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ORIGINAL ARTICLE

Evaluation of sea water ingress into an Indian atoll

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Abstract Groundwater is the prime source of fresh water in most part of world. The groundwater floats in the form of thin lens which is vulnerable to various stresses such as tide, cyclone, draught, abstraction, etc. The problem of getting this meager resource of fresh groundwater sustained for longer time, becomes more difficult task on tiny atoll with large population depending on it. In order to develop sustainable management scheme and identify vulnerable part of aquifer, systematic assessment of groundwater quality on such island have become imperative. Detailed hydrochemical study has been carried out to identify potential fresh groundwater resources on Andrott Island, UT of Lakshadweep, India. The analysis has given an early signal of deterioration in groundwater quality in some parts of the island during non-monsoon period, whereas the quality becomes slightly better during monsoon period. The study suggests immediate measures for arresting the deterioration in groundwater quality as well as augmentation for restoration of aquifer in some parts of the island.

Keywords Atoll · Groundwater · Aquifer vulnerability · Hydrochemistry · Seawater ingress

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Introduction

The overall development such as industrial, agricultural as well as increasing population has lead to increase in demand for potable water. In the recent years, to meet the increasing demand there has been indiscriminate exploitation of groundwater resources particularly in the areas where the surface water potential is negligible. There are several tiny atolls off western coast of India (Mallik 2001), where the population density is very high. Groundwater is the only source of fresh water on these atolls. It is in the form of thin fragile floating lens, which is often vulnerable to overexploitation, tidal waves, tsunami and cyclones, causing seawater ingress (Chandramohan et al. 1993; Singh and Gupta 1999a). There is continuous pumping of groundwater to meet various needs on these islands, which has lead to deterioration in groundwater quality. The new technology such as solar pump has added further pumpage of groundwater beyond the actual need. As a consequence of indiscriminate exploitation, the quality in some of these islands has already started deteriorating. In order to develop sustainable scheme for groundwater management, it has become essential to assess the groundwater quality on the island. Keeping this in mind, such study was carried out in one of the Lakshadweep islands, i.e., Andrott Island.

About the study area

Lakshadweep is an archipelago of coral islands in the Arabian Sea, off the western coast of India. In the range of 220–400 km off the western coast of India, there are about 36 islands, 12 atolls, 3 reefs and 5 submerged coral banks, spread over an area of 32 km^2 in the Arabian Sea (Chandramohan et al. 1993). Tens of these islands are habited. The eastern most habited island is Andrott Island, where more than 10,000 (10,720 as per 2001 census, population density as 2,233 km^{-2}) people live on the island (Fig. 1). This island is nearest to the main land. The areal extent of the island is about 4.9 km^2. Most of the islanders use groundwater for their various needs. There is no surface water storage on the island and there has been growing demand for potable water in the recent years, which has lead to increase in exploitation of groundwater. The overexploitation of groundwater on island has lead to decrease in fresh water potential as well as deterioration in groundwater quality due to seawater ingress.

Hydrogeology

Earlier workers have described geology, geomorphology and hydrogeology of the island (Nazeeb 1995; Wagle and Kunte 1993; Singh and Gupta 1999b; Mallik 2001; Revichanndran et al. 2001). The group of atolls lies on the prominent N–S Lakshadweep ridge. It is speculated that islands are buried continuation of Aravalli Mountain chain (northwest of Indian continent) and the Deccan Traps have been faulted down along the western coast of India. The ridge rises from the deep sea and is composed of basalt, which is capped by recent coral reef in the form of atoll and coral banks. Andrott Island is occupied by coral sand. The topography of the island is undulating and the ground surface is about few meters to 8.0 m above mean sea level (amsl). The island is of elliptical shape with major

