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AN INTEGRATED ASSESSMENT OF GROUNDWATER PHYSICOCHEMICAL QUALITY AND LAND USE/LAND COVER DYNAMICS IN THE PENNA RIVER BASIN, YSR KADAPA DISTRICT, INDIA

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ABSTRACT:
Groundwater is a critical component of water security in the semi-arid landscapes of southern India, where seasonal recharge, geology, agriculture and changing land cover can jointly influence water chemistry. This study presents an integrated assessment of groundwater physicochemical characteristics and land use/land cover (LULC) dynamics in the Penna River Basin within YSR Kadapa District, Andhra Pradesh, using the study framework and results developed during the 2022–2026 assessment period. The investigation covered sampling locations around Pulivendula, Muddanur, Mylavaram, Jammalamadugu and Peddamudium and evaluated seasonal patterns of chloride, total hardness, pH, nitrate, total dissolved solids (TDS), fluoride and iron. Spatial analysis was undertaken in a GIS environment, while LULC mapping was used to examine landscape changes from 2022 to 2025 and their potential relationship with groundwater quality. The results indicate clear seasonal and spatial variability, with fluoride showing a particularly dynamic pattern between pre-monsoon and post-monsoon conditions. The observed shift is consistent with the combined influence of groundwater concentration during dry periods and recharge-related dilution or mineral leaching after rainfall. LULC analysis shows that cropland remained the dominant class (>43%), while rangeland increased from approximately 32% in 2022 to 39% in 2024 before remaining near 37% in 2025. Tree cover declined from about 25% to 20%, and flooded vegetation decreased from approximately 15% to 12%. Water bodies, built-up land and bare land were comparatively stable. The combined evidence suggests that agricultural and vegetation-related land transitions are more important landscape changes than urban expansion during the study period. The study provides a GIS-supported baseline for groundwater surveillance and sustainable watershed planning in the Penna River Basin. Because the source presentation contains graphical rather than complete numerical observations for several water-quality parameters, detailed statistical significance and parameter-wise correlation coefficients should be added from the underlying analytical dataset before journal submission.

KEYWORDS:groundwater quality; Penna River Basin; YSR Kadapa; physicochemical parameters; fluoride; nitrate; TDS; GIS; remote sensing; LULC; seasonal variation

INTRODUCTION
Groundwater is an essential source of domestic, agricultural and ecological water supply in many semi-arid regions. Its chemical composition is controlled by interactions among rainfall recharge, aquifer materials, residence time, evaporation, soil processes and human activities. In river basins experiencing seasonal rainfall, groundwater chemistry may change substantially between dry and wet periods because recharge alters hydraulic gradients and solute concentrations. Monitoring these changes is therefore important for both public-health protection and sustainable resource management.

The Penna River Basin is environmentally and economically important in southern India. The study area within YSR Kadapa District has a semi-arid climate and seasonal rainfall, with a landscape composed of plateaus, hills and river valleys. These physical characteristics influence groundwater recharge, land use and the distribution of water resources. Agriculture is an important land-use activity, while groundwater supports rural livelihoods. Consequently, changes in agricultural land, vegetation and surface water features may influence recharge conditions and the movement or concentration of dissolved constituents.

Physicochemical parameters such as pH, chloride, total hardness, nitrate, TDS, fluoride and iron provide complementary information on groundwater condition. pH describes the acid–base status of water; TDS reflects the overall dissolved-solute burden; hardness provides an indication of calcium- and magnesium-associated mineralization; chloride can reflect natural mineral dissolution and anthropogenic inputs; nitrate may be influenced by agricultural and domestic sources; and fluoride can be strongly affected by water–rock interaction and concentration processes. Fluoride is of particular interest in groundwater studies because prolonged exposure to elevated concentrations may present a public-health concern. The World Health Organization identifies drinking-water quality management as a public-health priority and emphasizes risk-based assessment and surveillance of chemical hazards.

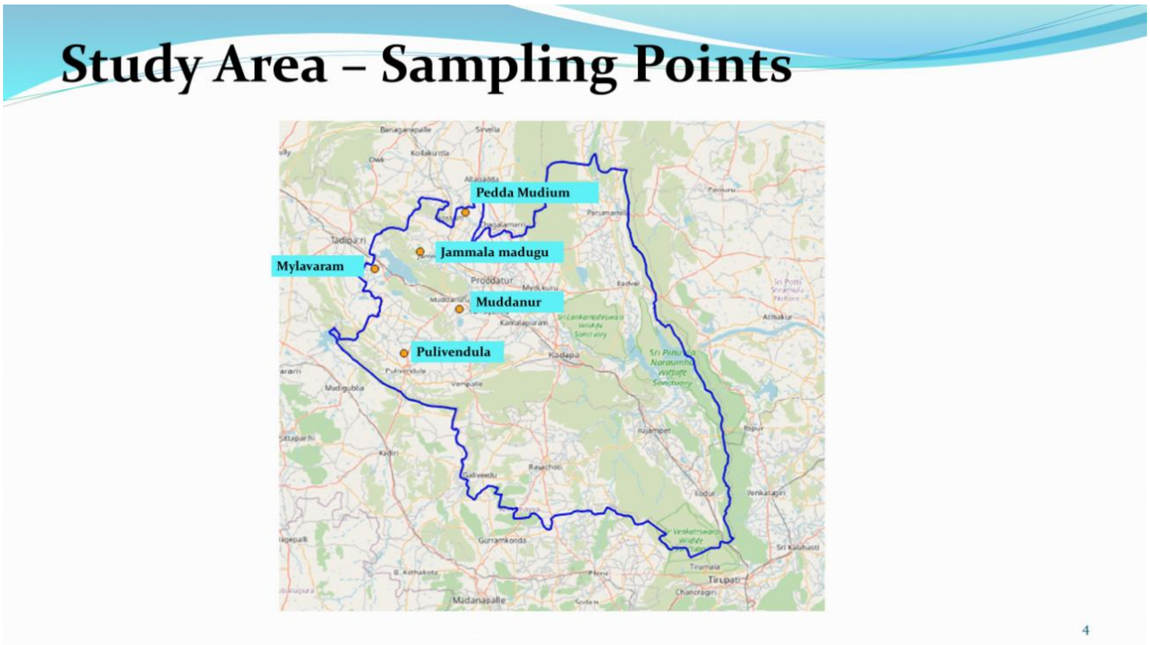
Remote sensing and GIS provide a complementary landscape-scale perspective. LULC classification can identify changes in cropland, rangeland, trees, flooded vegetation, water bodies, built-up land and bare land and can therefore help interpret spatial patterns observed in groundwater chemistry. An integrated groundwater–LULC approach is

especially useful where sampling observations are spatially limited but land-cover information is available over the full basin.
The present study therefore aims to combine seasonal groundwater-quality assessment with multi-year LULC analysis in the Penna River Basin of YSR Kadapa District. The specific objectives were to assess physicochemical and biological water-quality parameters, analyze LULC patterns and their temporal changes using GIS and remote sensing, evaluate the relationship between LULC changes and groundwater quality, identify environmentally stressed areas, and provide recommendations for sustainable water-resource management.

2. MATERIALS AND METHODS

2.1 Study area

The investigation was carried out in the Penna River Basin within YSR Kadapa District, Andhra Pradesh, southern India. The basin is described in the study presentation as a major east-flowing river system with a semi-arid climate and seasonal rainfall. The Penna River originates in the Nandi Hills and flows eastward toward the Bay of Bengal. The study landscape includes plateaus, hills and river valleys and supports agriculture, groundwater use and rural livelihoods.
Groundwater sampling and spatial assessment covered locations associated with Pulivendula, Muddanur, Mylavaram, Jammalamadugu and Peddamudium. These locations represent different parts of the basin and provide a basis for examining spatial and seasonal changes in groundwater chemistry.



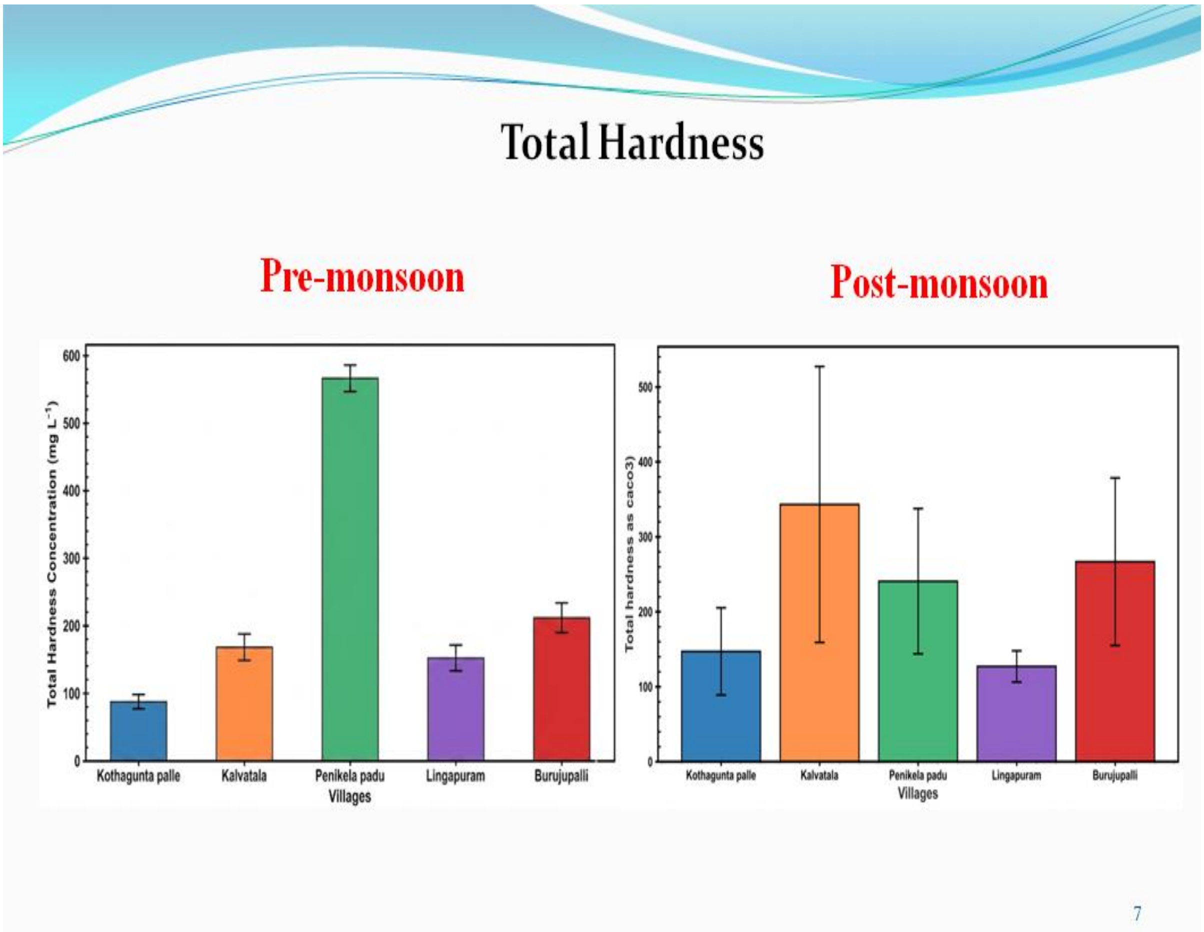
2.2 Study design and water-quality parameters

