	9.4±4.3	60.2±82.8	5.3±4.6
Iron (mg/L)	0.3	0.3	0.2±0.4	1.0±0.7	0.6±0.5	1.5±1.1	0.8±0.4	1.5±0.5
SO_4^{2-} (mg/L)	200	250	12.9±7.8	0.0±0.0	10.4±3.9	0.0±0.0	10.2±11.6	0.8±1.9
NO_3^- (mg/L)	45	50	0.7±1.1	0.6±0.3	1.1±2.3	0.6±0.3	1.1±1.6	0.5±0.3
Na^+ (mg/L)	200	200	71.7±43.0	16.7±6.6	213.7±329.8	40.6±28.9	38.8±12.5	23.4±6.7
K^+ (mg/L)	12	12	12.0±9.9	5.6±0.9	4.3±5.4	6.1±1.2	21.5±11.7	22.6±16.3
Ca^{2+} (mg/L)	75	75	73.2±42.57	40.5±13.9	51.6±36.3	40.4±10.8	69.7±40.7	36.2±24.1
Mg^{2+} (mg/L)	30	50	3.9±2.6	1.4±0.2	9.0±4.3	12.5±3.1	6.5±5.5	6.0±4.5

BIS – Bureau of Indian Standards, WHO – World Health Organisation, EC – Electrical Conductivity, TDS – Total Dissolved Solids, DO – Dissolved Oxygen, BOD – Biochemical Oxygen Demand, and TH – Total Hardness

Table 5 — Groundwater quality of Arattupuzha coastal segment based on TDS, EC, total hardness, nitrates and chlorides

Parameter	Range	% of sample: Pre-monsoon		Monsoon		Post-monsoon		Purpose/Remarks
		Dug wells (SG)	Bore wells (DG)	Dug wells (SG)	Bore wells (DG)	Dug wells (SG)	Bore wells (DG)	
TDS (mg/L)	< 500	83	100	66	100	33	100	Drinking
	500–1000	17	0	17	0	34	0	Permissible for drinking
	1000–3000	0	0	17	0	33	0	Suitable for irrigation
	> 3000	0	0	0	0	0	0	Unfit for drinking and irrigation
Electrical Conductivity (EC) (µS/cm)	0–333	0	0	0	0	0	40	Excellent
	333–500	0	20	17	0	17	0	Good
	500–1100	33	80	33	100	17	60	Permissible
	1100–1500	0	0	0	0	0	0	Brackish
	1500–10500	67	0	50	0	66	0	Saline
Total Hardness (TH) (mg/L)	< 60	0	0	17	0	0	40	Soft
	60–120	33	20	17	20	33	0	Moderate
	120–180	0	20	16	60	17	40	Hard
	> 180	67	60	50	20	50	20	Very hard
Nitrates (NO_3^-) (mg/L)	< 5	100	100	83	100	100	100	Excellent
	5–10	0	0	17	0	0	0	Good
	10–50	0	0	0	0	0	0	Permissible
	> 50	0	0	0	0		0	Poor
Chlorides (Cl^-) (mg/L)	≤ 50	33	100	83	100	83	100	Excellent
	≤ 150	33	0	0	0	0	0	Good
	≤ 250	17	0	0	0	17	0	Permissible
	> 250	17	0	17	0	0	0	Poor

occur due to the leaching of the soil and sediments. The maximum permissible limit for iron in drinking water is prescribed as not exceeding 0.3 mg/L[ref. 29]. Among all the samples (n = 11), 45 % of samples in PRM, 82 % in MON, and 100 % in POM seasons showed the total iron above the permissible limit[29] of 0.3 mg/L. Higher TDS levels were observed in MON (764.9±0.8 mg/L in dug wells and 312.4±82.8 mg/L in bore wells) and POM (947.9±707.0 mg/L in dug wells and 285.6±168.4 mg/L in bore wells). Calcium and magnesium were observed within the acceptable limit of BIS. The cations, Ca^{2+} and Mg^{2+} contributed to the temporary hardness of water as revealed from the Hill-Piper Trilinear diagram analysis[32] (Fig. 2). Sulphate concentrations were obtained very less due to the sulphate reduction reactions commonly occurred in the soils. SO_4^{2-} in dug wells showed an average values of 12.9±7.8 mg/L in PRM, 10.4±3.9 mg/L in MON and 10.2±11.6 mg/L in POM seasons. The desirable limit of sulphate is 200 mg/L for drinking water[29]. Alkalinity is observed in higher concentration levels in PRM (75 %) and POM (45 %) seasons. The percentage of samples above the permissible limit is presented in Table S2.

