A study on the seasonal dynamics of groundwater quality along the coastal belt of Visakhapatnam city

Budha Ravi Prasad, Kakarla Jagadeeswara Rao, Namuduri Srinivas and Kolli Suresh Kumar*
Department of Life Sciences-Environmental Science, GITAM (Deemed to be University), Visakhapatnam – 530045, Andhra Pradesh, INDIA
*skolli@gitam.edu

Abstract
Seasonal changes in groundwater quality bordering Visakhapatnam's coastal stretch in Andhra Pradesh, India have been studied. In line with drinking water specifications as per IS 10500 : 2012, samples of groundwater were collected from 15 identified locations before and after the monsoon seasons and tested for important chemical and physical parameters. To understand the differences in time and location, statistical measures such as minimum (Min), maximum (Max), mean (Avg), standard deviation (SD) and coefficient of variation (CV) were developed. To examine the water's potable condition and possibility for corrosive activity, indices like the Langelier Saturation Index (LSI), the Revelle Index (RI) 1941 and the Water Quality Index (WQI), as prescribed by Brown et al[8], were derived. The findings reveal that seasonal variations are considerably influenced by recharge due to monsoon, with samples collected after monsoon usually exhibiting better water quality.

Some sites, on the other hand, exceeded the maximum allowable levels for specific characteristics, stressing the need for continuous management and supervision. These results are in line with previous studies that demonstrate the significant influence of changes across seasons on the groundwater quality along the coast[19,53].

Keywords: Groundwater quality, Langelier saturation index, Revelle index and Water quality index.

Introduction

All over the world, groundwater ensures a reliable provision of freshwater that is required for residential, commercial and cultivation-related uses, especially in areas with limited availability or poor quality surface water. Urban residents rely on coastal aquifers, however these aquifers are in severe risk due to their individual hydrogeological characteristics and sensitivity to multiple forces. Due to aspects such as excessive utilization, changing climate and changes in land management caused by man-made activities, groundwater preservation has become a vital issue in these areas.

As urban development increases in many coastal stretches, protecting groundwater quality has now become a crucial issue that requires a thorough, site-specific examination of both natural and human influences. Furthermore, groundwater is a main provider of safe potable water, particularly in coastal regions where surface water is either contaminated or inadequate. Industrial activities, surface water runoff from urban areas and saltwater intrusion are the major causes of groundwater pollution in Visakhapatnam, a city along the coast in Andhra Pradesh, India, which is swiftly becoming more urbanized[50]. The distinctive hydrogeological features of coastal areas and their instability to both natural and anthropogenic influences are important topics[23,64].

Given these difficulties, it is essential for the sustainable resource management aimed at understanding seasonal variations in groundwater quality. Groundwater quality is strongly affected by variables such as monsoon rain distribution, recharge-discharge changes and tidal fluctuations[52,53]. Monsoon-induced recharging, which has been linked to notable seasonal shifts in hydrochemical characteristics, influences the extent of seawater intrusion[28].

Though groundwater quality concerns are becoming more widely acknowledged, thorough evaluations that explain seasonal and regional disparities are still relatively uncommon, particularly in rapidly developing coastal municipalities like Visakhapatnam. Because of its short distance to the Bay of Bengal, industrial growth and urbanization, the area is vulnerable to notable changes in groundwater chemistry. Fluctuations due to seasons affect the range of marine water intrusion along with the levels of key water quality indicators. Local groundwater-related factors, tidal movements and monsoon recharge are the reasons of these variations. Laying out plans for sustainable monitoring of groundwater, protection and management that are site-specific requires an insight of these distinctions. Taking this into account, the goal of this study is to evaluate the seasonal variations in groundwater quality along the coastline of Visakhapatnam, aiming at the primary factors that play a part in these changes.

Using statistical methods and widely used indicators of water quality, the study will observe the seasonal differences in the quality of groundwater across the coastal belt. The targets include identifying spatial and time-based trends, examining the influence of seawater intrusion and recommending effective management approaches of water quality[37,58]. To study the seasonal effects, a detailed evaluation of the groundwater quality along Visakhapatnam's coastline was conducted. A special junction of geological, climatic and land-use factors largely affects groundwater behaviour in this area. A detailed awareness of the physical and hydrogeological elements of this region is needed to interpret the noted changes in groundwater quality.

Material and Methods

Study Area: The study area was situated along the Visakhapatnam shoreline stretch along the eastern corridor of Andhra Pradesh, India. Its geographic coordinates fell between latitudes 17°42′12.4" N to 17°53′15.76" N and longitudes 83°18′20.3" E to 83°27′13.33" E. The region falls under the tropical monsoon climatic zone having an average yearly rainfall of 1113.1 mm, in most cases during the southwest monsoon season[21]. The broad-leaved forest that comprises of the area's vegetation is strongly influenced by the coastal climate[66]. Based on geology, Visakhapatnam is located in the mobile belt region of the Eastern ghats, which is made up of Precambrian rock formations namely Charnockite and Khondalite, with recent alluvial deposits scattered throughout[48]. The region's topography is not entirely predictable, with intermittent valleys and flood-prone areas. A variety of business, industrial, residential and port operations occupy the area's land, showing the city's speedy urbanization[69].

As per the hydrogeological reports from 157 monitoring sites across the city, the mean depth to groundwater is 12.41 meters below ground level[10]. Depending on the aquifer formation, the yield of groundwater can range from 1 to 5 liters per second. The infiltration values extend from 1.5 to 3.3 cm/hour, influenced by the properties of the soil; higher rates are seen in sandy soils and lower rates in clayey substrates[10].

Sample Collection and Analysis: Samples of groundwater were collected from 15 georeferenced locations as shown in figure 1, along the coastal stretch of Visakhapatnam, covering an approximate aerial distance of 26 kilometres. Sampling was conducted during two distinct hydrological periods: before monsoon (May) and after monsoon (November) seasons of the year. Clean, sterilized high-density polyethylene (HDPE) bottles were used for collection of samples to prevent contamination. Immediately after collection, samples were stored in iceboxes and forwarded to the laboratory for analysis. All analytical procedures followed the protocols outlined in APHA[1] Standard Methods for the Examination of Water and Wastewater**.** The physico-chemical parameters were determined using methodologies specified in IS 10500:2012 Indian standard specification for drinking water quality.

Parameters Analysed: As represented in figure 2, physico-chemical characteristics, consisting of general indicators like principal ions, trace elements and organic contaminants, were analysed in order to completely study the groundwater quality. A deep understanding of the natural chemical processes in geology and possible human impacts on water quality was assured by this wide analytical scope.