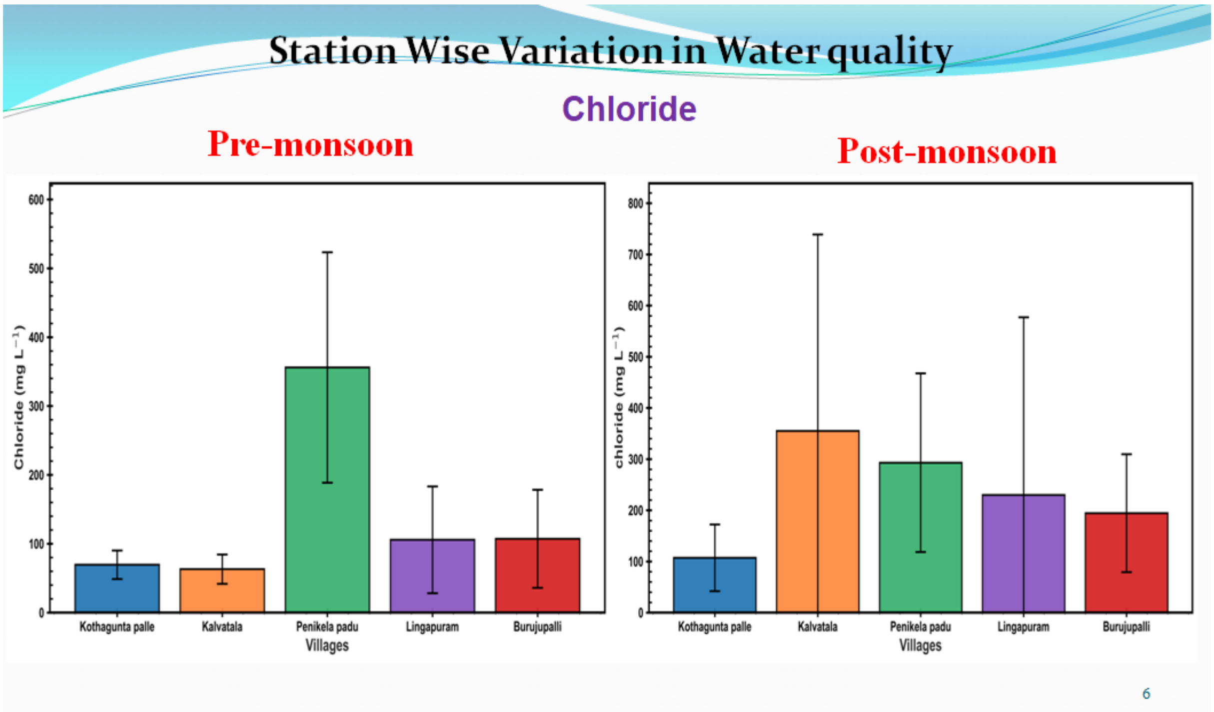
The assessment considered groundwater quality over the 2022–2026 study period, with seasonal comparison between pre-monsoon and post-monsoon conditions. The presentation reports statistical plots for chloride, total hardness, pH, nitrate, TDS, fluoride and iron. The study objectives also refer to physicochemical and biological water-quality parameters; however, complete biological measurements are not numerically reported in the supplied presentation. The present manuscript therefore focuses on the physicochemical parameters for which the presentation provides explicit evidence.

Parameter	Interpretive significance	Seasonal/spatial assessment in source
pH	Acid–base condition of groundwater	Pre-monsoon and post-monsoon plots
Chloride	Indicator of mineral dissolution and possible anthropogenic influence	Pre-monsoon and post-monsoon plots
Total hardness	General mineralization associated with hardness-forming ions	Pre-monsoon and post-monsoon plots
Nitrate	Potential indicator of agricultural/domestic nutrient inputs	Pre-monsoon and post-monsoon plots
TDS	Overall dissolved-solute concentration	Pre-monsoon and post-monsoon plots
Fluoride	Geogenic and concentration-related groundwater constituent with health relevance	Pre-monsoon and post-monsoon plots
Iron	Dissolved metal associated with aquifer/geochemical conditions	Pre-monsoon and post-monsoon plots

2.3 Statistical and spatial analysis

The supplied presentation documents statistical plotting of the principal groundwater parameters and spatial analysis of chloride, fluoride, nitrate, pH, total alkalinity, total hardness and TDS. The spatial outputs were developed to visualize pre-monsoon and post-monsoon distributions across the study area. Because the presentation does not provide the underlying interpolation algorithm, sample count, analytical precision, replicate design or numerical statistical-test outputs, these methodological details should be inserted from the laboratory/GIS records in the final manuscript rather than inferred.