Hydrogeochemical regime of the study area was evaluated by plotting major cations and anions in Hill-Piper Trilinear diagram[32]. Hill-Piper Trilinear diagrams are useful in understanding the hydrochemical facies and geochemical composition of the groundwater sources (Fig. 2). The triangular plots of cations and anions have a common baseline. The percentage concentration of major ions plotted in triangular plots was projected onto the diamond plot (Fig. 2a – c). Four major classifications were made on the diamond plot. The left corner is Ca-Mg-HCO_3 dominant water type, indicating temporary hardness. The right corner of the diamond plot represents the saline (Na-Cl) water type. Top corner of the plot is rich with $Ca^{2+}+Mg^{2+}$ and $Cl^{-}+SO_4^{2-}$, indicating permanent hardness. Bottom of the

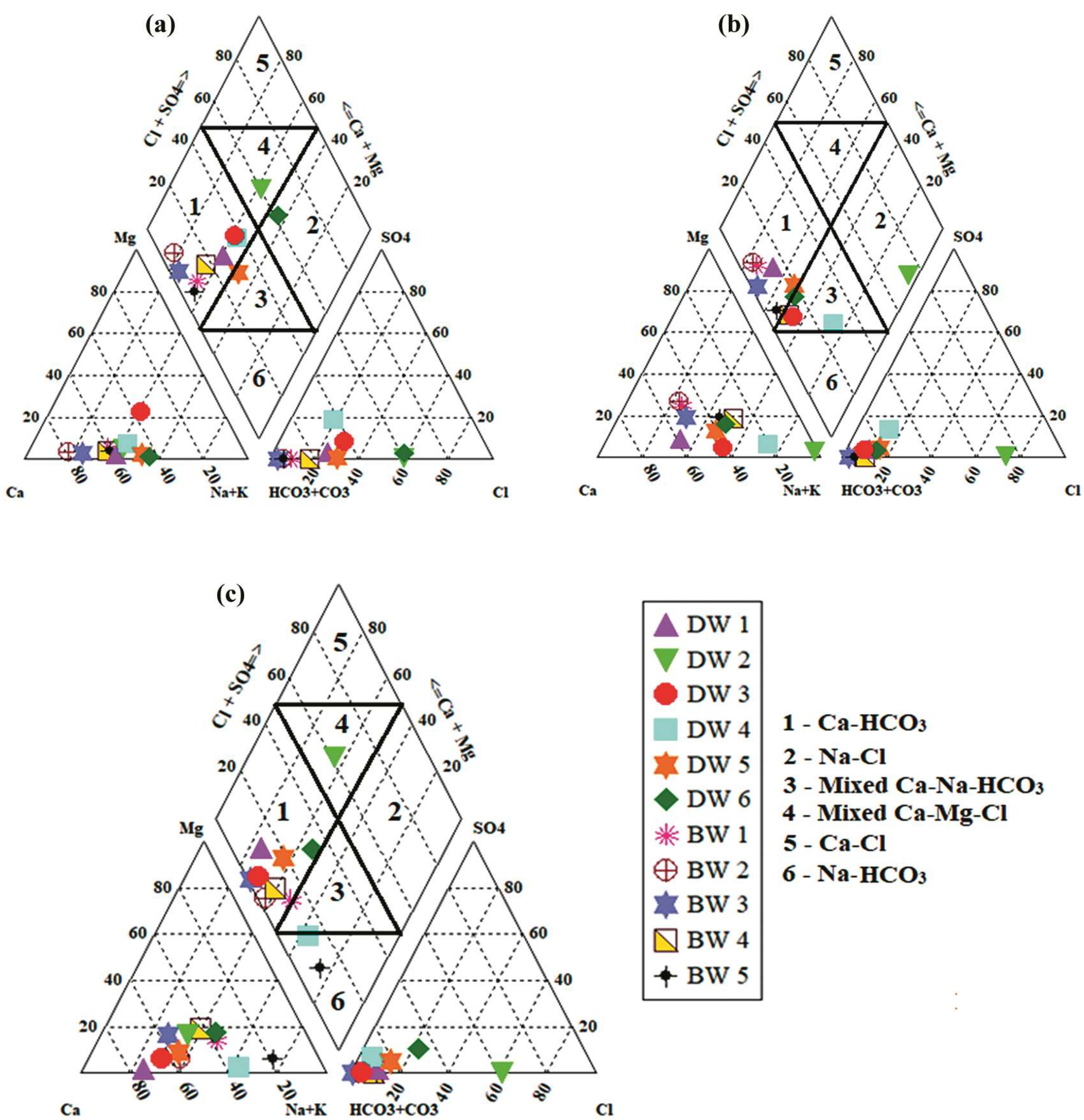

Fig. 2 — Hill-Piper Trilinear diagram showing the seasonal variation of groundwater facies for shallow [Dug Wells (DW)] and deep [Bore Wells (BW)] groundwater sources: (a) Pre-monsoon (PRM), (b) Monsoon (MON), and (c) Post-monsoon (POM)

diamond plot is composed of alkali carbonate (Na-HCO_3) water type.