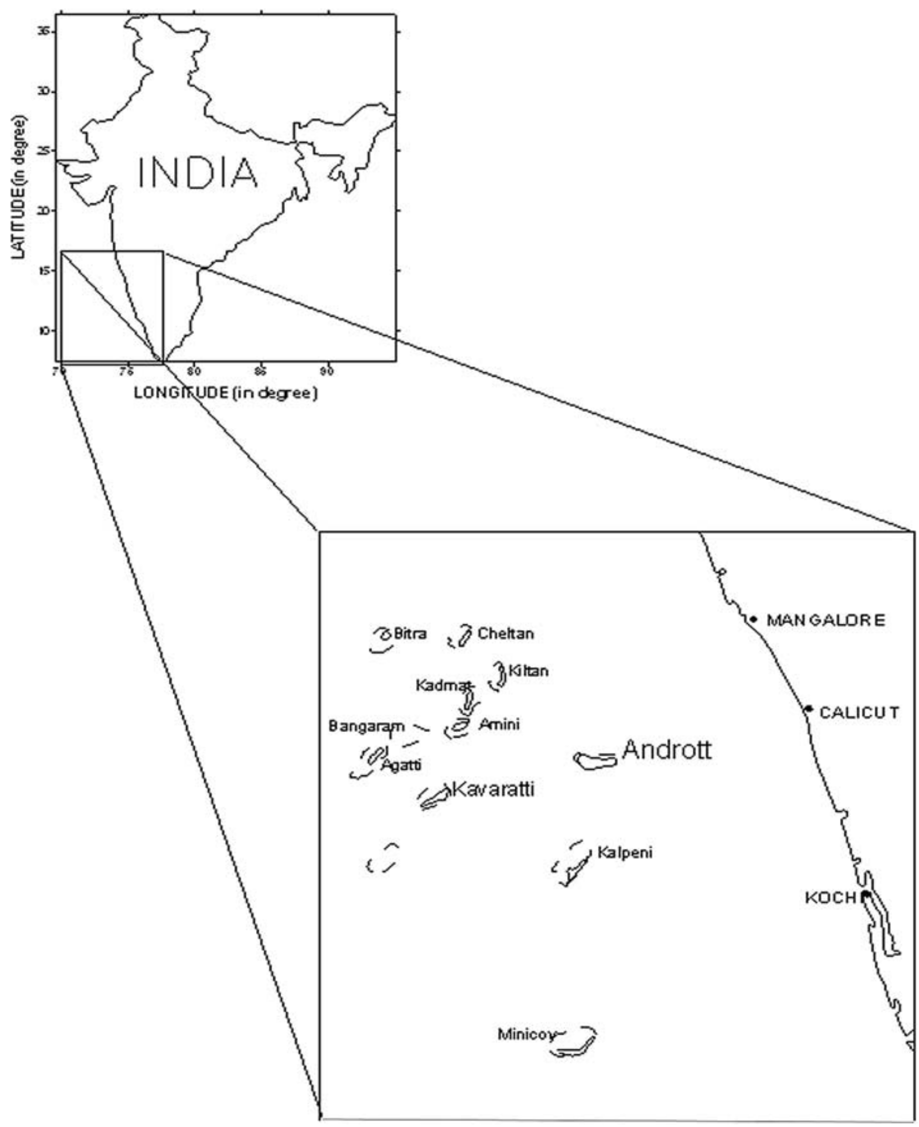

Fig. 1 Location map of the study area

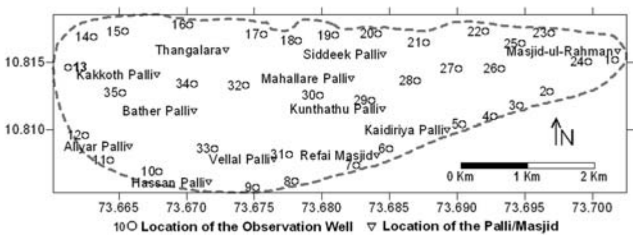

Fig. 2 Location of the observation wells at Andrott Island

axis in E–W direction, whereas all other islands have N–S. The island does not have any lagoon around it and is enveloped with sparkling white carbonate sand beach. There is no surface water storage on the island. The island is covered with coral sands and at some places shell limestone. Most of the rain occurs during the month of June to September (monsoon season). The average annual rainfall for the period of 2000–2005, on the island, is about 1,817 mm.

Due to high permeable coral sand on the surface, most of the rain percolate down and finally goes as subsurface runoff to sea. There are no signatures of drainage on the topography. Major vegetation on the island is coconut with about more than 100,000 trees.

The groundwater occurs in the coral sand underlined by shell limestone, in the form of floating lens. The groundwater is being exploited for various needs of islanders through hand-dug shallow wells. The recent development has brought many of these wells equipped with solar pumps, which in turn has increased the exploitation of groundwater. The diameter of the wells varies from less than a meter to about 2.0 m. The depth of the wells varies from less than a meter to about 7.0 m below ground surface. Groundwater is

Table 1 Major cations and anions for pre-monsoon season, Andrott Island, Lakshadweep

S. no.	pH	EC	TDS	TH	Ca	Mg	Na	K	HCO_3	Cl	SO_4	NO_3
1	6.60	1,745	1,134	530	68	87	170	4.1	477	319	46	9.8
2	7.27	3,550	2,308	731	76	131	452	15.6	482	865	96	17.0
3	7.24	2,040	1,326	641	46	128	180	6.1	464	411	62	9.4
4	7.10	1,356	881	400	82	47	121	4.1	305	206	38	99.0
5	6.90	925	601	350	76	39	55	5.4	390	96	18	0.88
6	7.15	807	525	290	78	23	49	2.7	409	32	14	0.9
7	6.76	960	624	410	74	55	36	7.0	445	60	23	0.84
8	6.98	1,217	791	420	126	26	94	6.7	439	156	41	7.3
9	6.92	1,581	1,028	455	56	77	151	2.8	470	238	53	6.6
10	6.81	1,357	882	530	104	66	90	2.6	458	138	48	122.0
11	7.13	2,350	1,528	751	20	170	190	2.6	708	340	96	2.8
12	7.02	1,455	946	410	70	57	148	1.6	348	252	86	0.7
13	7.25	1,480	962	420	146	13	134	0.8	354	255	48	0.4
14	7.00	1,500	975	370	118	18	160	25.9	403	181	72	100.0
15	6.93	1,150	748	450	110	43	60	9.4	476	99	48	14.0
16	7.00	1,615	1,050	450	92	53	156	9.2	519	209	72	2.0
17	6.86	975	634	375	110	24	49	5.3	360	89	38	24.0
18	6.97	1,140	741	455	104	47	53	3.3	494	85	38	0.0
19	6.85	1,415	920	490	124	44	100	7.4	458	138	72	86.0
20	6.89	1,355	881	295	56	38	158	12.0	433	142	62	34.0
21	7.06	1,390	904	485	42	92	104	4.9	488	181	48	1.7
22	7.04	1,300	845	440	86	55	94	19.6	488	145	46	6.8
23	7.08	1,620	1,053	370	54	57	202	6.4	433	287	41	0.6
24	6.90	1,540	1,001	460	30	94	126	3.3	482	213	36	0.07
25	6.92	1,430	930	405	26	83	141	5.1	494	181	48	0.9
26	6.95	1,504	978	290	72	27	210	2.0	592	160	29	0.13
27	7.24	1,234	802	410	28	83	78	7.2	494	92	43	0.15
28	6.86	1,080	702	355	108	21	68	6.4	409	92	36	0.15
29	6.84	827	538	360	64	49	40	5.0	421	57	24	0.45
30	6.98	1,130	735	405	114	29	62	0.8	427	99	43	0.08
31	6.85	1,220	793	335	84	30	121	4.5	506	89	48	0.27
32	6.95	598	389	250	68	19	16	1.7	268	28	24	0.1
33	6.79	1,452	944	340	126	6	181	0.8	677	110	26	0.11
34	7.00	953	619	310	114	6	60	0.1	384	60	34	0.05
35	7.11	873	567	435	76	60	20	2.2	476	43	31	0.1
Min	6.60	598	389	250	20	6	16	0.1	268	28	14	0.00
Max	7.27	3,550	2,307.5	751	146	170	452	25.9	708	865	96	122
Avg	6.98	1,374.97	893.73	424.94	80.80	54.21	117.97	5.85	455.17	175.66	46.51	15.69