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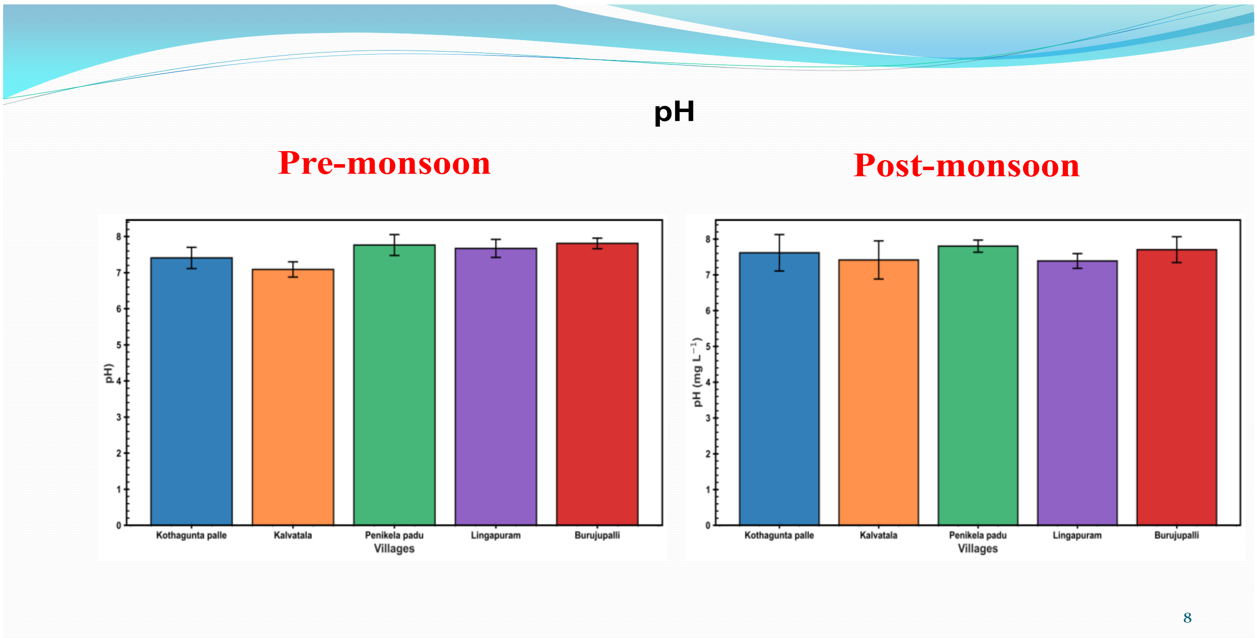
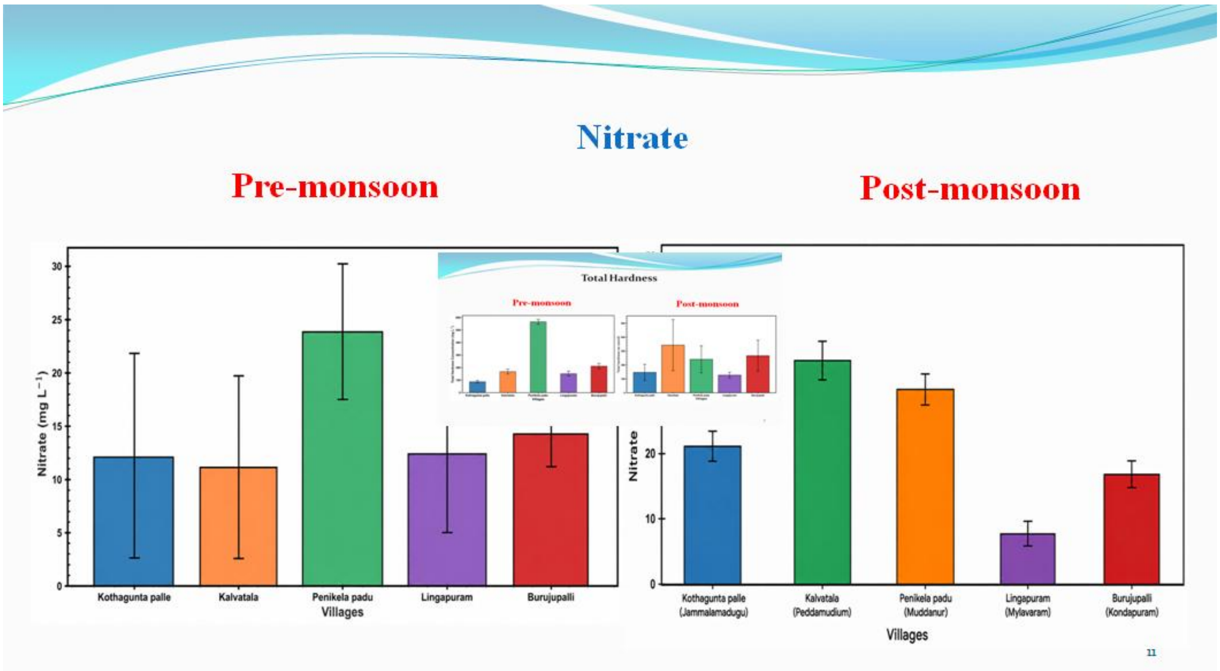
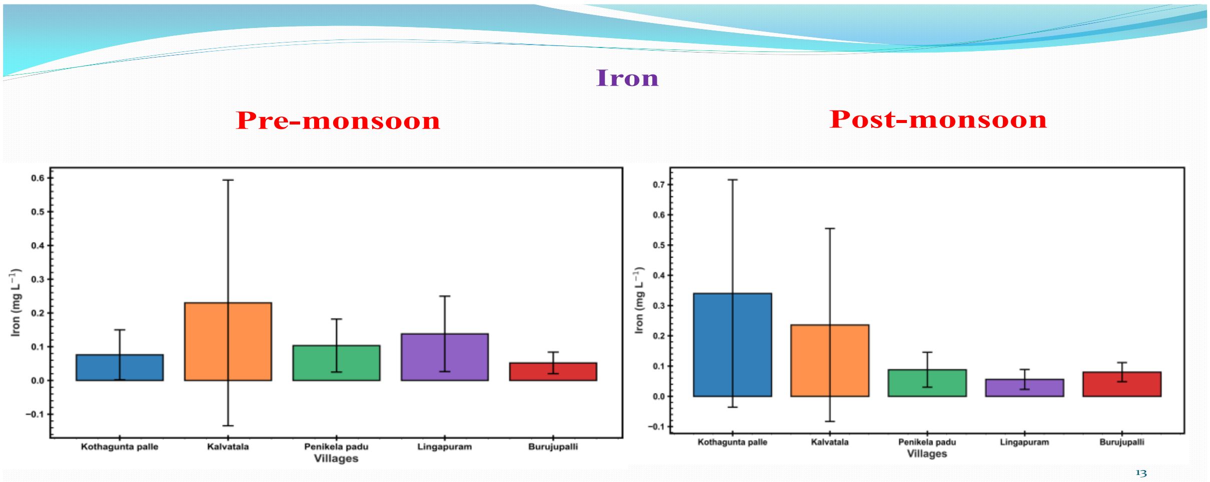
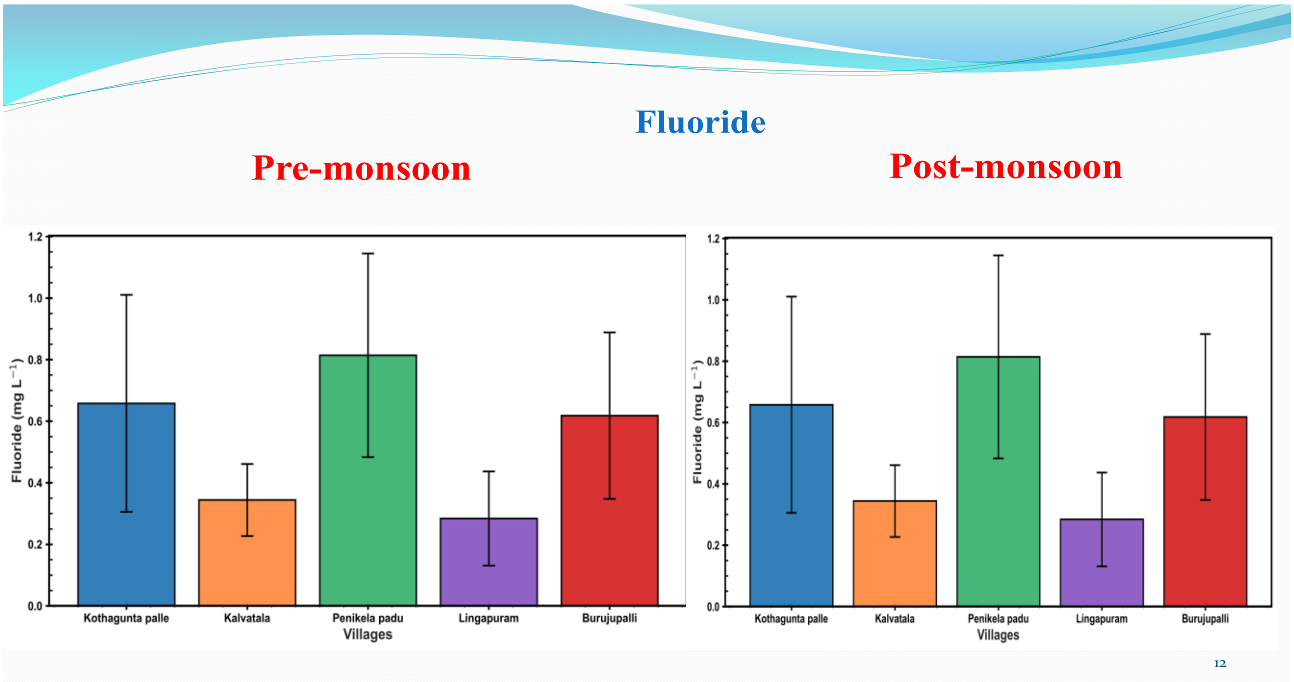
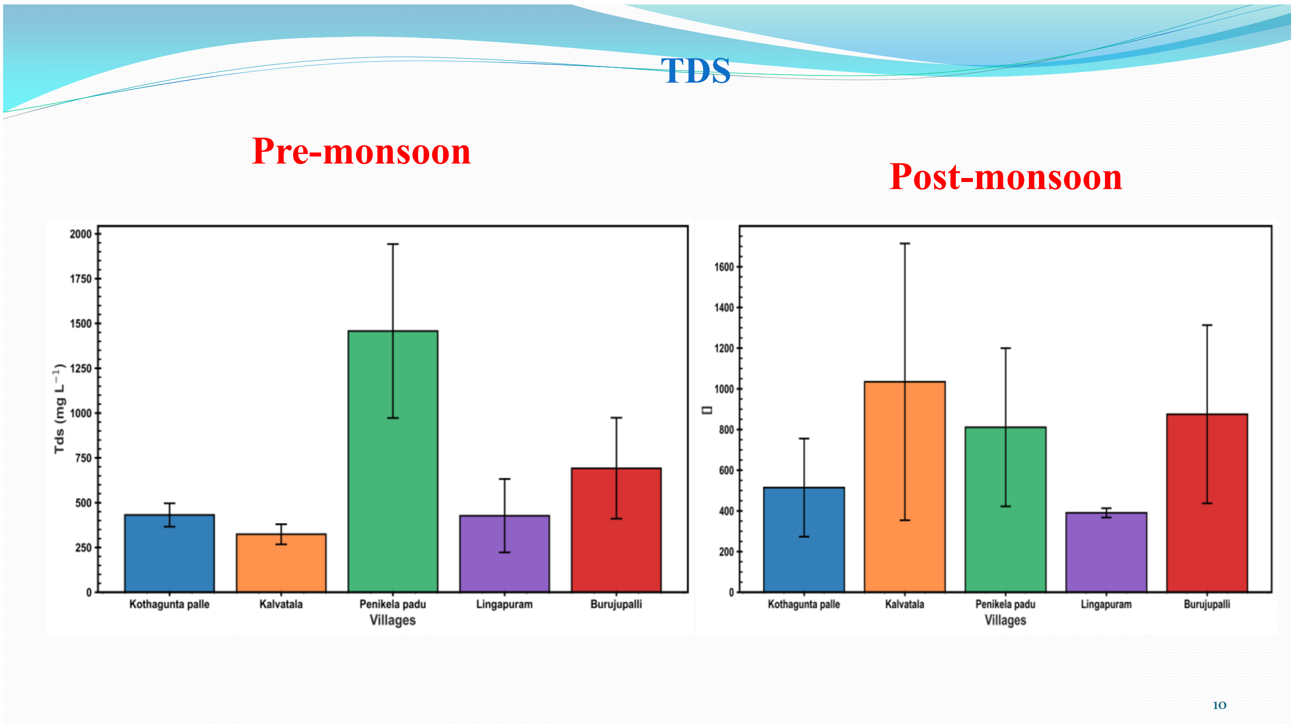

pH
Pre-monsoon
Post-monsoon
pH)
pH (mg L⁻¹)
Kothagunta palle
Kalvatala
Penikela padu
Lingapuram
Burujupalli
Villages
8


Nitrate
Pre-monsoon
Post-monsoon
Nitrate (mg L⁻¹)
Total Hardness
Pre-monsoon
Post-monsoon
Nitrate
Kothagunta palle
Kalvatala
Penikela padu
Lingapuram
Burujupalli
Villages
Kothagunta palle (Jammalamadugu)
Kalvatala (Peddamudium)
Penikela padu (Muddanur)
Lingapuram (Mylavaram)
Burujupalli (Kondapuram)
Villages
11

