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ASSESSING SPATIOTEMPORAL VARIABILITY OF MICRONUTRIENTS UNDER CHANGING HYDROCLIMATIC CONDITIONS IN THE TAMIRAPARANI RIVER BASIN, SOUTHERN TAMIL NADU

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ABSTRACT
The Tamiraparani river is the only perennial river in Tamil Nadu and serves as the vital lifeline for the southern districts of Tirunelveli, Thoothukudi, and parts of Virudhunagar, ensuring water security in a largely arid region. Originating in the Pothigai hills, it sustains agricultural, domestic and industrial needs, along with rich biodiversity. The present study investigates the temporal and geographical variability of micronutrient concentrations in surface and groundwater of Tamiraparani River watershed. Fourteen sites were chosen for collection of groundwater samples (n = 84) between November 2020 and February 2021, while sixteen locations were chosen for collection of river water samples (n = 96) between November 2021 and February 2022. The micronutrient level and adherence to drinking water standards were evaluated by analysing each sample. The findings show that micronutrient concentrations at every sampling location stayed within the World Health Organization in its acceptable bounds. In all research periods, temporal oscillations were more noticeable than geographical differences, according to variability analysis. In contrast to 2021, a relatively less degree of volatility was noted in 2022. Increased rainfall in 2022 is thought to have improved dilution and homogeneity of micronutrient concentrations throughout the basin, which is because there was less fluctuation. Furthermore, uniform micronutrient levels were found in the upstream, middle and downstream sectors, suggesting that localized pollution impacts were negligible. Overall, the results indicate that seasonal hydrological processes, rather than geographical variability are the key factors influencing the water quality in the basin, typically stays within reasonable limits. This study emphasizes the function of rainfall in controlling water quality in riverine systems and offers baseline insights on micronutrient dynamics.

KEYWORDS: Hydrochemistry; Groundwater; Spatial variability; Micronutrients; Seasonality.

1. INTRODUCTION

Human health, agricultural production and ecological integrity all depend heavily on water quality (Allan et al., 2021; Falkenmark & Rockström, 2006). River systems are dynamic biogeochemical reactors in which human inputs, hydrological processes and geochemical interactions control the distribution of micronutrients (Meybeck, 2003; Palmer et al., 2014). Micronutrient dynamics in riverine ecosystems have received more attention because of their dual function as necessary nutrients and possible pollutants at high concentrations (Alloway, 2013; Schwarzenbach et al., 2010). The Tamiraparani River Basin is an essential freshwater resource for industrial, household and agricultural uses (Central Water Commission 2018; Matta et al., 2020). Its longitudinal gradient, which stretches from densely populated downstream areas to agriculturally intensive midstream zones and upstream forested regions, offers a perfect natural system for examining spatial heterogeneity in micronutrient distribution (Vörösmarty et al., 2010; Meybeck & Helmer, 1989). Trace element concentrations along such river continua are greatly influenced by variations in land use, agricultural runoff and localized anthropogenic pressures (Tilman et al., 2001; Carpenter et al., 1998). Iron (Fe), zinc (Zn), copper (Cu) and manganese (Mn) are examples of micronutrients that exist in a variety of physicochemical forms controlled by pH, redox potential and interactions with dissolved organic matter (Stumm & Morgan, 1996; Tipping, 2002). These components are extremely vulnerable to hydrological variability, such as seasonal variations in flow and dilution processes caused by rainfall (Neal et al., 2006; Jarvie et al., 2020). In order to identify governing mechanisms and possible zones of accumulation or depletion, it is necessary to simultaneously examine geographical and temporal variability (Riedel et al., 2000; Sileika et al., 2006). High-resolution temporal monitoring in conjunction with geographically stratified sample is still restricted for micronutrient evaluation, despite a great deal of research on river water quality in India (Singh et al., 2004; Varol, 2011). By systematically evaluating micronutrient dynamics across many fortnights in several hydrological zones of the Tamiraparani River Basin, the current study closes this gap. Quantifying spatial-temporal variability, identifying main hydrogeochemical controls and evaluating adherence to global drinking water standards set by the World Health Organization are the goals (WHO, 2017).