The dominant cations such as Ca^{2+}, Mg^{2+} and anion HCO_3^- were present in groundwater during PRM and POM period. This indicates the reverse ion exchange process during this period. The dominance of Na^++K^+ was observed during the monsoon season, indicating an ion exchange process occurred between water and soil; where the minerals, Ca^{2+} and Mg^{2+} in water get exchanged with the sodium in the soils or rocks. Water is mainly having the alkaline earth and bicarbonate facies as observed during the PRM and POM periods (Table S3). It is seen that the groundwater contains more alkaline earth (Ca^{2+}+Mg^{2+}) than the alkali metals (Na^++K^+) and more weak acids (HCO_3^-+CO_3) than strong acids (SO_4^{2-}+Cl^-) as reported in earlier studies[33]. During PRM, the dominant hydrochemical facies was Ca-Na-HCO_3 and Ca-Na-HCO_3-Cl. This shows that the groundwater is dominated by alkali earth-alkali-bicarbonates (Table S3). The station DW2 showed mixed groundwater facies (Ca-Na-HCO_3-Cl water type), indicating saltwater intrusion. DW6 shows Na-Cl water type due to the excessive concentration of Na^+ (120 mg/L) in the PRM period. During MON season, DW2 showed Na-Cl water type indicating saline water (TDS = 2947 mg/L, Na^+ = 886 mg/L). In MON season, the dominant hydrochemical facies were Na-Ca-HCO_3 showing dominant groundwater characteristic of alkali-alkali earth-bicarbonates for four dug wells (DW3, DW4, DW5 & DW6), and a bore well BW4. Station DW2 belongs to saline facies, because it is situated near to the Arabian Sea in the west. Water showed alkaline conditions during the monsoon period. Ca-Na-HCO_3 was the dominant hydrochemical facies with dominant groundwater type alkali earth-alkali-bicarbonates at six sampling stations during POM season.

Durov diagram[34] for groundwater samples revealed that the samples were clustered on the ion exchange phase in the diagram (Fig. 3). The milliequivalent percentages (% meq/L) of major cations and anions are set to total 100 % in the two base triangles of cation and anions. The data plotted on the triangles were projected onto the middle square diagram. The water type based on the concentration of TDS is divided into four categories[33]. TDS < 500 mg/L