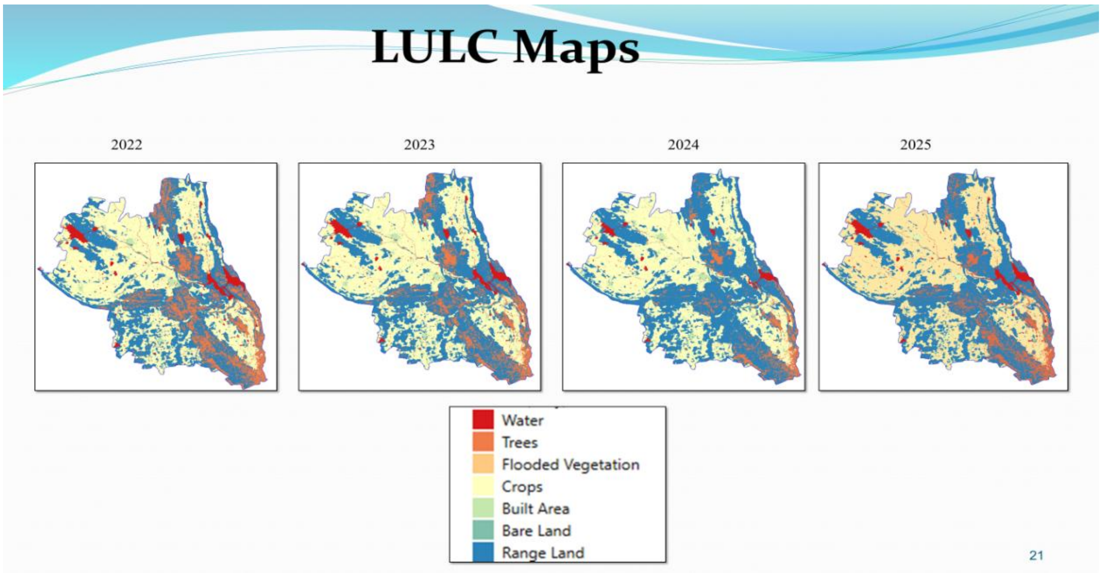

Iron
Pre-monsoon
Post-monsoon
Iron (mg L⁻¹)
Kothagunta palle
Kalvatala
Penikela padu
Lingapuram
Burujupalli
Villages
13





2.4 LULC mapping and temporal analysis

LULC maps were prepared for 2022, 2023, 2024 and 2025. The mapped classes included crops, rangeland, trees, water bodies, flooded vegetation, built-up land and bare land. The presentation used a primary axis for macro-landscape classes and a secondary axis for smaller classes so that localized transitions were not visually suppressed. The LULC statistics were then compared with groundwater quality patterns to explore possible landscape–water relationships.



3. RESULTS

3.1 Seasonal variability in groundwater quality

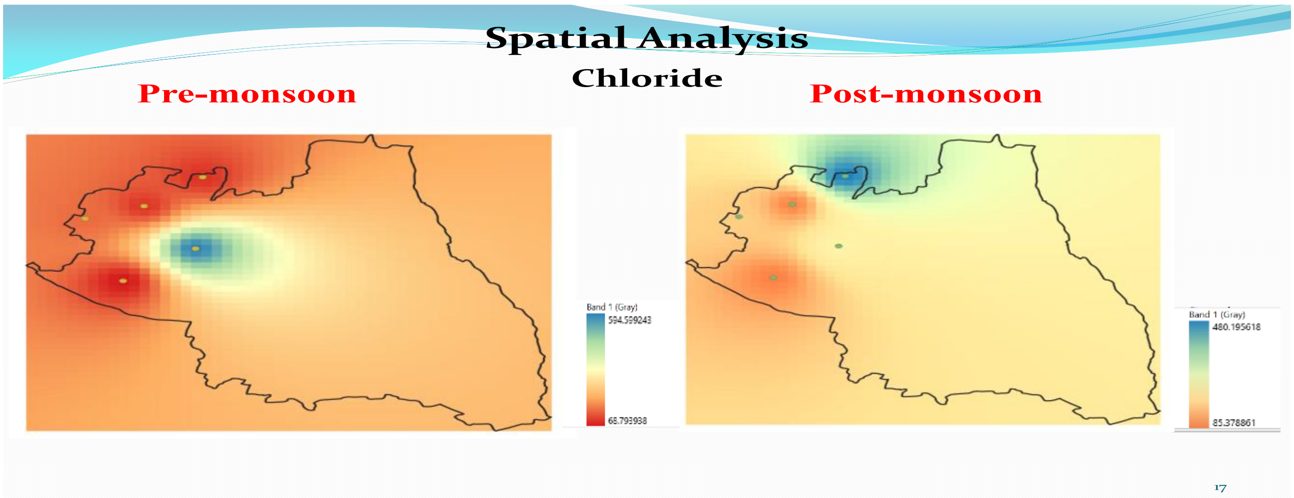
The groundwater plots demonstrate that the investigated physicochemical parameters vary between pre-monsoon and post-monsoon conditions. The seasonal comparison is most clearly expressed by fluoride. The presentation identifies migration of fluoride concentration zones between seasons, indicating that groundwater chemistry is spatially dynamic rather than controlled by a single uniform source across the basin.

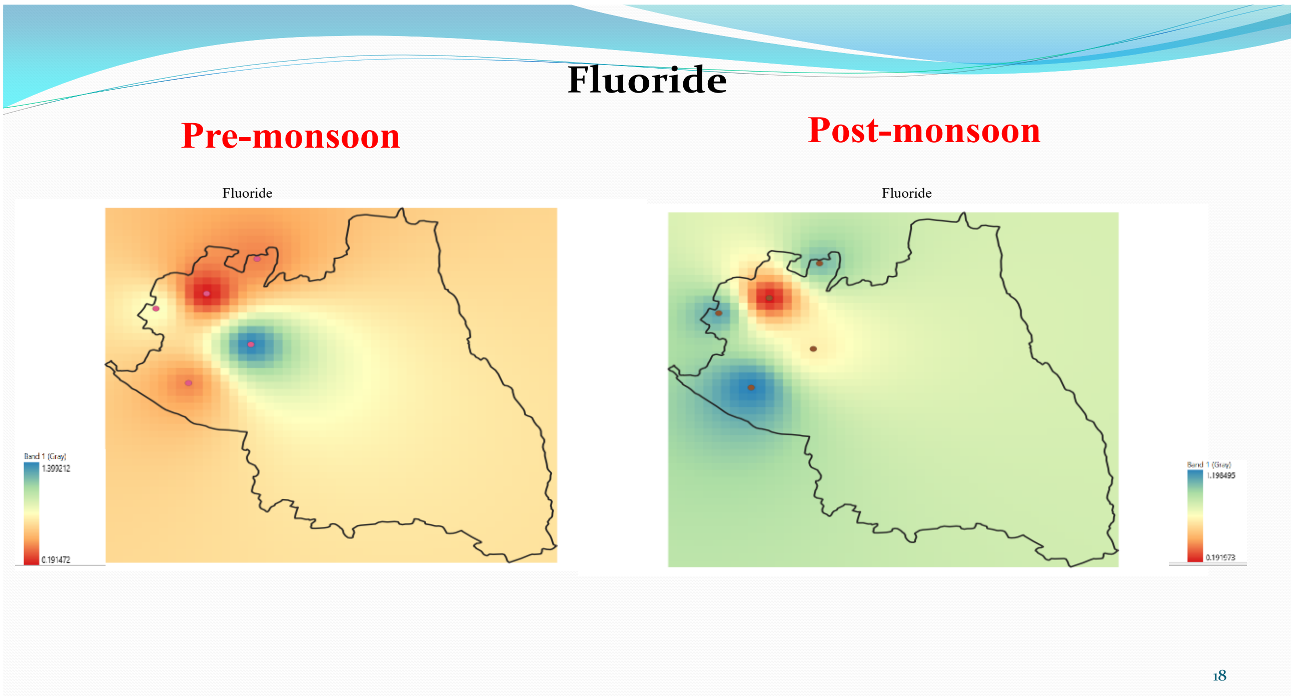
The pre-monsoon period is characterized in the study interpretation by lower groundwater levels and higher evaporation, conditions that can concentrate dissolved constituents. Following rainfall, recharge may dilute previously concentrated groundwater. At the same time, infiltrating water can interact with mineral-rich soil and rock and mobilize fluoride or other dissolved constituents. Thus, a reduction in concentration is not expected uniformly across the basin, and localized post-monsoon increases may occur where recharge enhances water–rock interaction.