All concentrations are in mg/l, EC in μS/cm, *TH* total hardness as $CaCO_3$, pH at 25°C

Table 2 Major cations and anions for post-monsoon season, Andrott Island, Lakshadweep

S. no.	pH	EC	TDS	TH	Ca	Mg	Na	K	HCO_3	Cl	SO_4	NO_3
1	6.80	938	563	440	112	38	68	3	561	190	32	0.90
2	6.94	1,408	845	460	58	76	82	4	683	349	37	1.60
3	6.84	987	592	420	50	71	70	3	488	210	46	0.85
4	6.85	674	404	384	90	38	55	2	449	96	27	1.10
5	6.78	722	433	360	53	55	50	2	464	111	27	0.93
6	7.04	686	412	228	66	15	48	2	512	85	22	0.40
7	6.81	682	409	428	37	81	61	2	517	71	25	0.60
8	6.77	825	495	360	40	62	32	1	508	113	26	0.93
9	6.95	1,053	632	512	118	52	38	1	556	204	33	0.85
10	6.84	882	529	564	77	89	52	2	605	119	30	0.45
11	6.97	1,515	909	692	64	128	44	2	752	338	31	0.46
12	7.00	1,118	671	492	96	60	60	2	542	252	51	1.10
13	6.70	705	423	372	46	61	68	3	347	113	33	13.8
14	6.94	1,228	737	568	80	88	70	4	576	216	48	20.6
15	6.85	859	515	504	54	88	66	2	600	111	31	Nil
16	6.68	1,092	655	500	43	94	54	2	620	193	32	1.40
17	6.72	581	349	392	98	36	38	1	517	54	23	6.00
18	6.82	823	494	468	102	51	61	2	454	113	26	Nil
19	6.85	1,213	728	524	115	57	60	3	625	261	30	16.80
20	7.03	906	543	556	138	51	22	Nil	474	105	27	Nil
21	6.85	996	598	452	59	73	40	1	395	184	37	16.0
22	6.78	862	517	404	54	64	29	1	405	159	25	6.90
23	6.86	1,182	709	480	40	91	52	2	410	309	41	1.90
24	6.78	582	349	416	46	72	60	2	434	48	26	0.40
25	6.96	932	559	464	104	49	34	1	547	133	34	4.60
26	6.91	744	446	472	128	36	59	3	537	77	18	Nil
27	6.85	794	476	412	59	63	70	3	542	88	27	Nil
28	7.01	778	467	408	93	42	44	1	547	88	27	0.39
29	6.68	491	295	304	62	36	32	1	376	45	21	Nil
30	6.73	718	421	244	78	12	40	2	508	91	29	0.40
31	6.81	865	519	400	67	56	32	1	625	68	33	0.53
32	6.68	457	274	300	37	50	28	1	332	40	21	0.33
33	6.79	858	515	312	154	40	67	4	664	85	24	0.60
34	6.84	651	391	400	106	33	52	4	469	57	25	0.40
35	6.97	696	417	428	82	54	60	2	542	62	28	0.39
Min	6.68	457	274	228	37	12	22	1	332	40	18	0.33
Max	7.04	1,515	909	692	154	128	82	4	752	349	51	20.6
Avg	6.85	871.51	522.6	432	77.30	58.94	51.37	2.11	519.40	138.21	29.95	3.50

All concentrations are in mg/l, EC in μS/cm, *TH* total hardness as $CaCO_3$, pH at 25°C

mainly used for domestic purposes, as hardly there is any industry or agriculture. Groundwater regime on the island floats on the seawater and tidal response to water table has been clearly noticed.