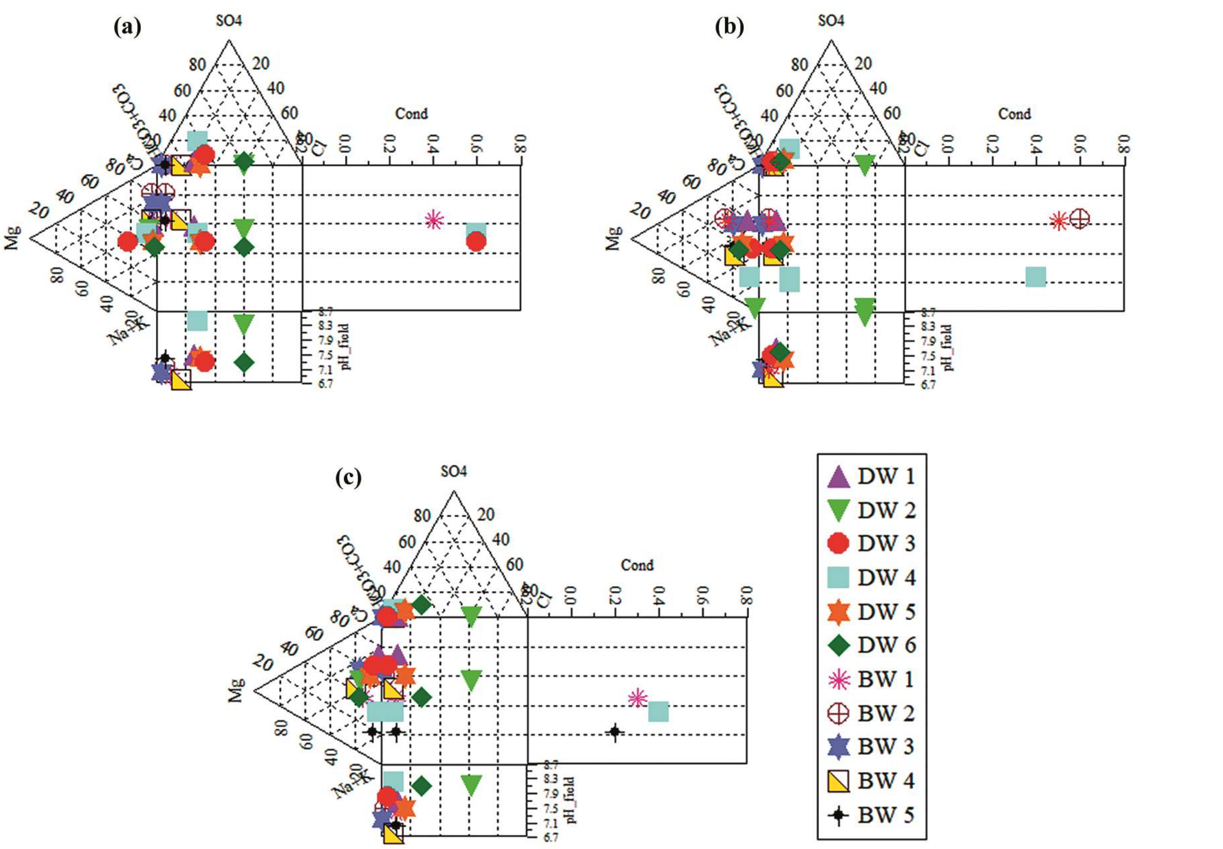

Fig. 3 — Durov diagram for shallow [Dug Wells (DW)] and deep [Bore Wells (BW)] groundwater sources: (a) Pre-monsoon (PRM), (b) Monsoon (MON), and (c) Post-monsoon (POM)

indicate the water is 'suitable for drinking'; TDS between 500 – 1000 mg/L represents 'permissible for drinking'; 1000 – 3000 mg/L is 'suitable for agriculture'; TDS > 3000 mg/L is 'unfit for drinking and irrigation' (Table 5). This allows a judicial judgment on water utility. According to BIS[29], the desired limit of TDS is 500 mg/L for drinking purposes. The most desirable value of the WHO[28] guideline is 500 mg/L. The FAO[31] standard range of TDS value for irrigation practices is 450 – 2000 mg/L. In SG sources, 83 % of the samples has less TDS concentration (< 500 mg/L) in PRM (100 % in DG sources), and is suitable for drinking. During MON, the TDS of 66 % of samples belonged to the drinking category (100 % in DG), and in POM (100 % in DG), 33 % of samples fall within the drinking category (Table 5). The relationship between TDS and TH is depicted in Figure 4. The groundwater is in fresh to moderately hard condition. The Stiff and radial diagrams (Figs. 5 & 6) showed the dominance of major cations and anions in shallow and deep groundwater sources during PRM, MON and POM seasons.

TDS and TH have significant contributions to the groundwater of Arattupuzha. Mg^{2+} and Ca^{2+} were found in comparatively lower concentrations in all the seasons. While, slightly higher concentrations of TH (246.8±154.5 mg/L in PRM) and TDS (947.9±707.0 mg/L in POM) were observed in shallow groundwater sources (dug wells). Classification of groundwater based on TDS, EC, TH, nitrates, and chlorides are

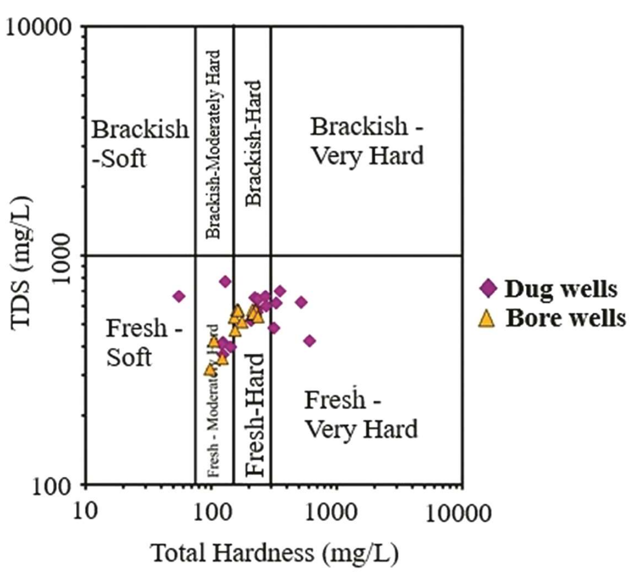

Fig. 4 — Relationship between TDS and TH for the shallow (Dug well) and deep (Bore well) groundwater sources

presented in Table 5. Shallow and deep groundwater sources having NO_3^- concentration < 5 mg/L indicate 'excellent' water quality. Almost 17 % of samples (SG sources) in MON showed nitrates within the range of 5 – 10 mg/L, indicating 'good' water. Chlorides based classification showed 'poor' water quality (Cl^- > 250 mg/L) for almost 17 % of SG sources during PRM and MON seasons.

Suitability of groundwater for drinking purposes

Drinking water should be uncontaminated, free from pollution, and freely accessible to all. Contaminated water should be treated before its direct consumption. To assess the quality of water for drinking purposes, WHO[28] and BIS[29] have laid down certain criteria. Accordingly, the top priority should be given to the highest desirable (or acceptable) limits prescribed for drinking purposes. The maximum permissible (allowable) limits may be extended only if there is no alternative water source is available[35]. In the present study, the groundwater quality of the coastal aquifer (Arattupuzha) is compared with the permissible limit of BIS for India (Table 4).