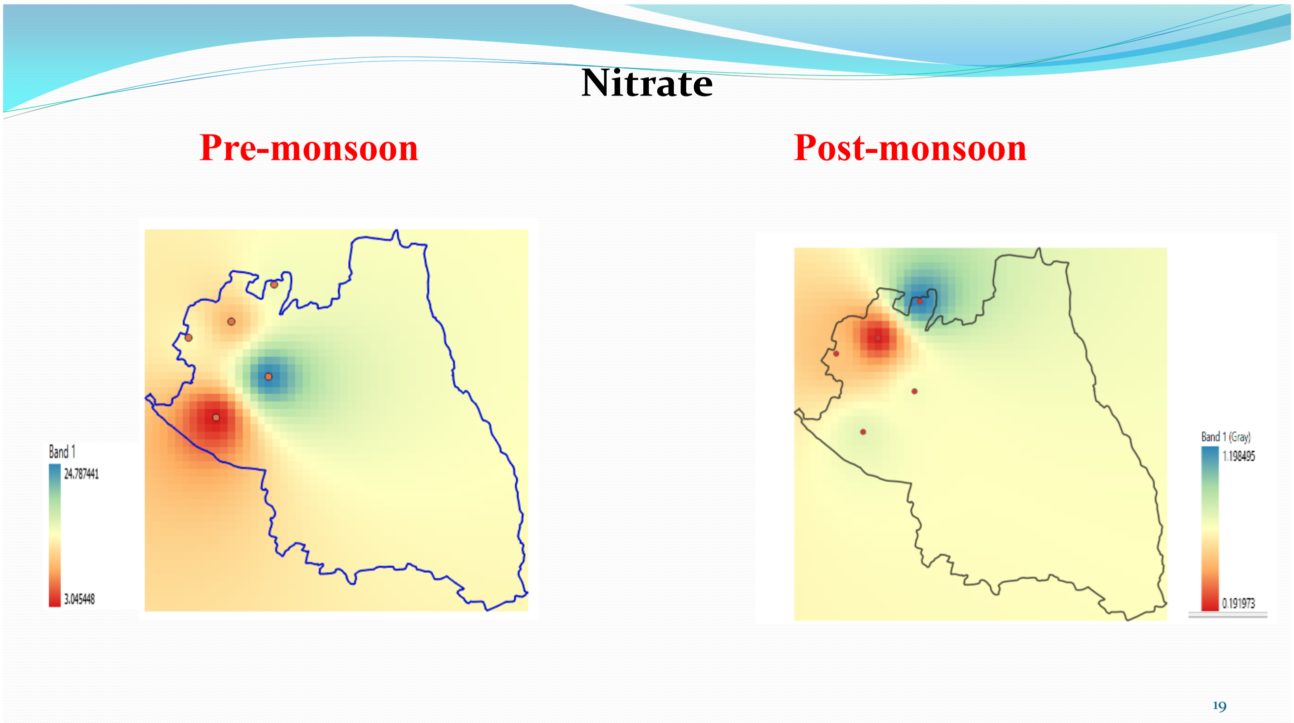
3.2 Spatial distribution of major parameters

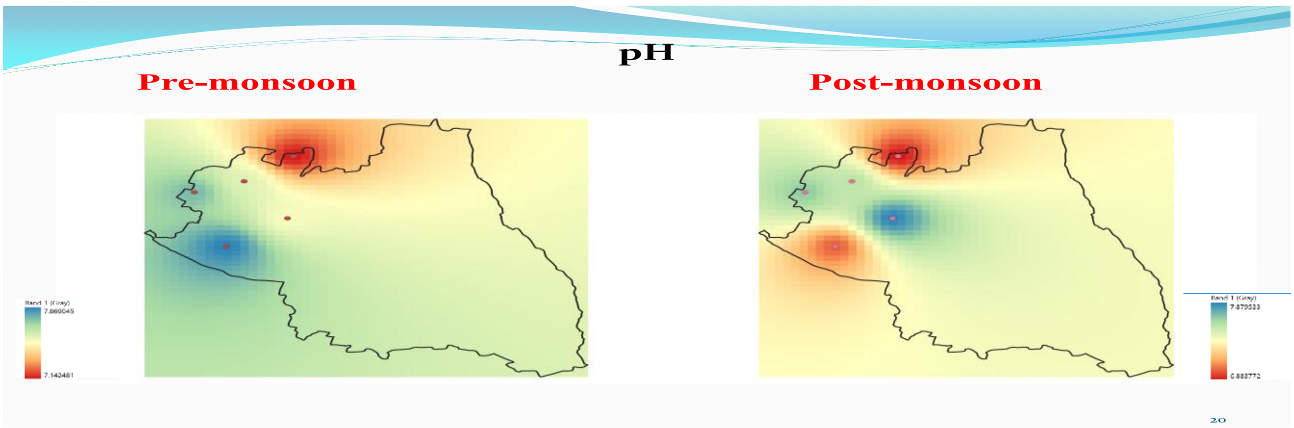
Spatial maps were prepared for chloride, fluoride, nitrate, pH, total alkalinity, total hardness and TDS for pre-monsoon and post-monsoon periods. The maps demonstrate spatial heterogeneity in groundwater chemistry and identify areas where concentrations differ from surrounding locations. The western portion of the study region is specifically identified in the presentation as a persistent high-concentration zone for fluoride and is therefore highlighted as a priority area for continued monitoring.

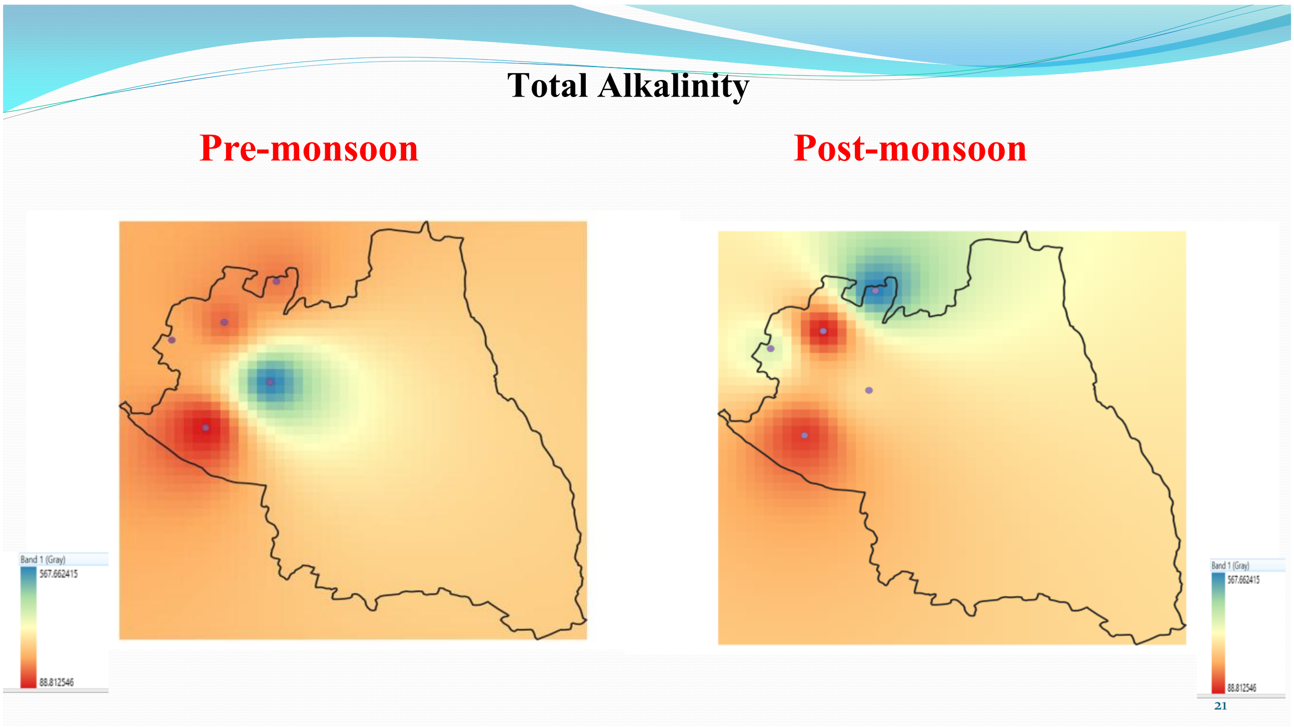
The spatial variation of chloride, nitrate, hardness and TDS indicates that groundwater mineralization and solute distribution are not spatially uniform. Such heterogeneity can result from differences in recharge, lithology, groundwater residence time, evaporation, agricultural activity and local land-use conditions. However, the supplied presentation does not report numerical correlation coefficients or statistical significance values, so causal attribution to any individual factor should be treated as a hypothesis for further testing.