Hydrochemical studies

In order to assess groundwater quality, water samples have been collected from the existing open wells during pre-monsoon and post-monsoon seasons on the island. Total 35 samples were collected in each season and the locations of these wells are shown in Fig. 2. The analysis of water samples were carried out to assess major cation and anion such as calcium (Ca), magnesium (Mg), sodium (Na), potassium (K), bicarbonates (HCO_3), chloride (Cl), sulphate (SO_4), nitrate (NO_3) including total hardness (TH), pH and electrical conductivity (EC). The results of chemical analysis are given in Tables 1 and 2. All the concentrations are expressed in milligrams per liter, except pH. EC is measured in micro-siemens per centimeter. The chemical analysis data have been interpreted using various plots such as Piper's trilinear, Gibbs and Wilcox diagrams, to assess the groundwater quality on the island. Further, principle component analysis (PCA) technique is also used to compare the similarities and dissimilarities of the ions simultaneously for pre- and post-monsoon samples.

Results and discussion

Comparison of some selected parameters of pre- and post-monsoon is shown in Fig. 3. It shows that EC and content of Cl are higher in pre-monsoon samples, whereas the content of Ca and HCO_3 are higher in post-monsoon samples. The higher content of Cl is indication of mixing of seawater during non-monsoon period, whereas the higher content of Ca may be due to dissolution of Ca from soil (coral) during infiltration process that takes place during monsoon.

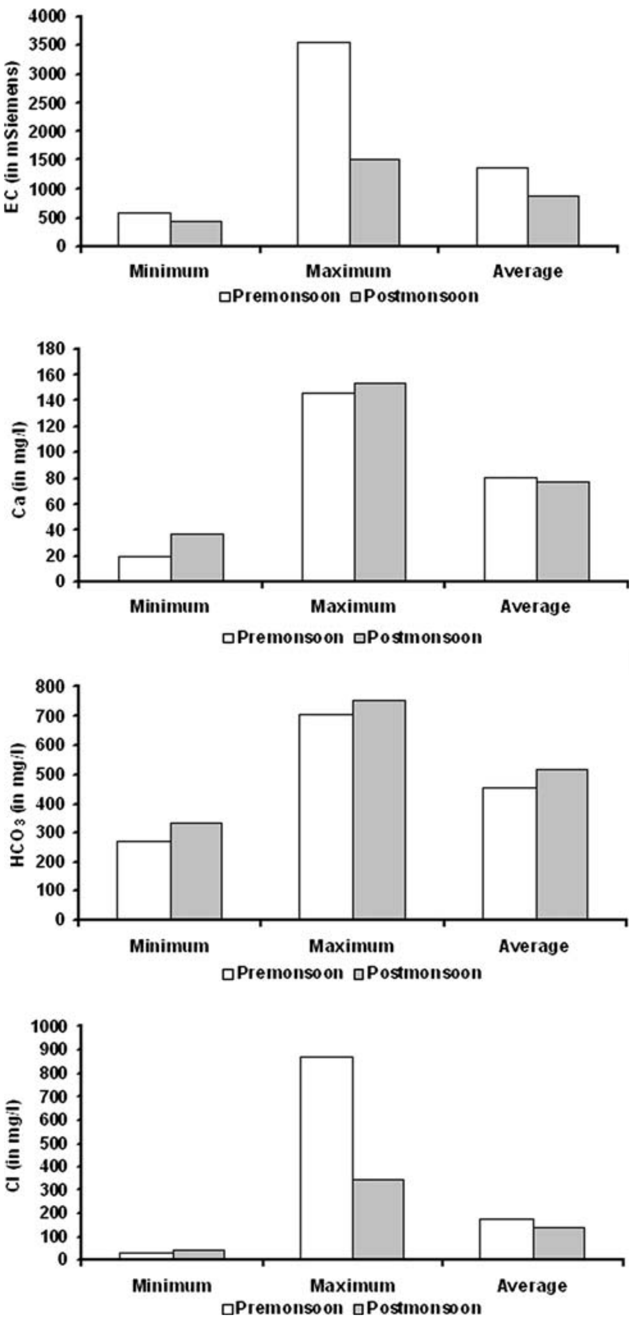

Fig. 3 Comparison of selected parameters during pre- and post-monsoon

To demarcate the zones of high EC and Cl content areally, these values are plotted and shown in Figs. 4 and 5 for pre- and post-monsoon periods, respectively. During the pre-monsoon period, higher content of Cl and EC is observed at the eastern side of the island and at the peripheral parts of the western side. But during the post-monsoon period, Cl content exceeds the permissible limit of drinking water quality standard [250 ppm, ISI (1983)] only at few locations in the eastern and western parts, whereas EC is within the permissible limit of drinking water standard [1,500 ppm, ISI (1983)]. As indicated in Fig. 4, the eastern part of the island is affected due to seawater ingress during non-monsoon period and it has reduced during post-monsoon period due to recharge, however, the effect remains visible in eastern as well as western part as shown by high Cl content in Fig. 5.