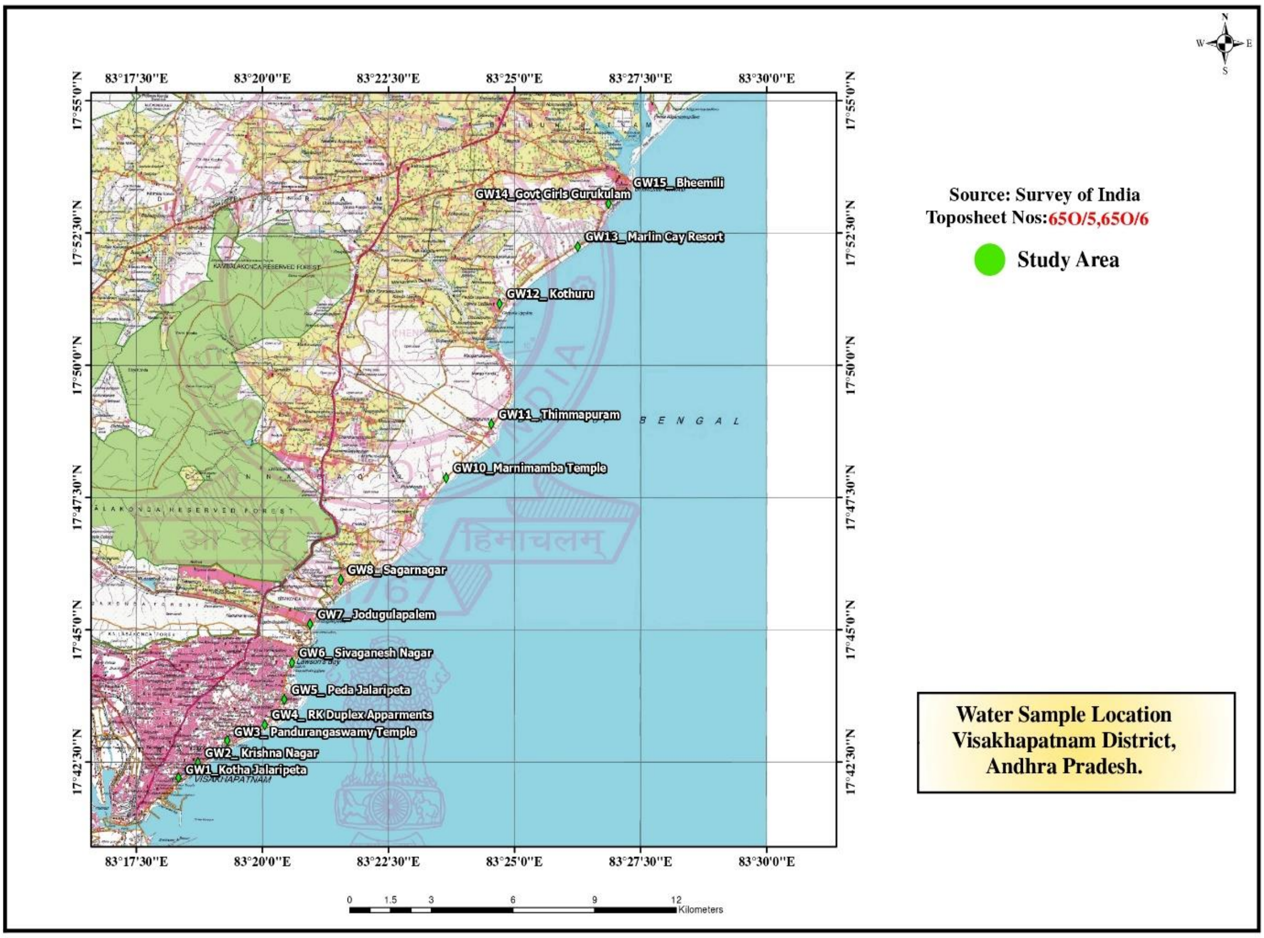

Figure 1: Map of sampling locations along the coastal belt of Visakhapatnam

Table 1
Details of sampling locations along the coastal belt of Visakhapatnam

S.N.	Location Code	Name of the Location	Latitude and Longitude	Source of sample
1.	GW1	Kotha Jalaripeta	17°42'12.4" N 83°18'20.3" E	Borewell
2.	GW2	Krishna Nagar	17°42'29.39" N 83°18'43.47" E	Borewell
3.	GW3	Pandurangaswamy Temple	17°42'54.26" N 83°19'18.39" E	Borewell
4.	GW4	RK Duplex Apartments	17°43'12.4" N 83°20'02.9" E	Borewell
5.	GW5	Peda Jalaripeta	17°43'40.72" N 83°20'26.32" E	Borewell
6.	GW6	Sivaganesh Nagar	17°44'22.7" N 83°20'35.1" E	Borewell
7.	GW7	Jodugulapalem	17°45'6.48" N 83°20'57.02" E	Borewell
8.	GW8	Sagarnagar	17°45'56.8" N 83°21'33.13" E	Borewell
9.	GW9	Govt. Girl Blind School	17°46'11.30" N 83°22'8.53" E	Borewell
10.	GW10	Marnimamba Temple	17°47'52.48" N 83°23'38.85" E	Borewell
11.	GW11	Thimmapuram	17°48'53.21" N 83°24'32.78" E	Borewell
12.	GW12	Kothuru	17°51'9.81" N 83°24'42.5" E	Borewell
13.	GW13	Marlin Cay Resort	17°52'14.73" N 83°26'15.51" E	Borewell
14.	GW14	Govt Girls Gurukulam	17°53'3.19" N 83°26'51.9" E	Borewell
15.	GW15	Bheemili	17°53'15.76" N 83°27'13.33" E	Borewell