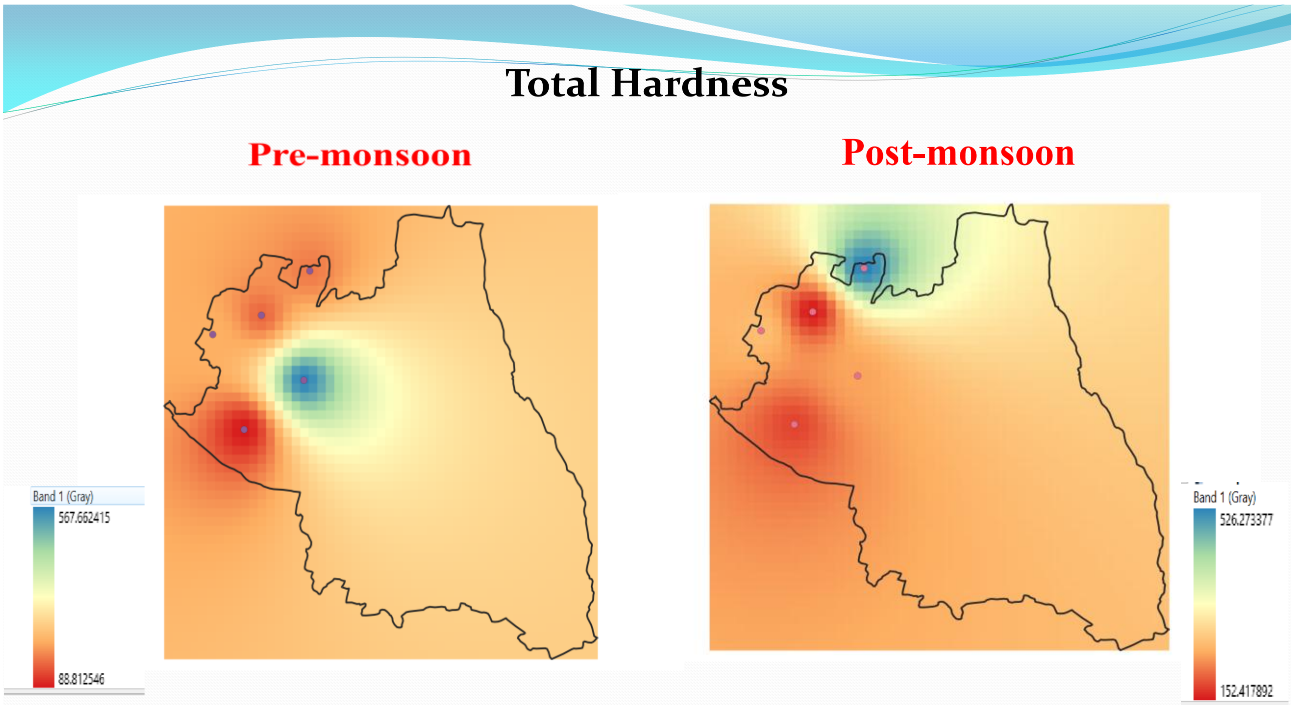


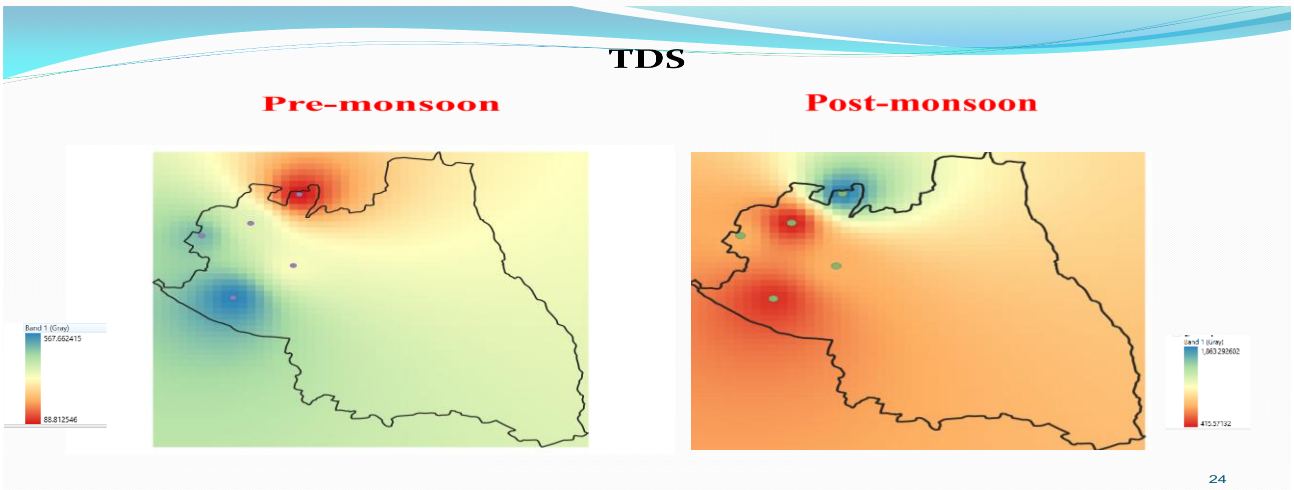

Fluoride
Pre-monsoon
Post-monsoon
Fluoride
Fluoride
18


Nitrate
Pre-monsoon
Post-monsoon
Band 1
24.787441
3.045448
Band 1 (Gray)
1.198495
0.191973
19


pH
Pre-monsoon
Post-monsoon
20


Total Alkalinity
Pre-monsoon
Post-monsoon
Band 1 (Gray)
567.662415
88.812546
Band 1 (Gray)
567.662415
88.812546
21


Total Hardness
Pre-monsoon
Post-monsoon
Band 1 (Gray)
567.662415
88.812546
Band 1 (Gray)
526.273377
152.417892


TDS
Pre-monsoon
Post-monsoon
Band 1 (Gray)
567.662415
88.812546
24

3.3 Temporal LULC dynamics, 2022–2025

LULC class	2022	2023	2024	2025
Cropland	~43%	~43%	~47.5%	~44.2%
Rangeland	~32%	~35%	~39%	~37%
Tree cover	~25%	Intermediate	Intermediate	~20%
Flooded vegetation	~15%	~15%	~12%	~12%
Water bodies	~11–14%	slight increase	within reported range	slight increase
Built-up land	~12%	slight decline	slight decline	~10%
Bare land	~10%	near stable	near stable	~10%

Cropland remained the dominant land-cover class throughout the mapped period, exceeding 43% in each year. Cropland increased to approximately 47.5% in 2024 before declining slightly to about 44.2% in 2025. Rangeland increased from approximately 32% in 2022 to 35% in 2023 and 39% in 2024, followed by a modest reduction to approximately 37% in 2025. Tree cover decreased from about 25% in 2022 to about 20% in 2025, while flooded vegetation declined from approximately 15% in 2022–2023 to about 12% in 2024–2025.

Water bodies fluctuated within approximately 11–14%, with slightly larger mapped extents in 2023 and 2025. Built-up land showed a small decline from about 12% to 10%, indicating that large-scale urban expansion was not the dominant landscape transition. Bare land remained close to 10% with limited temporal change. Overall, the LULC results point to a transition involving declining tree and flooded-vegetation cover and increasing rangeland and agricultural dominance.

3.4 LULC–groundwater quality relationship

The study framework explicitly examined relationships between LULC maps and groundwater-quality parameters. The combined spatial evidence suggests that land-cover change should be considered when interpreting groundwater chemistry, particularly in agricultural areas and locations where vegetation cover has declined. Increased agricultural dominance may alter recharge quality through nutrient inputs and irrigation return flow, while declining vegetation can change infiltration, runoff and soil moisture dynamics.

At the same time, the available presentation does not contain the numerical correlation matrix, regression coefficients or significance levels needed to establish a statistically demonstrated LULC–water-quality relationship. Accordingly, the present manuscript treats the observed association as spatial evidence rather than proof of causation. The underlying GIS and laboratory datasets should be used to calculate Pearson/Spearman correlations or other appropriate spatial-statistical measures before final journal submission.

4. DISCUSSION

4.1 Hydrochemical seasonality

Seasonality is a central feature of groundwater chemistry in semi-arid basins. During the pre-monsoon period, reduced recharge and strong evaporation can increase solute concentrations in shallow and moderately recharged groundwater. Post-monsoon recharge can have two contrasting effects: dilution of previously concentrated groundwater and enhanced mineral dissolution. The fluoride results in this study illustrate this dual mechanism, because the spatial high-concentration zones shift rather than simply disappear after the monsoon.

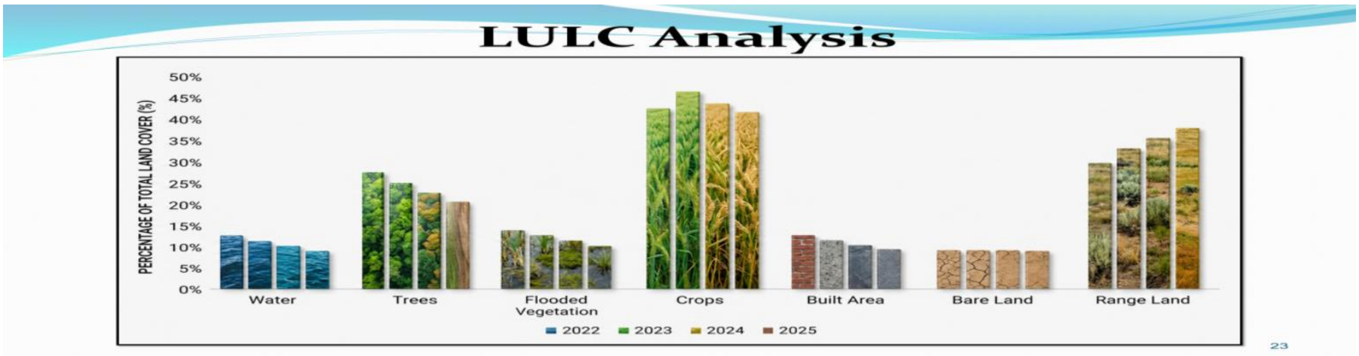
This interpretation is consistent with the broader principle that drinking-water quality should be evaluated using catchment-to-consumer risk management and continued surveillance rather than relying on a single sampling event. WHO guidance emphasizes protection of public health through systematic management of drinking-water hazards and updated health-based guidance. □cite□turn0search0□

4.2 Fluoride as a priority monitoring parameter

Among the assessed parameters, fluoride deserves particular attention because the presentation identifies persistent high-concentration zones in the western part of the study area and notes the potential for dental and skeletal fluorosis when elevated-fluoride water is consumed over long periods. The observed seasonal migration of fluoride zones indicates that monitoring programs should not rely only on a fixed annual sampling date. Repeated sampling before and after the monsoon can help distinguish concentration effects from recharge and mineral-leaching effects.

4.3 Agricultural and vegetation change

The LULC results show that agriculture remained the dominant land use, while rangeland expanded and tree and flooded-vegetation classes declined. This pattern is important from a watershed-management perspective because changes in vegetation and cultivation can modify infiltration, runoff, evapotranspiration and the pathways by which dissolved constituents reach groundwater. The comparatively stable built-up and bare-land classes suggest that the dominant landscape pressure during 2022–2025 was associated more with vegetation/agricultural dynamics than with rapid urbanization.



4.4 Implications for groundwater management

The study supports a targeted rather than uniform monitoring strategy. Priority should be given to locations identified by spatial mapping as having elevated fluoride or other dissolved-solute concentrations, especially where such hotspots persist across seasons. Agricultural zones should also be monitored because fertilizer application, irrigation practices and return flow may influence nitrate and overall mineralization. Protection of remaining tree and flooded-vegetation areas may contribute to maintaining watershed functions and recharge quality.