The present study area, seasonal dominance of TDS in SG sources is in the order of POM (947.9±707.0 mg/L) > MON (764.9±0.8 mg/L) > PRM (324.7±212.3 mg/L) and in DG sources MON (312.4±82.8 mg/L) > POM (285.6±168.4 mg/L) > PRM (185.0±52.7 mg/L). It is known that excess salt enrichment (EC > 1500 µS/cm) affects the tastiness of water making it unsuitable for drinking[3]. In PRM, salinity is mainly influenced by Cl^- (132.5±121.3 mg/L), SO_4^{2-} (12.9±7.8 mg/L) and Ca^{2+} (73.2±42.57 mg/L). Coastal regions are also under threat of anthropogenic activities, frequently occurring high tides, and natural hazards like tsunami and coastal erosion. This affects the quality of available freshwater in the phreatic aquifers. The chemical composition of groundwater is a measure of its suitability as a source of water for human consumption, irrigation, and industrial purposes. The variation in the quality of groundwater depends upon the water-soil-rock interactions as well as on the sources of various pollutants.

Water quality index of Arattupuzha coast

The results of groundwater physicochemical parameters were used to calculate WQI using the weighted arithmetic mean method. WQI was calculated for all the samples individually for all three seasons. The WQI based water type of individual

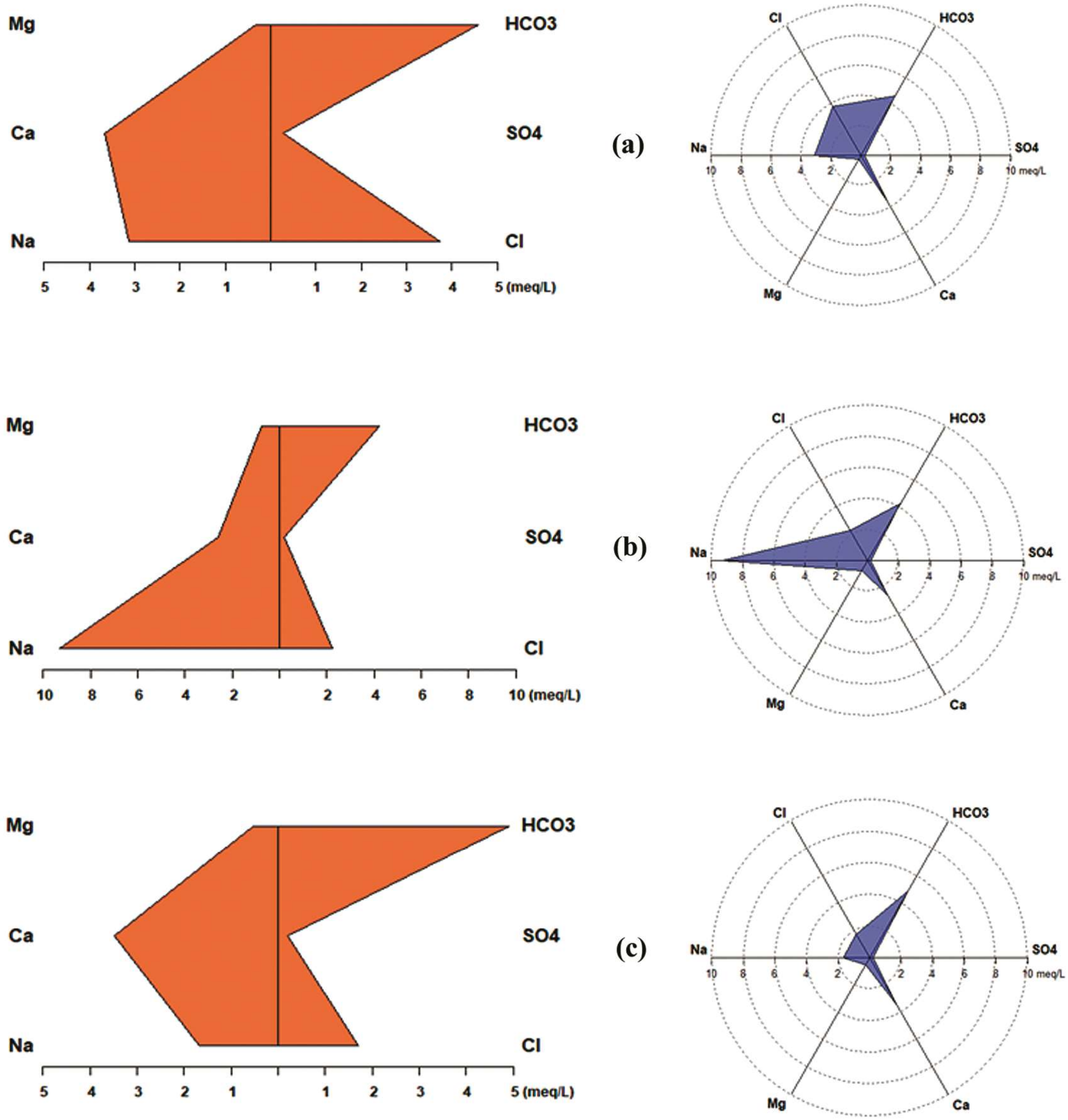

Fig. 5 — Stiff and radial diagrams for major cations and anions in shallow (Dug well) groundwater source: (a) Pre-monsoon (PRM), (b) Monsoon (MON), and (c) Post-monsoon (POM)