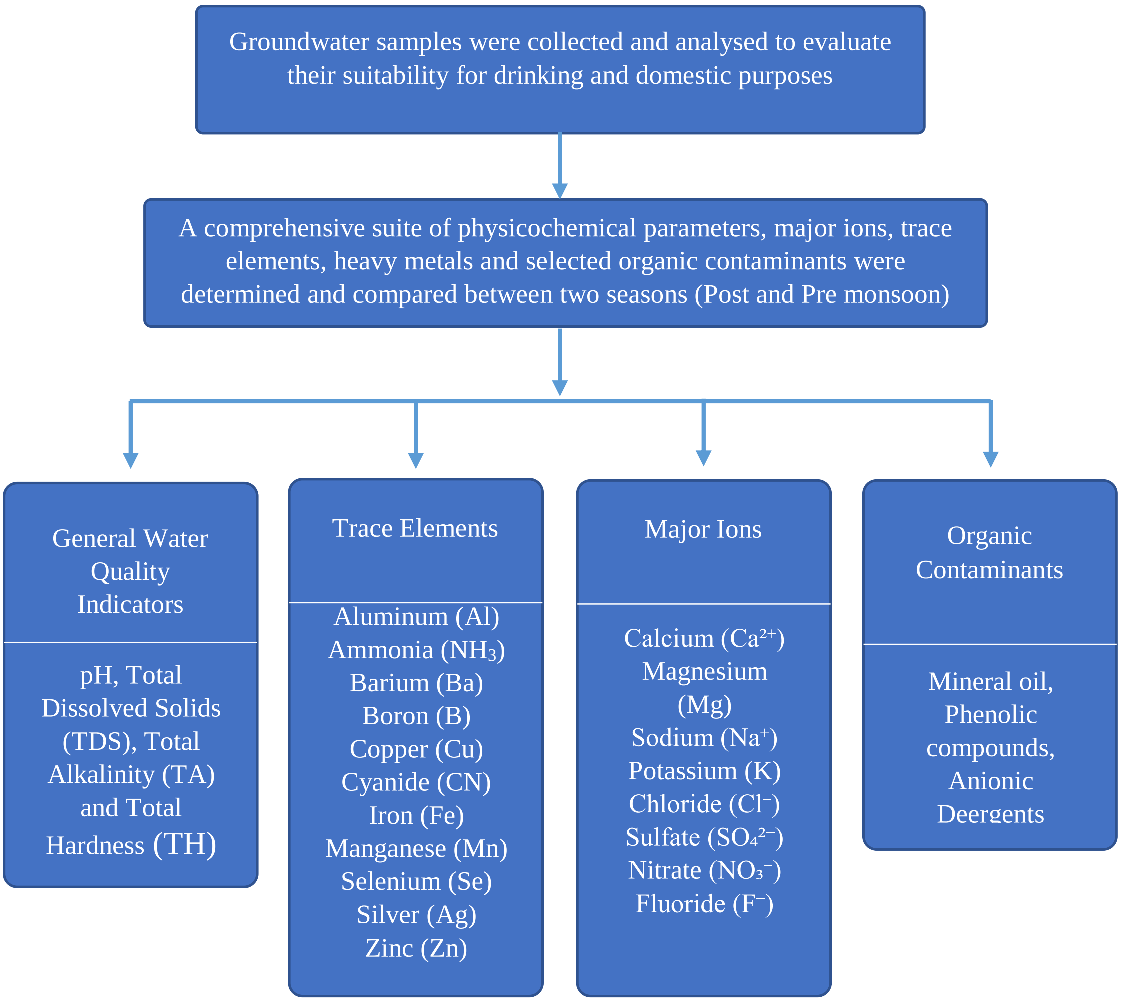

Figure 2: Schematic representation of the parameters analysed in the selected locations.

The basic indicators of water quality are color, pH, turbidity, total dissolved solids (TDS), calcium, fluorides, chlorides, magnesium, nitrates, sulfates, total alkalinity (TA) and total hardness (TH). These properties aid in defining the groundwater's basic chemical composition and suitability for human use. The analysis included basic and main components as well as trace elements like aluminum (Al), ammonia (NH_3), boron (B), barium (Ba), copper (Cu), iron (Fe), cyanide (CN), manganese (Mn), silver (Ag), selenium (Se), sulphide (H_2S) and zinc (Zn). If these metals are found in excess of acceptable limits, even minute quantities may be dangerous to health. In addition, because they could be caused by improper waste disposal or industrial waste discharge, organic impurities such mineral oil, phenolic compounds and anionic detergents were also analyzed. In accordance with the guidelines of APHA[1] and IS 10500:2012 drinking water standards, testing procedures including UV-Visible spectrophotometry. Inductively coupled plasma with Optical emission spectrometry (ICP-OES). Ion-selective electrodes were used where appropriate.

GIS tools: Based on the classification by index, the areas were classified using ArcMap 10.6 and maps were produced suitably. In water resource investigations, the combination of multiple sources data, the evaluation of seasonal change and the identification of areas of high contamination, all depend on the use of GIS tools[57]. A spatially explicit framework for decision-making is offered by GIS-based analysis, particularly in coastal zones where aquifer response varies greatly because of the area's closeness to the sea and diverse land use.

Statistical Analysis: The distribution and variation of groundwater quality characteristics were explained through a range of statistical description studies. Different calculations were performed for criteria such as Min, Max, Avg, SD and CV for both seasons. This data provides insight into seasonal variations in concentration values as well as the representative value and spread of each parameter. Parameters exhibiting high geographical or periodic fluctuation were identified with the help of the coefficient of variation, identifying areas of concern or major impact from outside sources such as city runoff or saline water intrusion. The seasonal comparison also enabled the identification of tendencies that could be linked to sources of contamination, natural groundwater recharge cycles or dilution effects. Microsoft spreadsheet application was used for all data analysis. These statistical outputs serve as the base for the following index-based and spatial data interpretation.

Water Quality Indices: Three key indices: Water Quality Index (WQI), Revelle Index (RI) and Langelier Saturation Index (LSI) were applied to fully examine the groundwater quality along the Visakhapatnam coastline.

Water Quality Index (WQI): WQI streamlines detailed quality data of water by combining multiple criteria brought together as one quantitative value that represents the total water quality. In this study, WQI was calculated using the index based on weighted mean recommended by Brown et al[8]. This method has been verified by various assessments of coastal groundwater quality[34,50]. Table 2 represents how groundwater quality is classified using the WQI range.

Revelle Index (RI): The Revelle index is an assessment tool used to measure salinity levels and saltwater intrusion into coastal groundwater. It is defined as the chloride ions ratio to the sum of bicarbonate and carbonate ions and is reported in meq/L:

$$RI = Cl^-/HCO_3^- + CO_3^{--})$$

The consequences of mixing in seawater can be identified using this indicator. The standard classification is:

- RI < 0.5: Fresh or unaffected groundwater
- 0.5 ≤ RI ≤ 6.6: Slightly affected to moderately affected
- RI > 6.6: Affected strongly (saline intrusion)[52].

Langelier Saturation Index (LSI): The LSI, a key indicator for determining the potential for scaling or corrosion of water, was developed by Langelier[33] in 1936. It checks whether calcium carbonate ($CaCO_3$) will form precipitate or dissolve in water. It is distinguished by:

$$LSI = pH - pHs$$

where pH is the measured water pH and pHs, or saturation pH, is calculated by temperature, TDS, alkalinity and calcium hardness.

Decoding LSI values:

- LSI > 0: Water is supersaturated → Tendency to form scale
- LSI = 0: Water is in equilibrium → Stable
- LSI < 0: Water is undersaturated → Tendency to be corrosive

In both residential and industrial applications where pipe scaling or corrosion is an issue, the LSI is very helpful for evaluating risks in distribution systems.

Results and Discussion

The characteristics of the sampled ground waters were assessed through analysis. Organic pollutants, primary ions, trace elements and key water quality parameters were the four main groups into which a complete range of parameters was separated.

Table 2
Groundwater quality classification according to WQI ranges

WQI Range as per Brown et al[8]	Classification
0 – 25	Excellent
26 – 50	Good
51 – 75	Poor
76 – 100	Very Poor
> 100	Unfit for Human Consumption

Fundamental markers of the water's physicochemical profile include pH, TA, TDS and TH. Calcium, chloride, sulfate, sodium and nitrate are major ions that assist in evaluating the geological processes and potential human impacts. Additionally, because of their importance in both natural occurrence and pollution issues, trace elements such as iron, manganese, copper and zinc were also studied. To better capture the effects of residential and industrial outputs, some organic contaminants were added such as mineral oils and phenolic chemicals. Each parameter is thoroughly examined beginning with pH, a quality parameter that regulates several biological and physico-chemical processes in aquatic settings.