2. MATERIAL AND METHODS

2.1 Study area and sampling design

The investigation was carried out along the longitudinal continuum of the Tamiraparani River Basin, a perennial river system with significant regional variability brought about by anthropogenic influence, terrain and changes in land use. Sixteen georeferenced sample sites were methodically created throughout upstream, middle and downstream reaches to capture this diversity. These sites represented heavily inhabited lower portions, intensively farmed agricultural zones and headwaters covered by forests, respectively. In order to provide thorough geographical coverage of the basin, the sample domain spanned 8°37.557′–8°42.270′ N latitude and 77°21.789′–78°04.133′ E longitude. Sampling was done at 15-day intervals from November to February over two consecutive hydrological periods (2020–2021 and 2021–2022) as part of a high-frequency temporal monitoring approach. The resolution of fine-scale temporal variability linked to seasonal hydrological processes, such as flow variations and dilution caused by rainfall, was made possible by this approach.

Details of Water Sampling sites

S. No.	Part of the river	Sampling sites	Name of the sampling sites	Geo- Coordinates	
				Latitude ° N	Longitude ° E
1.	Upstream	Site 1	Agasthiyar falls	8º42.270’	77º21.789’
2.		Site 2	Vickramasingapuram	8º42.560’	77º22.672’
3.		Site 3	Kannadiyan anaicut	8º41.087’	77º26.265’
4.		Site 4	Ambasamudram	8º41.730’	77º27.442’
5.		Site 5	Cheranmahadevi	8º42.116’	77º33.951’
6.	Midstream	Site 6	Suthamalli	8º41.175’	77º38.666’
7.		Site 7	Kurukuthurai	8º42.976’	77º41.956’
8.		Site 8	Tirunelveli	8º43.489’	77º42.603’
9.		Site 9	Vellakovil	8º44.818’	77º43.713’
10.		Site 10	Manapadai Veedu	8º46.628’	77º45.914’
11.		Site 11	Sivalaperi	8º46.863’	77º48.594’
12.	Downstream	Site 12	Maruthur anaicut	8º45.503’	77º49.104’
13.		Site 13	Karungulam	8º38.927’	77º51.380’
14.		Site 14	Sriviakundam	8º37.623’	77º54.725’
15.		Site 15	Eral	8º37.274’	78º01.159’
16.		Site 16	Authoor	8º37.557’	78º04.133’

2.2 Sample Collection and Processing

During the 2021–2022 monitoring period, 96 surface water samples were taken to ensure temporal consistency, each sampling session included all sixteen sites. To enable comparative analysis of longitudinal gradients in micronutrient distribution, the sites were divided into upstream (n = 5), midstream (n = 8), and downstream (n = 3) segments. To reduce contamination hazards and guarantee representativeness of in situ conditions, sampling was carried out using pre-cleaned, polyethylene containers in accordance with conventional methods. No chemical preservatives were used in order to maintain the dissolved original chemical makeup of micronutrients. In order to minimize the possibility of physicochemical changes like adsorption, precipitation or redox modification during storage, samples were transported under controlled circumstances to the laboratory as soon as they were collected and processed right away.

2.3 Methods of Analysis

Atomic Absorption Spectrophotometry (AAS), a highly sensitive and selective analytical method frequently used for trace metal measurement in aqueous systems, was used to assess the amounts of iron (Fe), zinc (Zn), copper (Cu) and manganese (Mn). To precisely depict dissolved micronutrient fractions and prevent pre-treatment artifacts, direct analysis of unfiltered samples was carried out. To guarantee linearity and accuracy, the instrument was calibrated using certified multi-element reference solutions throughout suitable concentration ranges. Reagent blanks, duplicate samples, and standard reference materials were analysed as part of quality assurance and quality control (QA/QC) processes to confirm analytical accuracy and repeatability. Robust measurement of micronutrient concentrations appropriate for later statistical and spatial-temporal analysis was guaranteed by the overall methodological approach.