stations for PRM, MON, and POM seasons are presented in Table S4. The seasonal variation in WQI of 6 shallow (DWs – Dug Wells) and 5 deep groundwater (BWs – Bore Wells) sources is presented in Figure 7(a). Groundwater exhibited higher WQI values during POM in DWs (DW1 = 355.1, DW2 = 268.2, DW3 = 291.2, DW5 = 162.6, DW6 = 188.8) and BWs (BW1 = 222.9, BW2 = 522.2, BW3 = 423.4, BW4 = 327.4, BW5 = 535.8) (Table S4). During POM season ($\overline{x}\pm\sigma$: 225.2±97.9), WQI ranged from 85.2 (DW4) to 355.1 (DW1). The WQI in DG sources/bore wells in POM season ($\overline{x}\pm\sigma$: 406.4±132.6), varied from 222.9 (BW1) to 535.8 (BW5). During this period, overall water quality of SG revealed 17 % of samples belongs to ‘very poor’ water quality, and 83 % belonged to ‘unfit for drinking purpose’ category. DG

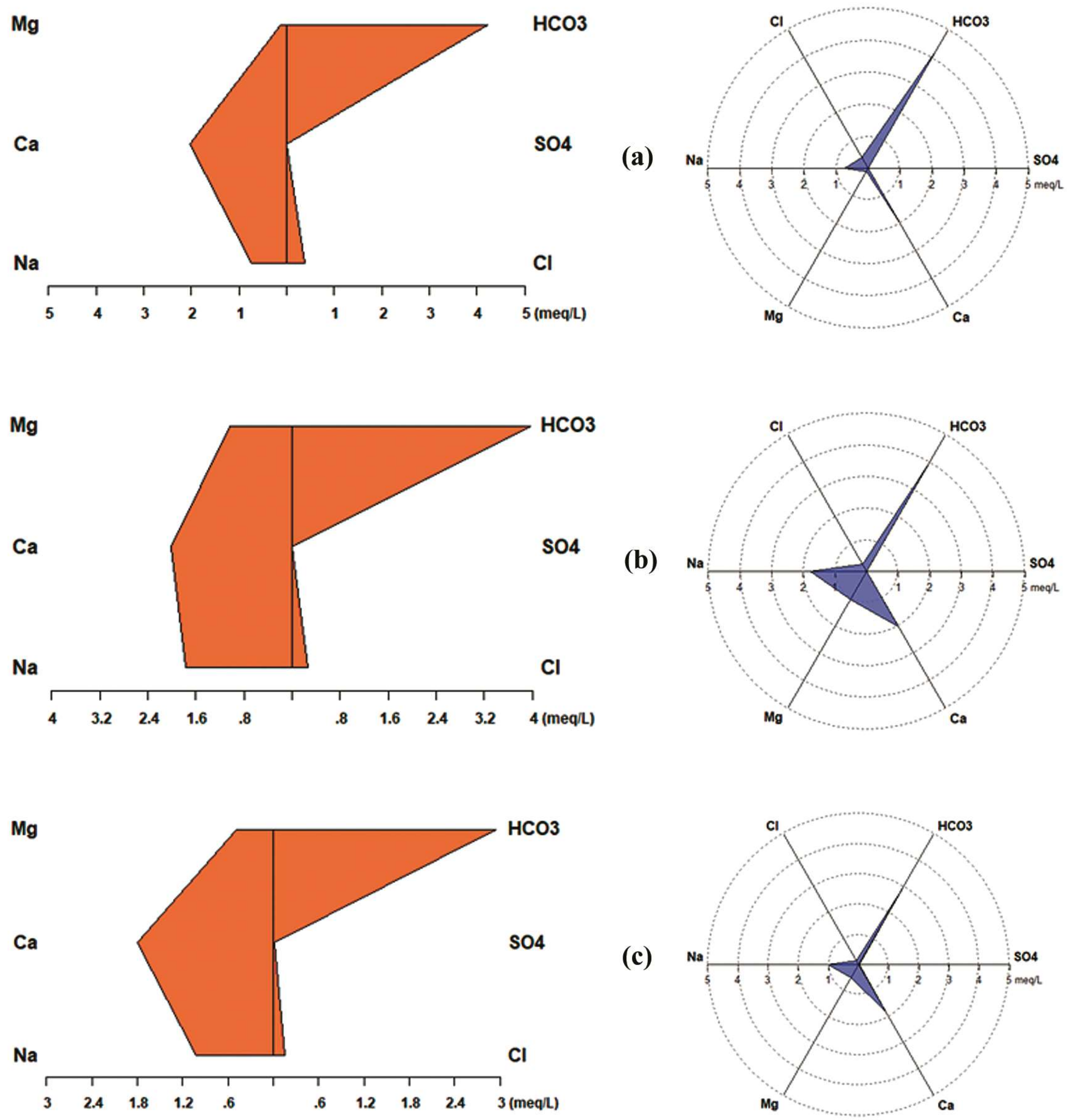

Fig. 6 — Stiff digaram and radial diagram for major cations and anions in deep (Bore well) groundwater sources: (a) Pre-monsoon (PRM), (b) Monsoon (MON), and (c) Post-monsoon (POM)

sources showed 20 % falls in 'poor' quality, and 80 % belongs to 'unfit for drinking purpose' category. The high concentration of total iron (1.5±1.1 mg/L, bore wells, POM) in groundwater contributes to higher weightage leading to the elevated WQI during POM season (Table 4).

The higher WQI observed in monsoon season at station BW1 (WQI = 889.9) is may be due to the ionic contribution from weathering and dissolution of soils[5]. Deep groundwater (Bore well sources) showed higher WQI values ($\bar{x}\pm\sigma$: 413.8±296.7) due to the excess