Relations b/w LULC vs Quality Parameters

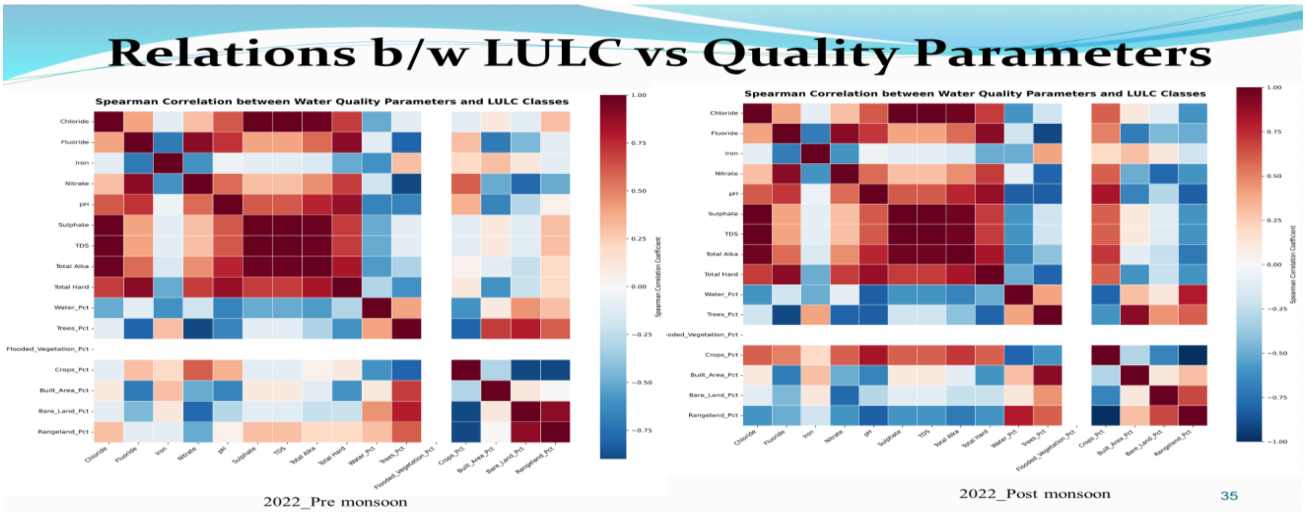
2022_Pre monsoon

Village	Chloride	Fluoride	Iron	Nitrate	pH	Sulphate	TDS	Total Alka	Total Hard	Water_pct	Trees_Pct	Flooded_Vegetation_Pct	Crops_Pct	Built_Area_Pct	Bare_Land_Pct	Rangeland_Pct
Kothagunta palle	93	0.48	0.19	5.8	7.35	33	474	200	120	0.08	0.73	0	78.85	5.63	0.005	14.68
Kalvatala	42	0.49	0.08	12.3	7.23	12	259	132	80	3.64	0.01	0	91.14	5.19	0	0
Penikela padu	397	0.71	0.017	18.8	7.58	92	1748	400	572	2.42	0.002	0	87.07	1.62	0	8.89
lingapuram	65	0.5	0.07	7.5	7.35	24	322	148	132	4.39	0.36	0	3.85	0.67	1.37	89.33
Burujupalli	85	0.53	0.1	18.7	7.71	30	408	200	180	0	0	0	95.73	0.57	0	3.68

2022_Post monsoon

Village	Chloride	Fluoride	Iron	Nitrate	pH	Sulphate	TDS	Total Alka	Total Hard	Water_Pct	Trees_Pct	Flooded_Vegetation_Pct	Crops_Pct	Built_Area_Pct	Bare_Land_Pct	Rangeland_Pct
Kothagunta palle	93	0.48	0.19	5.8	7.35	33	474	200	120	0.08	0.73	0	78.85	5.63	0.005	14.68
Kalvatala	42	0.49	0.08	12.3	7.23	12	259	132	80	8.23	0.64	0	14.85	2.28	0	73.98
Penikela padu	397	0.71	0.017	18.8	7.58	92	1748	400	572	2.42	0.002	0	87.07	1.61	0	8.87
lingapuram	65	0.5	0.07	7.5	7.35	24	322	148	132	4.42	0.36	0	3.87	0.66	1.37	89.30
Burujupalli	85	0.53	0.1	18.7	7.71	30	408	200	180	0	0	0	95.73	0.57	0	3.68

34



Relations b/w LULC vs Quality Parameters

2023_Pre monsoon

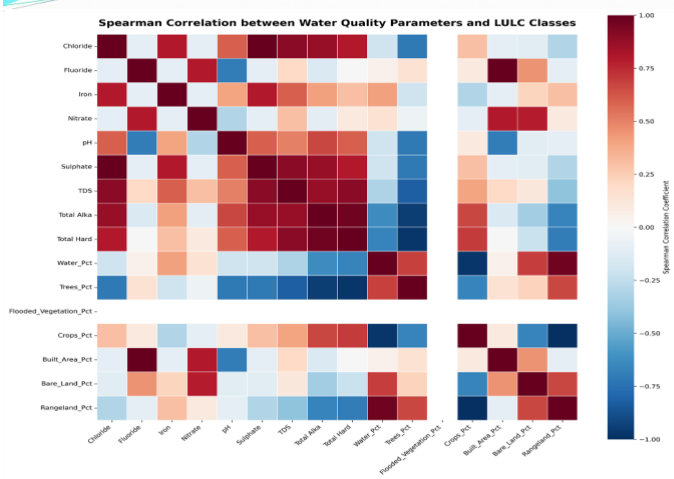
Village	Chloride	Fluoride	Iron	Nitrate	pH	Sulphate	TDS	Total Alka	Total Hard	Water_Pct	Trees_Pct	Flooded_Vegetation_Pct	Crops_Pct	Built_Area_Pct	Bare_Land_Pct	Rangeland_Pct
Kothagunta palle	40	0.86	0.04	26.8	7.05	10	471	140	192	0.08	1.22	0	81.53	5.87	0.01	11.26
Kalvatala	45	0.37	0.08	0.2	7.32	22	312	140	120	0.63	1.56	0	55.01	1.27	0	41.51
Penikela padu	397	0.71	0.17	18.8	7.58	92	1748	400	572	0	0	0	97.47	2.24	0	0.28
lingapuram	241	0.39	0.2	23.2	7.7	67	780	280	208	4.11	0.43	0	3.34	2.06	0.79	89.24
Burujupalli	142	0.32	0.07	16.4	7.88	60	774	288	228	0	0	0	95.05	0.56	0	4.37

2023_Post monsoon

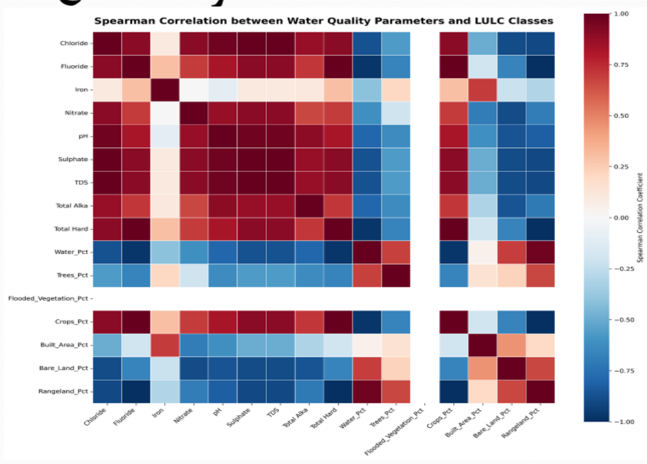
Village	Chloride	Fluoride	Iron	Nitrate	pH	Sulphate	TDS	Total Alka	Total Hard	Water_Pct	Trees_Pct	Flooded_Vegetation_Pct	Crops_Pct	Built_Area_Pct	Bare_Land_Pct	Rangeland_Pct
Kothagunta palle	155	0.49	0.8	16.6	7.55	31	422	200	188	0.08	1.22	0	81.53	5.87	0.01	11.26
Kalvatala	176	0.48	0.16	22.4	7.65	69	914	212	160	0.67	1.25	0	60.26	1.36	0	36.45
Penikela padu	283	1	0.19	19.2	7.81	77	1361	400	392	0	0	0	91.77	2.09	0	6.13
lingapuram	37	0.17	0.11	13.8	7.55	25	355	200	120	4.63	0.43	0	3.46	1.60	0.79052	89.07
Burujupalli	354	1.16	0.12	35.9	8	102	1509	380	432	0	0	0	95.0309	0.56	0	4.40

37

Relations b/w LULC vs Quality Parameters



2023_Pre monsoon



2023_Post monsoon

38

Relations b/w LULC vs Quality Parameters

2024_Pre monsoon

Village	Chloride	Fluoride	Iron	Nitrate	pH	Sulphate	TDS	Total Alka	Total Hard	Water_Pct	Trees_Pct	Flooded_Vegetation_Pct	Crops_Pct	Built_Area_Pct	Bare_Land_Pct	Rangeland_Pct
Kothagunta palle	62	1.18	0.11	16.6	7.42	36	479	188	164	0.13	1.68	0	75.84	6.14	0.007	16.18
Kalvatala	59	0.23	0.03	5.8	6.8	23	306	120	92	0.112	0.12	0	15.99	1.92	0.003	81.84
Penikela padu	198	0.6	0.08	22.5	8.15	80	1056	396	200	0.06	0	0	89.45	1.86	0	8.60
lingapuram	82	1.15	0.02	5.3	7.69	8	358	148	116	1.22	0.02	0	3.30	0.73	2.35	92.35
Burujupalli	85	0.44	0.03	12.4	8.03	48	544	224	208	0	0	0	84.64	0.58	0	14.76