In order to understand the role of various cation and anion in the groundwater chemistry during pre- and post-monsoon period, the data were plotted in the trilinear diagram (Piper 1944) as shown in Fig. 6. Majority of pre-monsoon samples have shown dominance of Na and HCO_3 whereas during the post-monsoon Ca and HCO_3 dominance are seen amongst cations and anions, respectively. This dominance of Na may be due to seawater mixing during pre-monsoon period. The dominance of bicarbonate as observed during both pre- and post-monsoon may be only due to interaction with coral formation. In the central diamond shaped field, majority of the pre-monsoon samples fall in ''no cation or anions exceeds 50%'' area, whereas all the post-monsoon samples fall in ''carbonate hardness exceeds

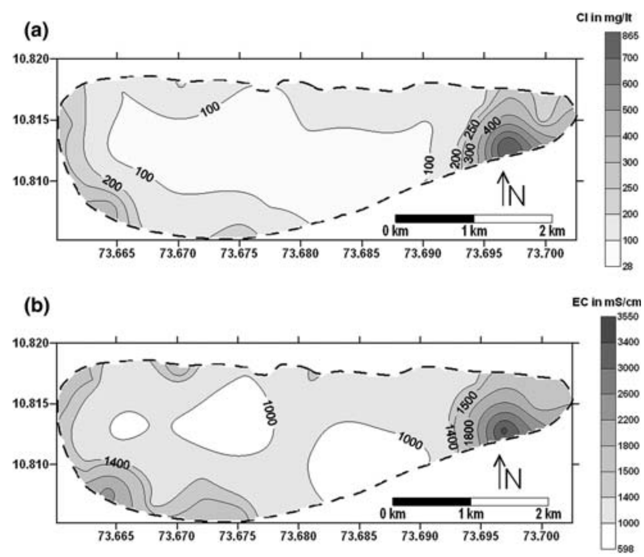

Fig. 4 Areal distribution of **a** chloride and **b** electrical conductivity during pre-monsoon

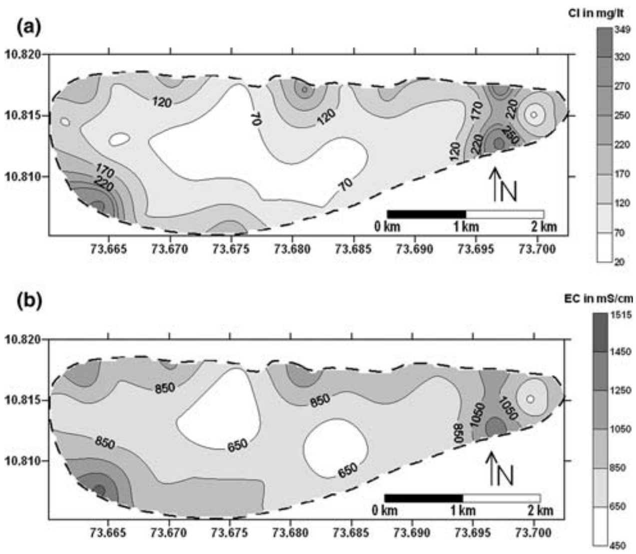

Fig. 5 Areal distribution of **a** chloride and **b** electrical conductivity during post-monsoon

50%'' area, indicating that the chemical properties are dominated by alkaline earth (Ca, Mg) or corals and week acids ($HCO_3 + CO_3$).

In order to visualize the sodium hazard among the water samples of the study area, the data has been plotted in the form of Richard's diagram (Richards 1954) as shown in Fig. 7. In this diagram sodium absorption ratio (SAR) is plotted against EC. The diagram classifies the water into two divisions: (a) conductivity classification, (b) sodium hazard classification. Both conductivity and sodium hazard are classified as low, medium, high and very high, they are represented by C1, C2, C3, C4 and S1, S2, S3, S4, respectively (Todd 1980). Majority of the pre-monsoon samples fall in very high to high sodium hazard and high salinity hazard zones indicating non-suitability of groundwater for agricultural purposes. The post-monsoon samples fall in the range of medium to low sodium hazard and high to medium salinity hazard zone indicating limited use for agricultural purposes. The number of samples of pre- and post-monsoon falling in different zones are given below:

Area	Character	No. of samples
S_4C_4	Very high SAR, very high conductivity	Pre-monsoon (1)
S_4C_3	Very high SAR, high conductivity	Pre-monsoon (12)
S_3C_3	High SAR, high conductivity	Pre-monsoon (7)
S_2C_3	Medium SAR, high conductivity	Pre-monsoon (10), post-monsoon (11)
S_1C_3	Low SAR, high conductivity	Pre-monsoon (3), post-monsoon (10)
S_2C_2	Medium SAR, medium conductivity	Post-monsoon (8)
S_1C_2	Low SAR, medium conductivity	Pre-monsoon (1), post-monsoon (6)

Various factors controlling groundwater chemistry are analyzed by the diagram (Gibbs 1970) shown in Fig. 8. The groundwater samples are scattered between the rock and evaporation dominance fields. Pre-monsoon samples are showing more of evaporation