3. RESULTS AND DISCUSSION

3.1 Spatial Distribution of Micronutrients

Strong geochemical gradients controlled by hydrological location and environmental factors were found in the geographical distribution of micronutrients in the Tamiraparani River Basin (Table 1). With increased concentrations seen in upstream areas like Ambasamudram, iron (Fe) showed the greatest fluctuation (10.39–14.41 ppm), suggesting significant lithogenic inputs through mineral weathering and no human interference (Stumm & Morgan, 1996; Meybeck, 2003). On the other hand, lower Fe levels in midstream zones like Tirunelveli indicate sedimentation, dilution, and potential adsorption onto suspended particles during downstream transport (Neal et al., 2006; Reddy & DeLaune, 2008). Zinc (Zn) showed moderate geographic heterogeneity, increasing gradually in downstream areas and peaking at Authoor (up to 1.43 ppm). This tendency is in line with trends observed in heavily used river basins (Alloway, 2013; Carpenter et al., 1998) and represents cumulative human inputs, such as home effluents and agricultural runoff. Particularly in Cheranmahadevi (1.68 ppm), copper (Cu) displayed localized enrichment, suggesting site-specific inputs and increased

mobility under advantageous physicochemical circumstances such complexation with dissolved organic matter (Tipping, 2002; Schwarzenbach et al., 2010). Manganese (Mn) showed very small fluctuation (0.10–0.42 ppm), indicating robust geochemical control. According to Davison (1981) and Stumm & Morgan (1996), its distribution is mainly regulated by redox buffering and equilibrium between dissolved and particulate phases, leading to comparatively consistent concentrations across the basin.

3.2 Temporal Variability and Fortnight Dynamics

Significant hydrological modulation of river chemistry was shown by the temporal evaluation over six fortnights (S1–S6), which showed notable variations in micronutrient contents. The third sampling interval (S3) consistently showed peak concentrations of Fe, Zn, Cu and Mn (Table 2), indicating accumulation under reduced flow conditions and increased water residence time, which improves solute retention and metal mobilization (Abbott et al., 2018; Boyer et al., 2006; Seitzinger et al., 2010). Particularly in low discharge circumstances, these enrichment periods are frequently associated with restricted dilution and enhanced interactions between dissolved constituents and sediment matrix (House, 2003; Walling & Fang, 2003). Dilution effects linked to higher discharge and rainfall inputs are indicated by subsequent reductions at later periods (S4–S6). In order to lower dissolved metal concentrations and homogenize water chemistry, high-flow conditions encourage mixing and shorten solute residence times (Yu et al., 2019; Minaudo et al., 2019; Dupas et al., 2024). These findings demonstrate that localized geochemical heterogeneity in riverine nutrient dynamics may be superseded by hydrological forcing. Additionally, dynamic physicochemical processes that change in response to shifting flow regimes and environmental conditions, such as adsorption–desorption equilibria, sediment resuspension and redox-driven transformations, are reflected in temporal variability (Stumm & Morgan, 1996; Reddy & DeLaune, 2008).

3.3 Interannual Variability

When the two monitoring periods (2020–2021 and 2021–2022) were compared (Table 3), the latter showed a significant decrease in both temporal and geographical variability. Fe's spatial variability dropped from 62% to 32%, while its temporal variability dropped from 70% to 40%. Zn, Cu and Mn showed similar patterns. Increased precipitation in 2021–2022, which improved dilution and encouraged homogeneity of dissolved constituents, is blamed for this decrease. Increased discharge conditions reduce localized concentration gradients by promoting longitudinal and lateral mixing (Abbott et al., 2018; Zoboli et al., 2016; Costa et al., 2022). Thus, interannual variations in river water chemistry are mostly controlled by climate variability, especially rainfall intensity. These results are consistent with previous basin-scale research showing that under high-flow circumstances, hydrological variability controls nutrient transport and frequently obscures land-use-driven regional heterogeneity (Wang et al., 2025; Zhao et al., 2024; McCrackin et al., 2019).