2024_Post monsoon

Village	Chloride	Fluoride	Iron	Nitrate	pH	Sulphate	TDS	Total Alka	Total Hard	Water_Pct	Trees_Pct	Flooded_Vegetation_Pct	Crops_Pct	Built_Area_Pct	Bare_Land_Pct	Rangeland_Pct
Kothagunta palle	56	0.083	0.06	4.1	8.31	34	492	360	80	0.13	1.68	0	75.84	6.14	0.007	16.18
Kalvatala	425	0.51	0.12	17.9	6.8	125	1529	472	340	0.57	0.06	0	59.13	1.25	0	38.96
Penikela padu	170	0.6	0.06	30.2	8	41	262	112	124	0.06	0	0	89.45	1.86	0	8.60
lingapuram	85	0.52	0.03	18.4	7.47	19	383	140	100	1.22	0.02	0	3.30	0.73	2.353487	92.35
Burujupalli	51	0.2	0.1	14.1	8.11	41	277	124	136	0	0	0	84.64	0.58	0	14.76

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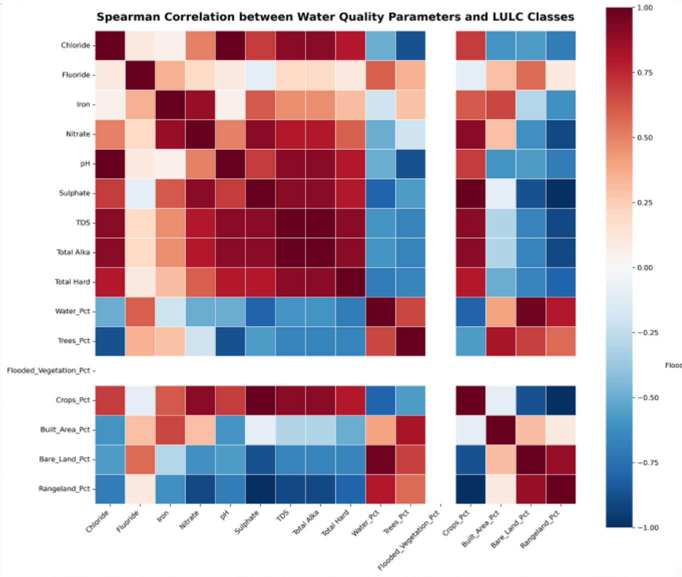
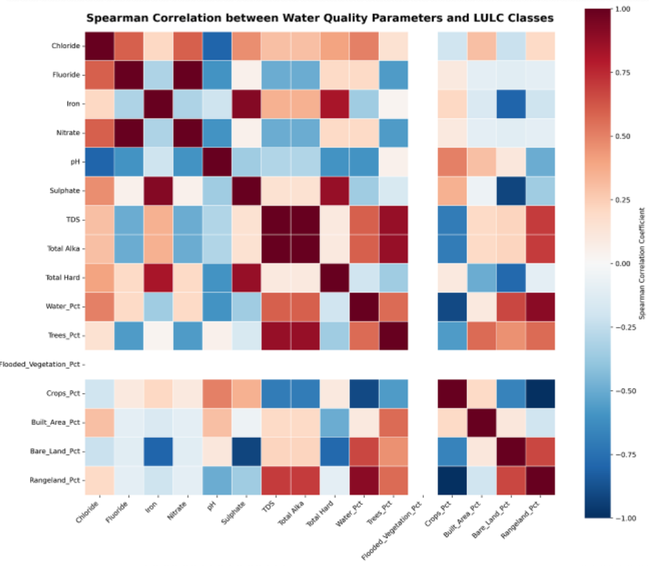
Relations b/w LULC vs Quality Parameters



2024_Pre monsoon



2024_Post monsoon

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Relations b/w LULC vs Quality Parameters

2025_Pre monsoon

Village	Chloride	Fluoride	Iron	Nitrate	pH	Sulphate	TDS	Total Alka	Total Hard	Water_Pct	Trees_Pct	Flooded_Vegetation_Pct	Crops_Pct	Built_Area_Pct	Bare_Land_Pct	Rangeland_Pct
Kothagunta palle	68	0.42	0.03	3	7.87	22	404	176	88	0.11	1.38	0	77.73	6.70	0.01	14.04
Kalvatala	91	0.41	0.08	14.8	7.14	41	413	192	168	3.59	0.00	0	90.54	5.85	0	0
Penikela padu	595	1.4	0.05	24.8	7.52	280	1941	580	568	0.07	0	0	87.31	1.83	0	10.77
lingapuram	93	0.19	0.3	9.4	7.58	47	414	168	152	4.71	0.15	0	7.21	0.85	0.57	86.48
Burujupalli	142	0.82	0.07	13.5	7.76	58	596	280	212	0	0	0	85.20	0.54	0	14.25

2025_Post monsoon

Village	Chloride	Fluoride	Iron	Nitrate	pH	Sulphate	TDS	Total Alka	Total Hard	Water_Pct	Trees_Pct	Flooded_Vegetation_Pct	Crops_Pct	Built_Area_Pct	Bare_Land_Pct	Rangeland_Pct
Kothagunta palle	56	0.083	0.06	4.1	8.31	34	492	360	80	0.11	1.38	0	77.73	6.70	0.01	14.04
Kalvatala	425	0.51	0.12	17.9	6.8	125	1529	472	340	0.81	2.07	0	18.13	1.31	0.005	77.65
Penikela padu	170	0.6	0.06	30.2	8	41	262	112	124	0.07	0	0	87.31	1.83	0	10.77
lingapuram	85	0.52	0.03	18.4	7.47	19	383	140	100	4.74	0.15	0	7.24	0.83	0.57	86.43
Burujupalli	51	0.2	0.1	14.1	8.11	41	277	124	136	0	0	0	85.20	0.54	0	14.25

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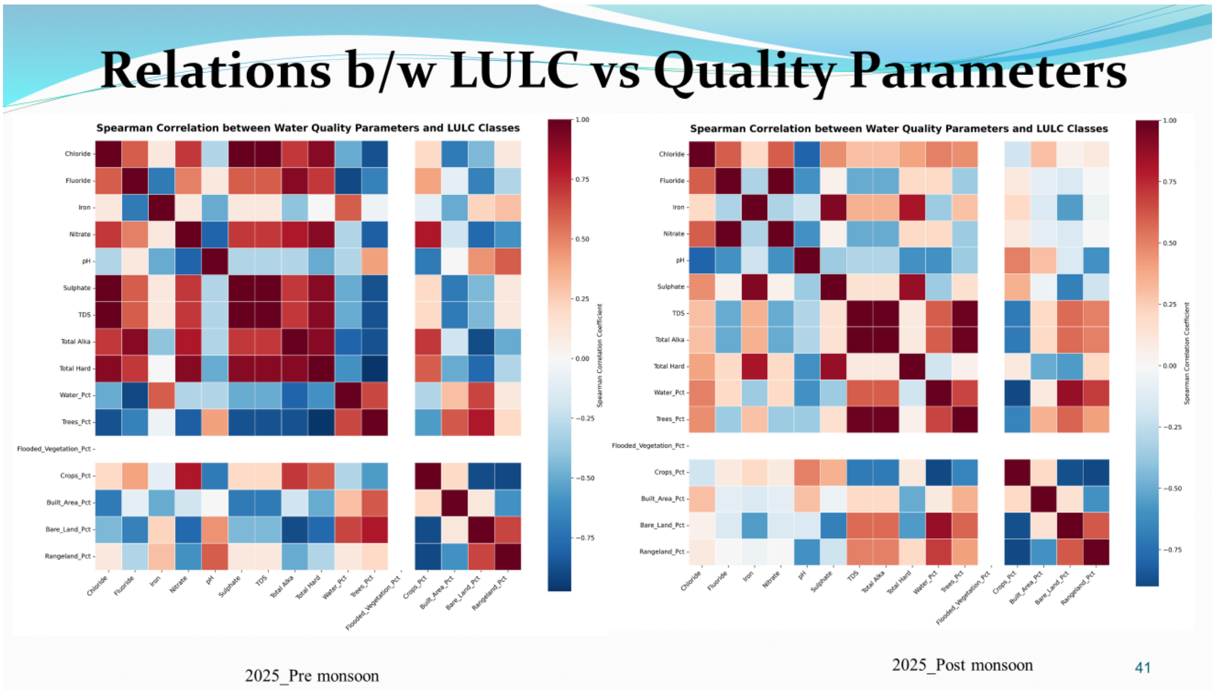

5.CONCLUSIONS

This study presents an integrated assessment of groundwater quality dynamics and land use/land cover (LULC) changes in the Penna River Sub-Basin of YSR Kadapa District, Andhra Pradesh, India, using hydrochemical analysis, GIS-based spatial interpolation, and LULC evaluation. Groundwater quality data collected during pre-monsoon and post-monsoon seasons between 2022 and 2026 reveal substantial spatial and temporal variability among the selected villages.

Groundwater in the study area is generally characterized by neutral to slightly alkaline conditions. However, significant variations were observed in chloride, nitrate, sulphate, total dissolved solids (TDS), alkalinity, and hardness concentrations. Among the monitored locations, Penikela Padu consistently exhibited elevated concentrations of chloride, TDS, sulphate, alkalinity, and hardness, indicating intensive mineralization processes and potential anthropogenic influences. Fluoride concentrations remained largely within permissible limits, although localized enrichment was observed in certain seasons, suggesting geogenic contributions from fluoride-bearing minerals within the aquifer matrix.

Spatial interpolation using the Inverse Distance Weighting (IDW) technique successfully identified contamination hotspots and revealed distinct seasonal shifts in groundwater quality patterns. Pre-monsoon conditions generally exhibited higher concentrations of dissolved constituents due to evaporation and reduced recharge, whereas post-monsoon groundwater quality reflected dilution effects and enhanced groundwater recharge.

The LULC analysis conducted between 2022 and 2025 revealed significant landscape transformation within the basin. Cropland remained the dominant land-use category, while rangeland expanded considerably at the expense of tree cover and flooded vegetation. These changes indicate increasing anthropogenic pressure on the watershed and highlight the growing influence of agricultural activities on environmental processes

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