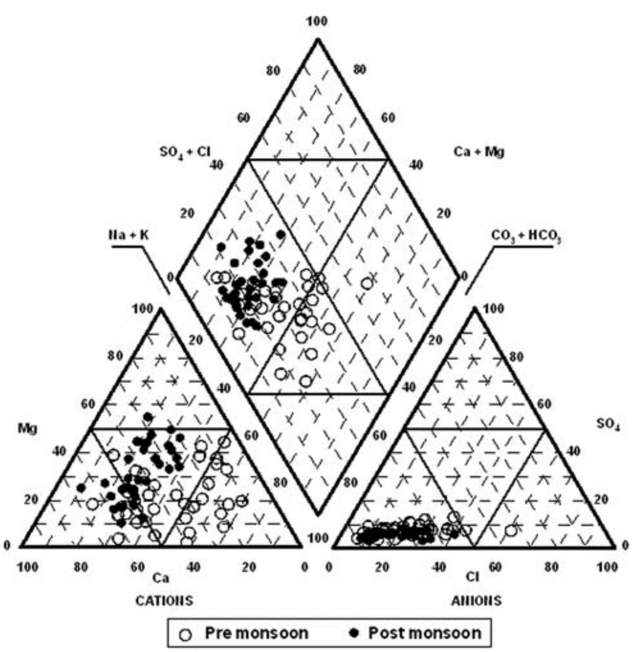

Fig. 6 Piper's trilinear diagram

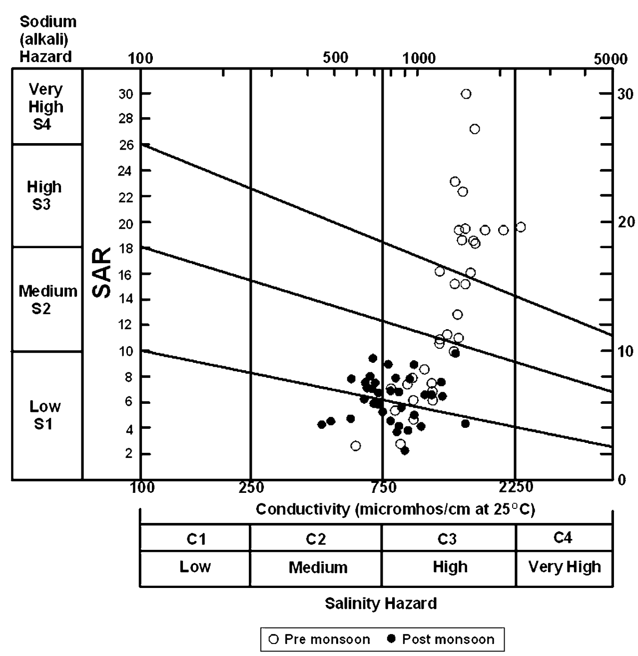

Fig. 7 Richard's diagram

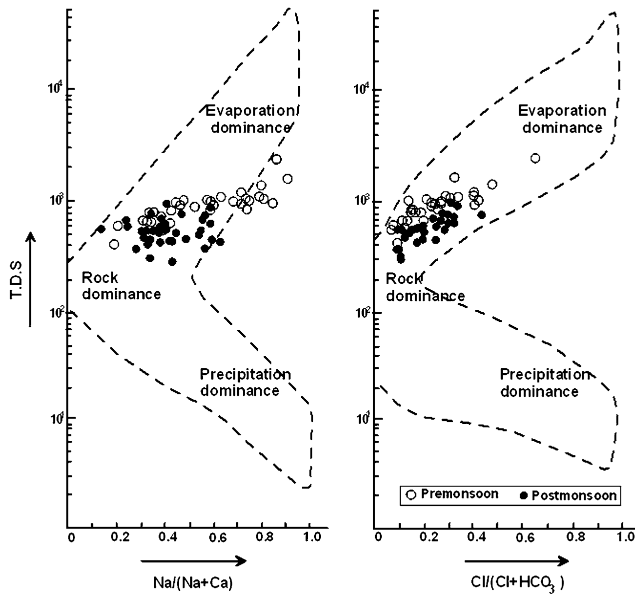

Fig. 8 Gibb's diagram

dominance whereas the post-monsoon samples are showing rock dominance. The host lithological units are mainly controlling the groundwater chemistry of post-monsoon and the evaporation, pre-monsoon samples.

Principle component analysis

Principle component analysis (PCA) is a popular multivariate technique, which identifies the most important components contributing to the data structure and the interrelationships in large number of variables. In other words, PCA is a simple mathematical reduction of the data without any elaborate assumptions (Anderson 1958; Morrison 1964), which enables us to describe the information with considerably fewer variables than was originally present.

In the present investigation, the pre- and post-monsoon hydrochemical data are subjected for PCA using standard statistical packages on computer. The variables considered are TDS, TH, Ca, Mg, Na, K, HCO_3, Cl, SO_4, and NO_3. Correlation matrices have been calculated to know the inter relationship between the variables and are presented in Tables 3 and 4. Some selected cross plots are shown in the Fig. 9. Cross plot of sodium with EC shows the correlation 0.88 during pre-monsoon, whereas during post-monsoon it is found 0.39. Similarly, the correlation between the chloride and EC is found 0.92 and 0.39 during pre- and post-monsoon, respectively. Na and Cl are showing strong correlation with EC during the pre-monsoon,