Table 3
Pre-Monsoon statistical summary of groundwater parameters

S.N	Parameter	Units	Min	Max	Avg	SD	CV
1	Colour	Hazen	1.02	5.54	2.49	1.21	0.48
2	pH	-	6.62	8.05	7.36	0.36	0.05
3	Turbidity	NTU	0.09	6.15	1.80	1.87	1.04
4	Total Dissolved Solids	mg/l	376	1130	687.80	230.15	0.33
5	Aluminium (as Al)		0.01	0.02	0.02	0.00	0.18
6	Barium (as Ba)		0.02	0.16	0.11	0.04	0.36
7	Boron (as B)		0.03	0.32	0.13	0.09	0.67
8	Calcium as Ca		17.40	129.00	68.55	31.73	0.46
9	Chlorides as Cl		68.10	366.00	140.37	69.96	0.50
10	Fluorides as F		0.33	1.41	0.71	0.36	0.51
11	Magnesium as Mg		5.85	145.00	39.50	34.21	0.87
12	Iron (as Fe)		0.01	0.02	0.01	0.01	0.39
13	Manganese (as Mn)		0.01	0.59	0.15	0.20	1.31
14	Nitrates as NO_3		2.78	34.20	11.96	7.01	0.59
15	Sulphates as SO_4		21.30	139.00	59.90	30.05	0.50
16	Total Alkalinity as $CaCO_3$		110.00	451.00	277.13	115.86	0.42
17	Total Hardness as $CaCO_3$		67.70	810.00	334.18	192.00	0.57
18	Zinc (as Zn)		0.01	0.40	0.13	0.12	0.93
19	Sodium as Na		63.10	244.00	127.93	56.85	0.44
20	Potassium as K		2.60	59.60	10.65	13.95	1.31

Table 4
Post-Monsoon statistical overview of groundwater parameters

S.N.	Parameter	Units	Min	Max	Avg	SD	CV
1	Colour	Hazen	1.05	4.83	2.49	1.04	0.42
2	pH	-	7.00	8.41	7.58	0.43	0.06
3	Turbidity	NTU	0.11	7.21	1.89	2.25	1.19
4	Total Dissolved Solids	mg/l	321	1098	665.93	226.00	0.34
5	Aluminium (as Al)		0.01	0.02	0.02	0.00	0.20
6	Barium (as Ba)		0.01	0.15	0.10	0.04	0.45
7	Boron (as B)		0.03	0.32	0.13	0.08	0.65
8	Calcium as Ca		19.50	126.00	66.48	30.13	0.45
9	Chlorides as Cl		51.20	358.00	133.45	70.00	0.52
10	Fluorides as F		0.29	1.32	0.69	0.34	0.50
11	Magnesium as Mg		6.56	138.00	37.82	32.34	0.86
12	Iron (as Fe)		0.01	0.01	0.01	0.00	0.07
13	Manganese (as Mn)		0.01	0.33	0.09	0.11	1.20
14	Nitrates as NO_3		2.16	31.85	11.31	6.63	0.59
15	Sulphates as SO_4		15.70	147.00	56.66	31.44	0.55
16	Total Alkalinity as $CaCO_3$		95.80	410.00	264.45	104.08	0.39
17	Total Hardness as $CaCO_3$		75.90	753.00	322.13	177.64	0.55
18	Zinc (as Zn)		0.01	0.42	0.14	0.13	0.92
19	Sodium as Na		57.20	234.00	123.51	57.59	0.47
20	Potassium as K		1.89	58.60	10.20	13.95	1.37

pH: One of important factor affecting the biological and chemical properties of water is pH. It may not be a direct health risk, but it has a big impact on flavor and controls the solubility and movement of metals and other contaminants in groundwater[70]. Groundwater typically has a pH between 6.5 to 8.5; deviations from this range could indicate contamination or natural geochemical processes like mineral dissolution or oxidation[38,59]. GW11 (6.62) had the lowest pH in the pre-monsoon period, whereas GW6 (8.05) had the highest. During the period of post-monsoon, the pH increased slightly, with values ranging from 7.00 at GW10 to 8.41 at GW12, as displayed in table 3. These values are within the acceptable limits of 6.5 to 8.5 set by IS 10500:2012.

The rise in average pH from 7.36 to 7.58 post-monsoon, as shown in table 4, may be attributed to dilution of acidic components and increased recharge from slightly alkaline surface waters[36]. Elevated pH measurements during the pre-monsoon may be caused by industrial effluents, which often increase groundwater alkalinity[7].

Total dissolved solids: The TDS served to be a sum of the concentration of all soluble organic and inorganic solids in water which includes ions such as calcium, sodium, magnesium, chloride, sulphate and bicarbonate. It is often regarded as a composite indication of water quality since TDS directly influences taste, palatability, scaling potential, usability for drinking purpose and irrigation. Muthu et al[40] stated that high TDS in coastal aquifers are commonly connected with both sources resulting from human activities such as fertiliser runoff, industrial discharges and home effluents and naturally occurring processes, such as mineral weathering and seawater intrusion. In the present study, the TDS levels have exhibited significant exceedances of the acceptable limit of 500 mg/L in both seasons. Pre-monsoon TDS values ranged from 376 mg/L at GW13 to a high of 1130 mg/L at GW12, with a mean of 688 mg/L.

In the post-monsoon season, TDS slightly decreased, ranging from 321 mg/L again at GW13 to 1098 mg/L at GW12, with a seasonal mean of 666 mg/L as displayed in tables.

Despite minor reductions after monsoon rainfall, TDS levels remained elevated in several locations including GW1, GW4, GW5, GW6, GW7, GW8, GW9, GW10, GW12 and GW14. In both seasons, a sizable portion of samples were above the allowable limit, suggesting moderate to excessive salinity, especially in urban and coastal areas.

Reduced aquifer recharge, elevated evapotranspiration and solute concentration from falling water tables could all be responsible for the comparatively higher pre-monsoon TDS levels. Although the persistence of elevated values at many places suggests the likelihood of seawater intrusion or pollution from surface operations, post-monsoon reductions suggest dilution effects from rainfall recharge[19,68]. These results highlight the necessity of routine monitoring, particularly in coastal regions that are susceptible.

Total Hardness: Occurrence of bivalent cations, especially calcium (Ca^{2+}) and magnesium (Mg^{2+}), which enter the aquifer system through mineral weathering and geochemical processes, is the key factor responsible for total hardness in groundwater. One important chemical property of water quality that affects its usefulness for residential, commercial and agricultural uses is hardness. Increased hardness impacts soil permeability and agricultural productivity, diminishes soap efficiency and creates scaling in appliances and pipelines. Anthropogenic activities, such as industrial effluent disposal and seawater intrusion, are other factors that contribute to coastal regions[5,31]. Total hardness in the current study has exceeded the IS 10500:2012 acceptable limit of 200 mg/L. Most groundwater samples in both seasons exhibited high levels of hardness.

Values of pre-monsoon ranged from 67.7 mg/L (GW2) to 810 mg/L (GW8), with a mean of 334.18 mg/L while post-monsoon values ranged from 75.9 mg/L (GW2) to 753 mg/L (GW8), averaging 322.13 mg/L. GW8, GW12, GW9 and GW7 exhibited consistently high levels of hardness, suggesting that calcium and magnesium ions predominate. These findings indicate that there is significant lithological control over the water, which is generally hard to very hard with minimal seasonal variation.

Total Alkalinity (TA): The main sources of groundwater alkalinity, which is essential for buffering pH, are bicarbonates, carbonates and hydroxides. In both seasons, elevated levels were over the IS 10500:2012 standard (200 mg/L), especially at GW14, GW8 and GW7. This suggests strong buffering due to carbonate-rich aquifers and limited post-monsoon dilution. Coastal influences like seawater mixing and anthropogenic factors also contribute[5,14,30,42,62,68].