concentration of total iron than the permissible limit of 0.3 mg/L, prescribed by WHO for drinking water. It is worth mentioning that the corrosion and dissolution of iron from the pump set and supply tube plays important in the quality degradation of drinking water[6].

During PRM season, the WQI of Shallow Groundwater (SG) sources ($\bar{x}\pm\sigma$: 74.5±95.5) ranged from 15.1 (DW3) to 255.9 (DW6) and 33 % revealed

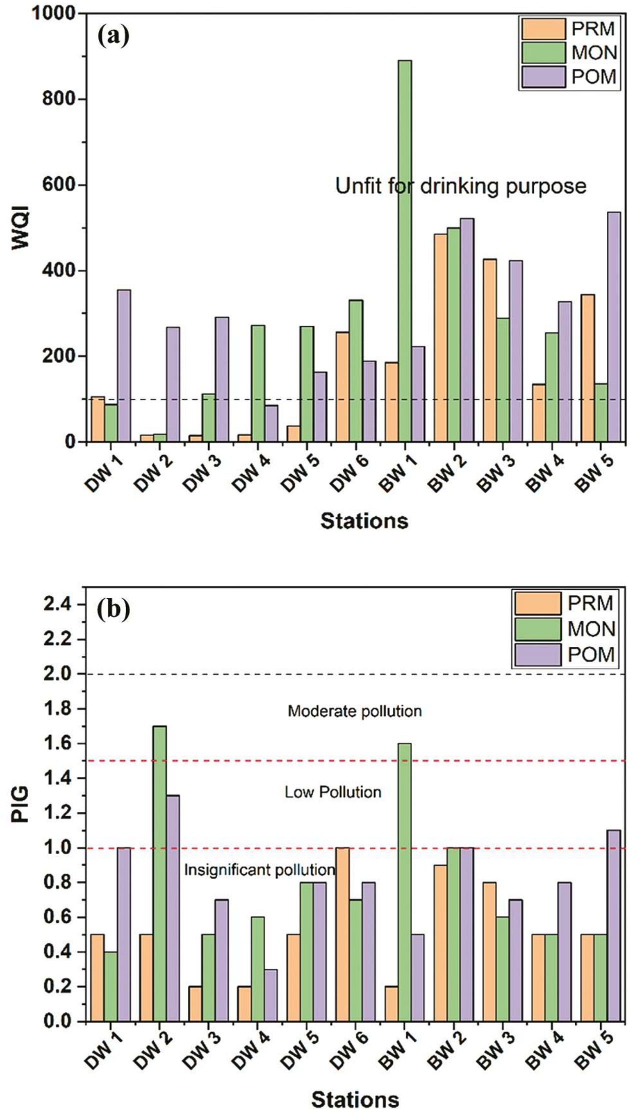

Fig. 7 — Seasonal variation of (a) WQI and (b) PIG in shallow (Dug Wells - DW) and deep (Bore Wells - BW) groundwater sources

'excellent' quality. Deep Groundwater (DG) sources ($\bar{x}\pm\sigma$: 315.1±151.4) showed variations from 134.5 (BW4) to 485.4 (BW2). In SG sources the Fe in PRM observed within the permissible limit (0.3 mg/L) of drinking water standard. Whereas, all DG sources/bore wells (100 %) were observed 'unsuitable for drinking purpose' during PRM and MON seasons because of high iron content (1.0±0.7 mg/L in PRM, and 1.5±1.1 mg/L in MON). In MON season, WQI in SG sources was increased in all the stations ($\bar{x}\pm\sigma$: 181.9±125.3) and varied from 18.5 (DW2) to 330.9 (DW6). The WQI in DG sources/ bore wells ($\bar{x}\pm\sigma$: 413.8±296.7) varied from 135.9 (BW5) to 889.9 (BW1). In this season, overall groundwater quality of SG showed 17 % of samples with 'excellent' water quality; 17 % 'very poor' and 66 % 'unsuitable for drinking purpose'. DG sources revealed 100 % of samples in 'unfit for drinking purpose' category due to elevated total iron concentration observed in MON season[1,5-8].