Table 3 Correlation matrix of pre-monsoon hydrochemical data

	TDS	TH	Ca	Mg	Na	K	HCO_3	Cl	SO_4	NO_3
TDS	1.000	0.782	–0.231	0.689	0.937	0.291	0.412	0.959	0.754	0.082
TH	–	1.000	–0.251	0.859	0.528	0.138	0.413	0.736	0.679	0.117
Ca	–	–	1.000	–0.711	–0.183	0.065	–0.240	–0.219	–0.121	0.282
Mg	–	–	–	1.000	0.478	0.067	0.428	0.649	0.555	–0.063
Na	–	–	–	–	1.000	0.302	0.362	0.909	0.642	0.059
K	–	–	–	–	–	1.000	–0.019	0.273	0.381	0.340
HCO_3	–	–	–	–	–	–	1.000	0.182	0.238	–0.214
Cl	–	–	–	–	–	–	–	1.000	0.682	0.042
SO_4	–	–	–	–	–	–	–	–	1.000	0.246
NO_3	–	–	–	–	–	–	–	–	–	1.000

Table 4 Correlation matrix of post-monsoon hydrochemical data

	TDS	TH	Ca	Mg	Na	K	HCO_3	Cl	SO_4	NO_3
TDS	1.000	0.719	0.063	0.628	0.278	0.270	0.625	0.939	0.657	0.289
TH	–	1.000	0.157	0.734	0.154	0.049	0.481	0.598	0.427	0.209
Ca	–	–	1.000	–0.460	–0.010	0.138	0.302	–0.071	–0.128	–0.014
Mg	–	–	–	1.000	0.225	0.072	0.329	0.577	0.446	0.176
Na	–	–	–	–	1.000	0.846	0.313	0.295	0.342	0.118
K	–	–	–	–	–	1.000	0.327	0.263	0.228	0.194
HCO_3	–	–	–	–	–	–	1.000	0.418	0.183	–0.104
Cl	–	–	–	–	–	–	–	1.000	0.679	0.283
SO_4	–	–	–	–	–	–	–	–	1.000	0.369
NO_3	–	–	–	–	–	–	–	–	–	1.000

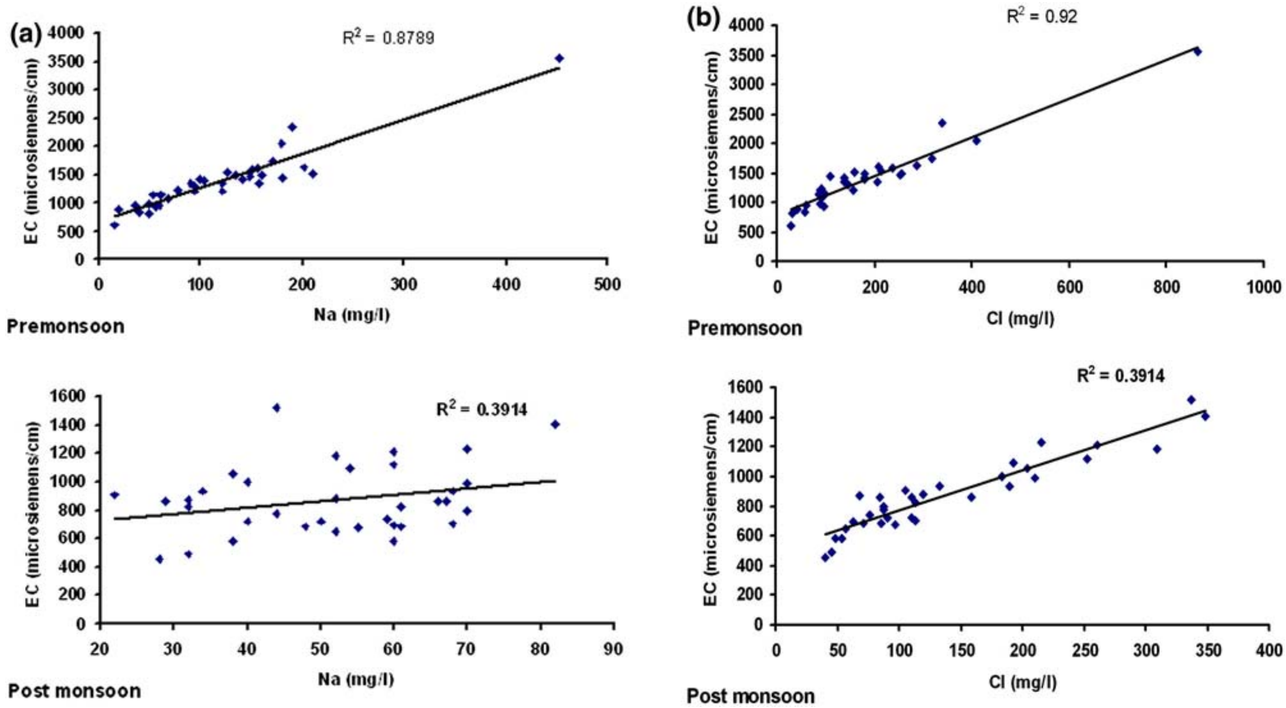

Fig. 9 Cross-plots of EC with (**a**) sodium (b) chloride during pre- and post-monsoon

whereas weak correlation during the post-monsoon season.