The total alkalinity levels in the current study have crossed the limit of 200 mg/L set by IS 10500:2012 in a majority of samples across both seasons. Pre-monsoon values ranged from 110 mg/L (GW15) to 451 mg/L (GW14), with a mean of 277.13 mg/L. Post-monsoon values varied from 95.8 mg/L (GW10) to 410 mg/L (GW14), with a slightly lower mean of 264.45 mg/L as displayed in table 3. These results are consistent with patterns seen in comparable coastal hydrogeological environments, where both geological and marine sources influence groundwater's chemical development. To manage water quality and evaluate the effects of saline encroachment in sensitive coastal zones, alkalinity monitoring is crucial, along with monitoring of other important ions[5,14].

Fluoride (F^-): Groundwater naturally contains fluoride, which is mainly produced by dissolving of minerals that contain fluoride including biotite, apatite and fluorite. Dental and skeletal fluorosis can result from excessive fluoride intake, especially above 1.5 mg/L, even if fluoride at ideal amounts (0.6–1.2 mg/L) supports dental health and prevents cavities[30]. A combination of lithological composition, pH, residence time and evapotranspiration regulate fluoride concentrations in coastal aquifers. Fluoride mobilisation is generally enhanced by higher pH values and longer groundwater-rock interaction[62]. Fluoride levels during pre-monsoon ranged from 0.33 mg/L (GW15) to 1.413 mg/L (GW8), with a mean of 0.71 mg/L. Post-monsoon results ranged from 0.293 mg/L (GW10) to 1.324 mg/L (GW8), with an average of 0.69 mg/L.

GW6, GW7, GW8 and GW14 consistently exceeded the permissible level in both seasons, suggesting a geogenic source such as fluoride-bearing minerals present within the aquifer. The seasonal consistency highlights the need for Defluorination strategies in these hotspots. The post-monsoon season somewhat lowers fluoride concentrations point to dilution brought on by monsoonal recharge, which lowers the concentration of dissolved ions.

However, seawater intrusion, increased fluoride mineral dissolution, or geochemical circumstances that promote fluoride desorption from aquifer matrices could also be the cause of persistent fluoride levels close to or beyond the limit, especially in coastal zones[32]. To protect the public health in impacted areas, routine monitoring and defluoridation procedures are required. The intricate interaction between geogenic and hydrological variables is reflected in the regional variation of fluoride concentrations over the coastal aquifers of Visakhapatnam. Fluoride-bearing rocks, especially fluorite (CaF_2), can release fluoride ions into groundwater through incongruent dissolution in hard rock aquifer systems, such as those in the Eastern Ghats region, especially when the pH is alkaline[51].

Chloride (Cl^-) and Sodium (Na^+): Chloride is a conservative ion and a crucial marker of salinity and possible seawater intrusion[17]. Pre-monsoon chloride ranged from 68.1 mg/L (GW13) to 366 mg/L (GW12), averaging to 140.37 mg/L. Post-monsoon values ranged from 51.2 mg/L (GW13) to 358 mg/L (GW12), with a mean of 133.45 mg/L. Chloride levels in most samples were found within the IS 10500:2012 regulatory limit of 250 mg/L, except at GW12. The persistent exceedance at GW12 may be due to saline intrusion or anthropogenic activities. The slight post-monsoon decrease aligns with seasonal dilution from rainfall recharge. Chloride values exceeding 200 mg/L typically indicate potential seawater mixing. The Cl^-/Na^+ molar ratios close to 0.86 further suggest marine influence[17,25]. Continued monitoring and control of over-extraction are recommended.

Sodium, influenced by seawater ingress and anthropogenic activities, ranged pre-monsoon from 63.1 mg/L (GW3) to 244 mg/L (GW6), with a mean of 127.93 mg/L. Post-monsoon values were from 57.2 mg/L (GW13) to 234 mg/L (GW6), averaging 123.51 mg/L. GW6, GW2, GW5 and GW12 consistently showed high sodium levels. Although IS 10500:2012 sets no drinking water guideline for sodium, high concentrations can affect health and reduce soil quality for irrigation[65,67]. The sustained values across seasons indicate cumulative marine and urban influences[2,55].

Nitrate (NO_3^-) and Calcium (Ca^{2+}): Nitrate, mostly from agriculture and sewage, showed pre-monsoon values from 2.78 mg/L (GW9) to 34.2 mg/L (GW4), with a mean of 11.96 mg/L. Post-monsoon ranged from 2.16 mg/L (GW9) to 31.85 mg/L (GW4), with a mean of 11.31 mg/L. All results remained below the 45 mg/L IS 10500:2012 limit. Meanwhile, the GW4 showed the highest concentrations in both seasons. Slight post-monsoon reductions suggest dilution, though persistent inputs from fertilisers and urban runoff remain likely[12,45]. Substantially, the calcium concentrations in the pre-monsoon season were found between 17.4 mg/L (GW2) and 129 mg/L (GW12), with a mean of 68.55 mg/L and post-monsoon ranged from 19.5 mg/L (GW2) to 126 mg/L (GW12), mean 66.48 mg/L. Levels exceeded the 75 mg/L IS 10500:2012 limit at several locations, especially GW12. Elevated pre-monsoon values may result from prolonged residence time and rock-water interaction. The coastal lithology suggests calcareous contributions[42,47].

Magnesium (Mg^{2+}): Magnesium values pre-monsoon extended from 5.85 mg/L (GW2) to 145 mg/L (GW8), mean 39.50 mg/L; post-monsoon ranged from 6.56 mg/L (GW2) to 138 mg/L (GW8), mean 37.82 mg/L. BIS (IS 10500:2012) limit of 30 mg/L exceeded at GW4, GW6, GW7, GW8, GW9, GW14 and GW7.These results indicate hard to very hard water conditions, with saline intrusion and mineral dissolution contributing[11,68].

Cyanide (CN^-): The cyanide was undetected in samples of both seasons. This indicates minimal industrial activity and effective control measures in the area. Natural attenuation processes may further reduce cyanide risks if ever introduced[6,27].

Sulphate (SO_4^{2-}) and Manganese (Mn): Sulphate levels pre-monsoon ranged from 21.3 mg/L (GW13) to 139 mg/L (GW5), mean 59.91 mg/L; post-monsoon from 15.7 mg/L (GW13) to 147 mg/L (GW5), mean 56.66 mg/L. All samples fell below 200 mg/L, the acceptable limit as per IS 10500:2012. Seasonal consistency suggests natural lithogenic origin, with occasional localised anthropogenic input near coastlines[22,43]. Further, the manganese levels pre-monsoon ranged from <0.01 mg/L to 0.59 mg/L (GW7). Post-monsoon ranged from <0.01 mg/L to 0.334 mg/L (GW3). The IS 10500:2012 acceptable limit of 0.1 mg/L exceeded at GW3, GW5 and GW7 in both seasons. Elevated levels reflect reducing conditions and geogenic mobilisation of Mn^{2+}. Slight seasonal dilution was observed but hotspot persistence requires treatment. In coastal Visakhapatnam, such conditions are often intensified during pre-monsoon due to reduced recharge, allowing for more extensive redox-driven dissolution of Mn-bearing minerals[74].