In MON and POM, (n = 11) a higher percentage (82 %) of samples falls in 'unfit for drinking purposes' category compared to PRM (64 %). This may be explained by higher concentrations of iron (1.5±1.1 mg/L), Ca^{2+} (69.7±40.7 mg/L in dug well sources and 22.6±16.3 mg/L in bore well sources), Mg^{2+} (6.5±5.5 mg/L in dug wells and 6.0±4.5 mg/L in bore wells), and K^+ (21.5±11.7 mg/L in dug wells and 22.6±16.3 mg/L in bore wells) in samples after the rainfall, and subsequent weathering and dissolution in MON and POM seasons.

Pollution Index of Groundwater (PIG)

In the present study, the evaluation of groundwater samples by PIG showed that the majority of the stations belong to an insignificant pollution condition[35]. Water samples in PRM, MON, and POM showed insignificant pollution status (Fig. 7b). Station DW2 is geographically located almost 20 m away from the Arabian Sea in the west. Groundwater was contaminated by salt intrusion and high tides that frequently occurred. Well water in this region is only used for gardening and washing. Salt ingress in aquifers of coastal regions of Kerala is a grave concern. The water type of station 'DW2' showed Na-Cl (saline) during MON due to the increased Na^+ and Cl^- concentration. The results of PIG for shallow and deep groundwater sources are given in Table S5.

Conclusion

The physicochemical parameters of the groundwater were assessed to report the quality of groundwater along a placer mineral-enriched coastal stretch of the Arattupuzha segment (Alappuzha, Kerala, India) as a case of drinking water palatability. Results revealed that in the PRM season, the groundwater quality is safer than in the other seasons. On comparison of results with the regulatory guidelines showed that most of the groundwater doesn't meet the standard guidelines of WHO and BIS for direct consumption unless conventionally disinfected or pre-treated. The total hardness is recorded as more than the acceptable limit (> 600 mg/L). The pH of all the stations is found neutral to alkaline conditions (6.5 – 8.5). Alkalinity was observed within the permissible limit (200 mg/L). The abundance of cations and anions in PRM and POM was in the order of $Ca^{2+} > Mg^{2+} > Na^+ > K^+$ for cations and anions $HCO_3^- > Cl^- > SO_4^{2-} > NO_3^-$. In MON, ionic dominance was $Na^+ > Ca^{2+} > Mg^{2+} > K^+$ due to the ion exchange. Total iron (Fe) was the most significant contaminant present (> 0.3 mg/L) in all seasons. This is one of the prime reasons for the higher WQI for the groundwater. The NO_3^- concentration in groundwater is the outcome of the input from the agrochemical fertilizers applied in the soils.

Shallow groundwater in PRM was in 'good' water quality condition (74.5±95.5) compared to the MON (181.9±125.3), and POM (225.2±97.9). WQI of deep groundwater showed the water is 'unfit for drinking purpose' in all the seasons (PRM: 315.1±151.4, MON: 413.8±296, POM: 406.4±132.6). This indicated that the drinking water resource does not meet the required standards. The majority of the well water sources in Arattupuzha coast exhibited 'poor' water quality (unfit for drinking purposes). The Pollution Index of Groundwater (PIG) showed water with 'insignificant pollution' (PIG < 1). The 'low pollution' status (1.0 < PIG < 1.5) was observed in sampling locations DW1, DW2, BW2 and BW5 during POM season. However, intermittent water quality monitoring, disinfection and treatment are required for the safe use of water. It is recommended that the water used for drinking must be treated conventionally, at least before direct consumption, and for food processing. For manufacturing and commercial purposes, conventional water treatment procedures have to be followed to obtain good-quality water.

Supplementary Data

Supplementary data associated with this article is available in the electronic form at https://nopr.niscpr.res.in/jinfo/ijms/IJMS_52(10)463-476_SupplData.pdf

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Conflict of Interest

The authors declare that there is no known competing or conflict of interest.

Ethical Statement

All authors agreed to the ethical principles.

Author Contributions

BK: Formal analysis, investigation, data analysis, and writing-original draft; VSA: Supervision, conceptualisation, methodology, writing-original draft, and writing-review & editing; and MM: Writing, review & editing.

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