As explained above, the eigen values are helpful in deciding the number of components required to explain the data variation. In the present case, the cumulative percent of trace of first three eigen values account for 77.50 and 74.20% of the total variance for pre- and post-monsoon data, respectively. Hence, these first three component scores are used to explain the background hydrochemical processes without losing much of the significant characteristics. The component scores are cross-plotted, i.e., I versus II, I versus III and II versus III as shown in Fig. 10. Among the principle components of pre-monsoon, component I is negative for Ca, component II is negative for TH, Mg and HCO_3, whereas component III is negative for TDS, Ca, Na, HCO_3 and Cl. Cross plots of component I versus III, component II versus III and component I versus II separates out sample nos. 2, 3, 4, 10, 11, 13, 14, 19, 26, 27 and 33 which have TDS of range 790–2,272, Na of range 78–452 and Cl of range 92–865 mg/l. the rest of samples are having TDS of range 383–1,117, Na 16–202 and Cl 28–319 mg/l. Most of the samples separated out from the cluster are located nearer to the coast.

Of the principle components of post-monsoon, component II is negative for TDS, TH, Mg, Cl, SO_4 and NO_3, whereas component III is negative for Mg, Na, K, SO_4 and HCO_3. Cross plots of component I versus III, component II versus III and component I versus II separates out samples no. 2, 3, 9, 11, 13, 14, 26, 32 and 33, which have TDS of range 274–909, Na of range 28–82 and Cl of range 40–349 mg/l. the rest of samples are having TDS of range 295–728, Na 22–70 and Cl 45–309 mg/l. Most of the samples separated out from the cluster are located nearer to the coast.

Conclusions

- The various plots for chemical analysis data clearly suggest seawater ingress during non-monsoon period in the western as well as eastern part of the Andrott Island.
- Groundwater is also affected due to dissolution of calcium from the coral soil and aquifer formation in the island.
- The western and eastern parts of the island where groundwater quality begins to deteriorate during the non-monsoon period, the aquifer system becomes more vulnaerable to seawater ingress.

It is suggested to minimize the groundwater abstraction in these zones and implement rainwater harvasting measures to augment groundwater resources.

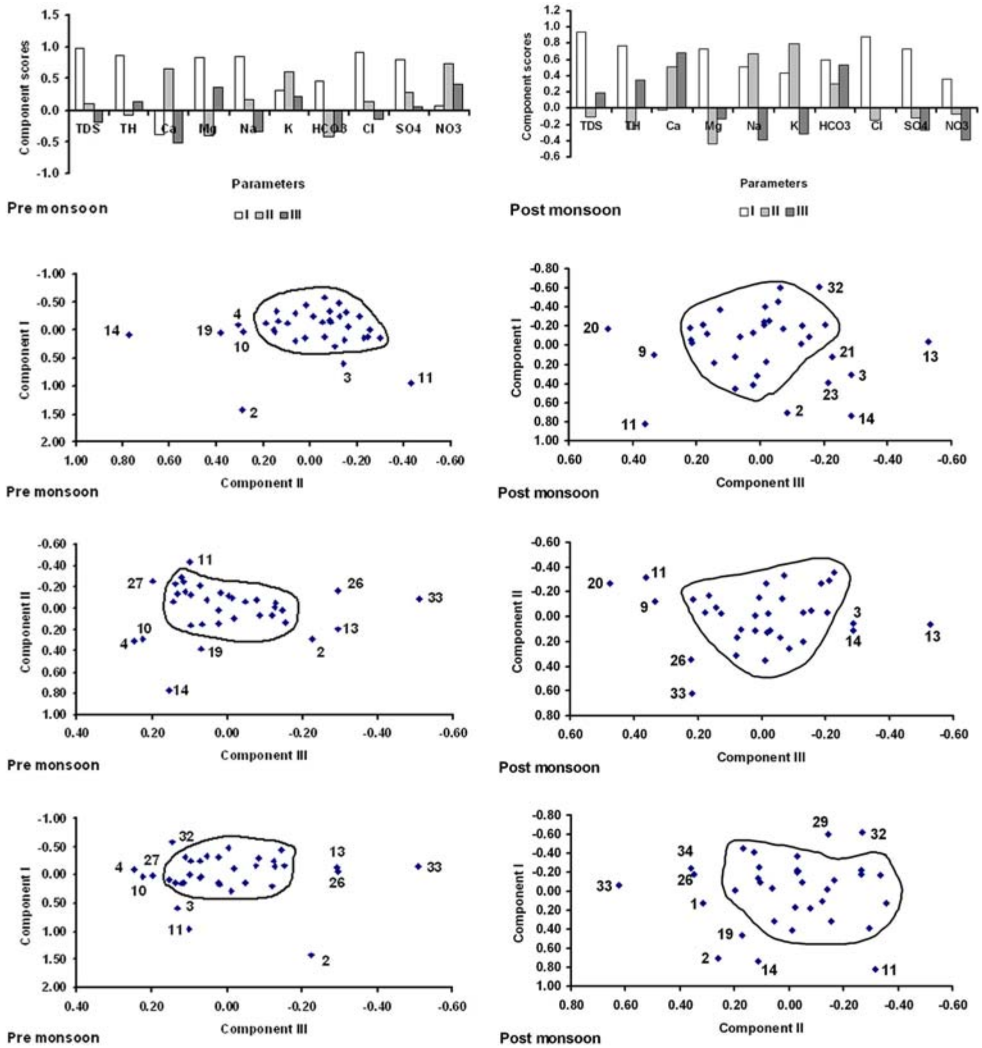

Fig. 10 Principle component cross plots of pre- and post-monsoon

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