Post-monsoon dilution slightly reduces concentrations, but locations with persistent enrichment, especially in low-lying or clay-rich zones, remain at risk. Elevated Mn levels not only compromise aesthetic quality causing staining and metallic taste but also raise health concerns over prolonged exposure, particularly for vulnerable populations.

Water Quality Indices Analysis

Water Quality Index (WQI): The WQI, computed utilizing the procedure given by Brown et al[8], reveals notable spatial and seasonal variations in quality of groundwater across the study area. These computed values classify water purity into categories spanning from "Good" to "Unfit for Human Consumption." Table 5 summarizes the WQI values and their respective quality classifications for prior and after monsoon periods.

The WQI classification indicated the differences in the ground water quality across the study area. Locations such as GW1, GW2, GW3, GW10, GW11 and GW15 as shown in table 5, have consistently exhibited WQI values below 50 during both the seasons, indicating good quality groundwater. These sites are anticipated to be likely less influenced by the anthropogenic activities and benefit from the natural infiltrations processes through geological formations[63,68].

In contrast, sites GW4, GW5, GW9, GW12 and GW13 fall within the poor to very poor-quality category (WQI between 51 and 100) with GW12 showing post-monsoon deterioration more likely due to the leaching of surface contaminants and salt mobilisation during recharge events[29]. Study sites such as GW6, GW7, GW8 and GW14 have reported WQI values exceeding 100 in both the seasons, classifying them as, not safe for human consumption. The observed quality at these locations may result from factors including untreated water disposal, seawater intrusion, or other anthropogenic activities around[44].

Table 5

WQI values by site and season Sampling Location	Pre-monsoon WQI	Post-monsoon WQI	Classification (Pre)	Classification (Post)
GW1 – Kotha Jalaripeta	47.8	46.8	Good	Good
GW2 - Krishna Nagar	42.4	44.6	Good	Good
GW3 - Pandurangaswamy Temple	43.6	46.1	Good	Good
GW4 - RK Duplex Apartments	66.5	63.2	Poor	Poor
GW5 - Peda Jalaripeta	80.2	85.4	Very Poor	Very Poor
GW6 - Sivaganesh Nagar	125.0	121.0	Unfit	Unfit
GW7 - Jodugulapalem	100.2	100.3	Unfit	Unfit
GW8 - Sagarnagar	143.0	134.9	Unfit	Unfit
GW9 - Govt. Girl Blind School	89.1	80.3	Very Poor	Very Poor
GW10 - Marnimamba Temple	40.2	35.6	Good	Good
GW11 - Thimmapuram	43.4	38.8	Good	Good
GW12 - Kothuru	72.4	80.3	Poor	Very Poor
GW13 - Marlin Cay Resort	68.7	58.3	Poor	Poor
GW14 - Govt Girls Gurukulam	106.6	102.9	Unfit	Unfit
GW15 - Bheemili	38.1	47.9	Good	Good

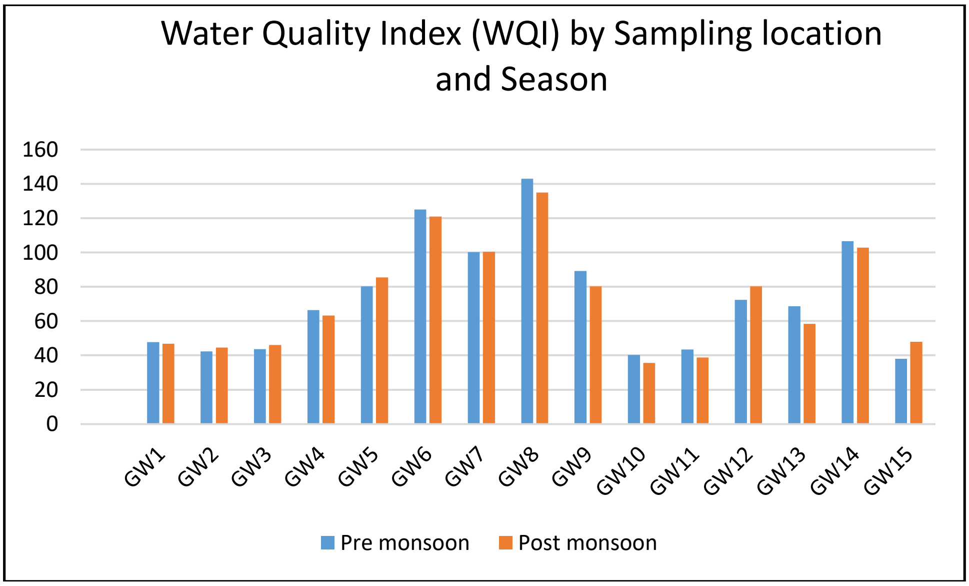

Figure 3: Bar chart of WQI by site and season

Revelle Index Interpretation: A diagnostic tool for assessing salinisation and seawater intrusion in ground waters of the coastal is the Revelle index (RI), which denotes the ratio of chloride concentration to the sum of carbonate and bicarbonates. While RI values below 0.5 reflect unaltered groundwater, values above 0.5 generally indicate human or marine sources of salinity[52]. The Revelle index values for the study sites have ranged from 0.48 to 2.13 during the season prior to the monsoon and 0.45 to 2.16 following the rainy season, thereby indicating a moderate salinization across the study areas with minimal seasonal variations. During the pre-monsoon season, only site GW14 reported an RI value below 0.5, further classifying it as unaffected by salinity, while all other sites have showed an RI values above 0.5, reflecting varying degrees of salinity influence.

This pattern may be attributed to factors such as limited natural recharge, excessive groundwater extraction and possible inland intrusion of saline water. Post-monsoon analysis showed improvement at sites GW8, GW13 and GW14, where RI values below 0.5, are anticipated likely due to effective dilution resulting from monsoonal recharge. However, sites such as GW10, GW11, GW12 and GW15 continued to exhibit RI values exceeding 1.5, indicating persistent salinity stress in the respective areas. These observed trends in RI values underline significant hydrogeochemical implications for the region.

Table 6
Revelle Index Values and Classification (Pre-monsoon and post-monsoon)

S.N.	Sampling Location	Revelle Index (Premonsoon)	Classification (Premonsoon)	Revelle Index (Postmonsoon)	Classification (Postmonsoon)
1	GW1 – Kotha Jalaripeta	0.69	Slightly Affected	0.76	Slightly Affected
2	GW2 - Krishna Nagar	1.00	Slightly Affected	1.00	Slightly Affected
3	GW3 - Pandurangaswamy Temple	0.78	Slightly Affected	0.73	Slightly Affected
4	GW4 - RK Duplex Apartments	0.68	Slightly Affected	0.68	Slightly Affected
5	GW5 - Peda Jalaripeta	1.17	Slightly Affected	1.18	Slightly Affected
6	GW6 - Sivaganesh Nagar	1.05	Slightly Affected	0.96	Slightly Affected
7	GW7 - Jodugulapalem	0.55	Slightly Affected	0.53	Slightly Affected
8	GW8 - Sagarnagar	0.52	Slightly Affected	0.45	**Unaffected**
9	GW9 - Govt. Girl Blind School	0.55	Slightly Affected	0.51	Slightly Affected
10	GW10 - Marnimamba Temple	1.54	Slightly Affected	1.66	Slightly Affected
11	GW11 - Thimmapuram	1.50	Slightly Affected	1.53	Slightly Affected
12	GW12 - Kothuru	2.13	Slightly Affected	2.16	Slightly Affected
13	GW13 - Marlin Cay Resort	0.54	Slightly Affected	0.49	**Unaffected**
14	GW14 - Govt Girls Gurukulam	0.48	**Unaffected**	0.46	**Unaffected**
15	GW15 - Bheemili	1.69	Slightly Affected	1.67	Slightly Affected

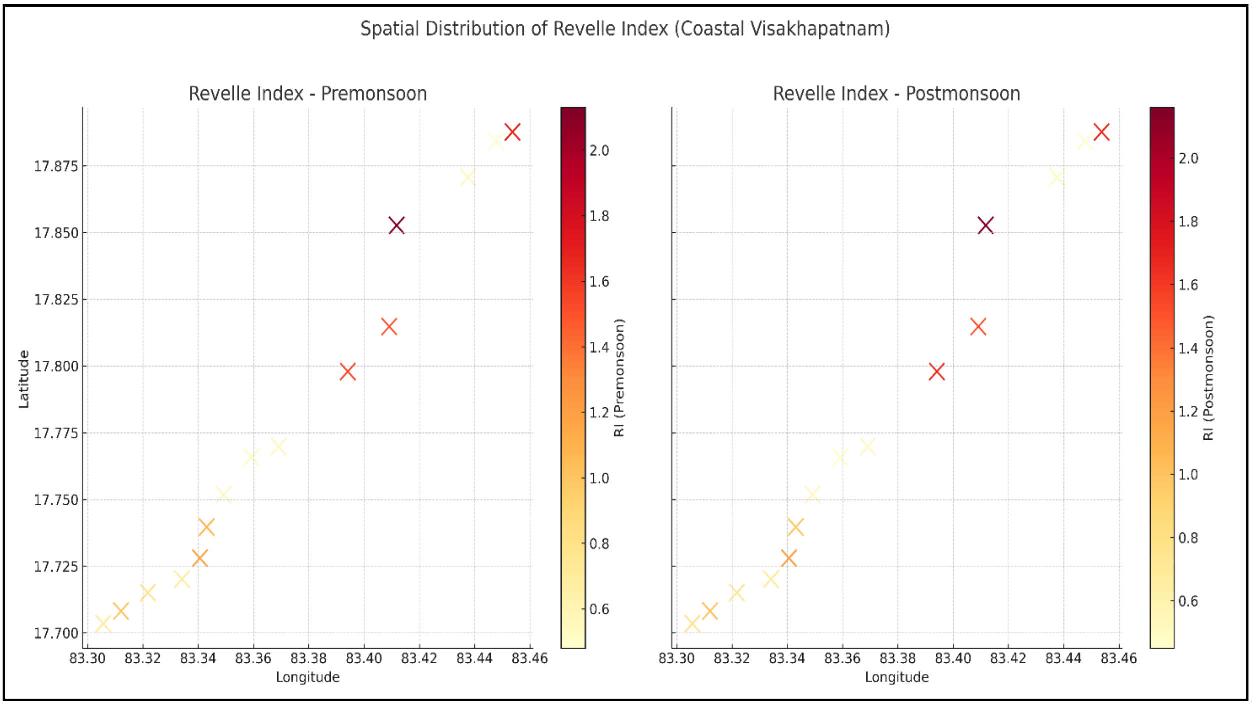

Figure 4: Revelle Index heatmap (Pre-Monsoon and Post-monsoon)

The consistently high RI values in GW10, GW11, GW12 and GW15 over a period, indicate chronic saline groundwater problems, which may be due to the proximity to the coast and in turn, inland migration of saline water[16].

In addition, hydrogeological investigations revealed that relatively high RI values from GW8, GW13 and GW14 indicate the existence of saline water of high density resulting from a combination of geological, topographic and human impact factors that typically characterize those areas in coastal settings[39]. Furthermore, studies by Sarkar et al[54] emphasise that high groundwater withdrawal for industrial and irrigation purposes exacerbates salinity intrusion in vulnerable coastal aquifers. Such rapid reduction in the RI values of GW8, GW13 and GW14 in post-monsoon months seems to be in the right direction, indicating that the seasonal recharge could result in the dilution of the saltwater condition in the aquifer. These findings underline the importance of being able to predict site-specific hydro geochemical reactions in groundwater in rapidly urbanized coastal zones.

Langelier Saturation Index (LSI): Based on the link between pH and pHs at which water is in equilibrium with calcium carbonate, LSI is a crucial instrument to determine the scale-forming and corrosive characteristics of water[33]. A positive LSI exhibits a tendency for calcium carbonate precipitation (scaling), while a negative LSI indicates under-saturation in the water and may dissolve calcium carbonate (corrosive). The magnitude of LSI reflects the severity of the condition. In this study, LSI values were computed for 15 groundwater samples taken from coastal Visakhapatnam during pre-monsoon and post-monsoon seasons. The results are summarized in table 7.

The computed Langelier saturation index (LSI) values show that the groundwater pH falls within the slight scaling to slightly corrosive periods, maximum during the monsoon season. Scaling causes were quite evident during the post-monsoon season, where increased LSI values were observed at many monitoring sites. Most significantly, at GW5 (1.13), GW9 (0.84) and GW12 (1.37) respectively, the LSI values were above 0.85 and indicated signs of moderate to high scaling potential. In such case, the system becomes over-saturated with calcium carbonate, therefore increasing the chance of scale precipitate on water infrastructure such as distribution system, well screen and aquifer matrices. Though samples taken post- monsoon started to have positive LSI values in common as well, which demonstrated that an increase in the scale formation was observed following the monsoonal recharge.

A contrasted trend to the one observed in the post-monsoon season was found in the corrosive tendencies in some groundwater of the study area such as GW10 (−0.78), GW11 (−1.11) and GW15 (−0.84), which showed negative LSI values, indicative of undersaturation with calcium carbonate. Such a situation where water is chemically aggressive by having a degree of capability of eroding entities such as metallic and cementitious components which then later pose a danger to the sustainability of water infrastructure. Seasonal shifts were noted not only in the river water but also in several sampled wells, which showed seasonal transitions. An example of this is GW2, which moved from being corrosive (−0.47) in the pre-monsoon period to being stable (0.02) come the post-monsoon period. Notably, GW3 and GW13 maintained quartz merely in both seasons as a result of a slightly improved recharge caused by a minor amount of precipitation. Particularly, GW8 and GW11 exhibited mild corrosion in the pre-monsoon period and switched to scale formation after the monsoon with the rise of dilution and intensified alkalinity of fresh water, the hydro chemical feature that is exceptional for coastal aquifers.

Table 7
LSI values for groundwater samples in pre- and post-monsoon seasons

Location	Pre-pH	Pre-pHs	Pre-LSI	Post-pH	Post-pHs	Post-LSI	Water Stability Status
GW1 – Kotha Jalaripeta	7.62	7.03	0.59	7.60	7.16	0.44	Supersaturated – Scaling potential
GW2 - Krishna Nagar	7.45	7.92	-0.47	7.90	7.89	0.02	Near Stable (Post-monsoon)
GW3 - Pandurangaswamy Temple	7.49	7.63	-0.14	7.52	7.60	-0.08	Undersaturated – Corrosion potential
GW4 - RK Duplex Apartments	7.32	5.98	1.34	7.15	7.07	0.08	Supersaturated – Scaling potential
GW5 - Peda Jalaripeta	7.25	7.2	0.05	8.33	7.20	1.13	Supersaturated – Scaling potential
GW6 - Sivaganesh Nagar	8.05	7.36	0.69	7.53	7.49	0.04	Supersaturated – Scaling potential
GW7 - Jodugulapalem	7.16	7.05	0.11	7.37	7.12	0.25	Supersaturated – Scaling potential
GW8 - Sagarnagar	7.26	6.95	0.31	7.60	7.10	0.50	Supersaturated – Scaling potential
GW9 - Govt. Girl Blind School	7.88	7.05	0.83	8.03	7.19	0.84	Supersaturated – Scaling potential
GW10 - Marnimamba Temple	7.05	7.83	-0.78	7.00	8.00	-1.00	Undersaturated – Corrosion potential
GW11 - Thimmapuram	6.62	7.73	-1.11	7.01	7.88	-0.87	Undersaturated – Corrosion potential
GW12 - Kothuru	7.62	6.96	0.66	8.41	7.04	1.37	Supersaturated – Scaling potential
GW13 - Marlin Cay Resort	7.40	7.6	-0.2	7.43	7.74	-0.31	Undersaturated – Corrosion potential
GW14 - Govt Girls Gurukulam	7.28	6.89	0.39	7.54	7.03	0.51	Supersaturated – Scaling potential
GW15 - Bheemili	6.93	7.77	-0.84	7.31	7.67	-0.36	Undersaturated – Corrosion potential

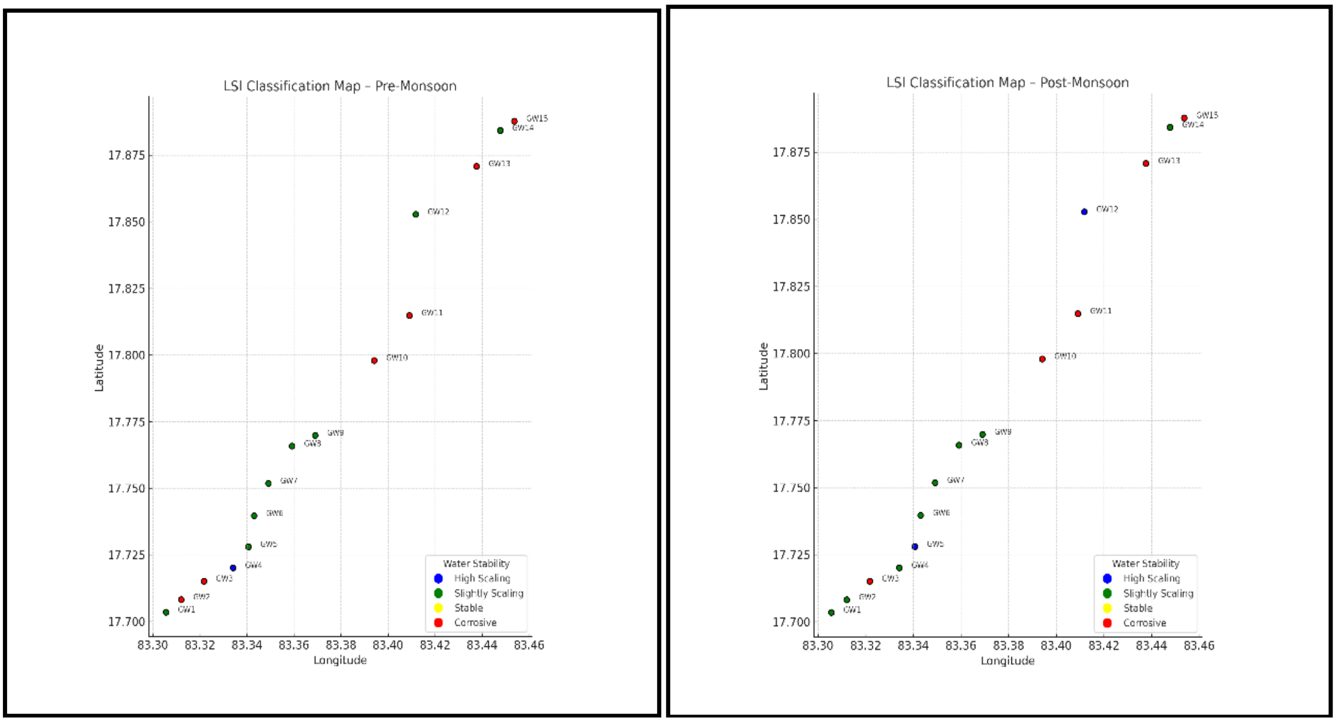

Figure 5: LSI classification map (Pre and Post-monsoon)

Conclusion

This study has employed a complex multi-index analysis based on WQI methodology, RI and LSI to establish the underground water situation in the study regions. The research showed disastrous contamination of groundwater in certain locations with reference to seasonal variations, which can be attributed to natural geo-hydrological conditions as well as anthropogenic activities. The WQI results confirm that nearly 40% of the studied sites fall under the 'good' category, while about 27% of the sites are marked as poor in quality fit for consumption.

The exposure of shallow groundwater zones to surface contamination, rises during the 'monsoonal recharge', especially at sites as GW12. These variations underscore the need for context-specific assessments that consider not only spatial differences but also the temporal influence of climatic factors such as rainfall. The assessment of the RI results proved to be of notable value in understanding the salinity conundrum in that area. Sites like GW10, GW11, GW12 and GW15 are silenced perennially (the mean winter value >1.5) because of the overextraction of groundwater and conversely, seawater intrusion alters the hydraulic gradients.

At the same time, the post-monsoon (GW8, GW13, GW14) reductions in RI are illustrating the ability of seasonal recharge to dilute salinity and in such a way, to bring water habitat quality back to presentable condition. Such findings are not only alike those of reviewed regional studies from analogous coastal groundwater systems but also highlight the cognizance of frequent consideration of the lithological condition, hydro geomorphological factors as well as human-induced effect on salinity. Moreover, the LSI parameter shows a trend towards moderate deposit on various measured locations, more notably in the post-monsoon period, whereas it gives a substantial sign of corrosion on specific sites (GW10, GW11, GW15) due to aggressive chemical environment of groundwater, especially during pre-monsoon season.

The integration of WQI, RI and LSI into a unified interpretive framework allowed for a comprehensive understanding of groundwater dynamics in a complex coastal environment. The examination highlights the necessity of localized water management approaches that include regulated groundwater abstraction, artificial recharge interventions, continuous monitoring of corrosive/scaling tendencies and strict pollution control measures targeting urban and industrial sources.

Sustainable groundwater governance in monsoon-dependent and salinity-prone areas like Visakhapatnam requires a science-policy interface that incorporates hydrogeochemical monitoring with predictive modelling, long-term data series and policy implementation. Further research focus is required in future on the mapping of seawater intrusion fronts, aridity resistance of the aquifers in the light of regional climate features and the development of adaptive solutions of water shortages in quickly growing coastal cities.

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