3.4 Hydrogeochemical Controls

The micronutrient behaviour of Tamiraparani river is controlled by integrated hydrogeochemical processes that include organic complexation, adsorption mechanisms and redox reactions. Redox conditions have a significant impact on iron and manganese, which undergo oxidation-reduction processes that limit their solubility and phase partitioning. These metals precipitate as insoluble oxides in oxic settings, but they dissolve and move more readily in reducing environments (Davison, 1993; González-Santana et al., 2020; Sunda & Huntsman, 1994). On the other hand, Zinc and copper are more susceptible to complexation with dissolved organic matter and adsorption–desorption processes. In aquatic systems, these interactions have a major impact on their mobility, transport and bioavailability (Tipping, 2002; Sigg et al., 2000; Buffle & Leppard, 1995). Furthermore, in areas with a high sediment load, interaction with suspended particles is crucial for their downstream transit (Turner, 2004; Horowitz, 1991).

3.5 Evaluation of Water Quality

Every micronutrient content that was tested fell within the World Health Organization's acceptable standards for the quality of drinking water. Manganese levels were below the permissible range of 0.4 ppm, and copper concentrations (0.35–1.68 ppm) stayed below the 2.0 ppm threshold. Iron levels did not show serious contamination, while zinc values were much below the maximum permitted limit of 5 ppm. Significant natural buffering capability throughout the river system is suggested by the uniform compliance across upstream, midstream and downstream parts. On another aspect, localized Cu and Zn enrichment suggests possible human inputs, especially from home discharge and agricultural runoff (Fural et al., 2025; Zhang et al., 2019; Xiao et al., 2026).

3.6 Integrated Monitoring & Hydrology

The comprehensive evaluation shows that the distribution of micronutrients in the Tamiraparani River Basin is more affected by temporal variability than by geographical variability. While human inputs and localized geochemical conditions are reflected in regional variations, overall concentration patterns are dominated by temporal dynamics driven by hydrological variability. The decreased variability seen in the wetter year emphasizes how climate forcing controls the chemistry of river water. In order to capture quick changes in nutrient dynamics and enhance predictive knowledge of riverine systems, these results highlight the significance of high-frequency monitoring techniques (Blaen et al., 2016; Kirchner et al., 2023; Harvey & Gooseff, 2015).

4. CONCLUSION

The study shows that hydrological variability, geochemical processes and localized human effects are the main factors controlling micronutrient dynamics in the Tamiraparani river basin. Manganese was mostly constant because of redox buffering, zinc and copper displayed site-specific enrichment and iron demonstrated strong lithogenic control. Spatial heterogeneity was less influential than temporal changes, especially flow-dependent dilution and concentration effects. Higher rainfall periods showed less variability. Metal mobility and speciation are controlled by hydrogeochemical processes such redox transformations and organic complexation. All micronutrient concentrations stayed within acceptable bounds in spite of these variations, demonstrating an efficient natural buffering capacity. These results

emphasize how crucial coordinated watershed management and frequent monitoring are essential for maintaining river water quality in the face of shifting environmental conditions.

Table 1. Variations of Fe (ppm) and Zn (ppm) in Tamiraparani River water (2021-22)

S.No	Sampling sites	Fe (ppm)						Zn (ppm)					
		S1	S2	S3	S4	S5	S6	S1	S2	S3	S4	S5	S6
1.	Agasthiyar falls	13.34	13.43	13.73	13.21	13.44	13.49	0.55	0.63	0.83	0.41	0.48	0.54
2.	Vickramasingapuram	13.43	13.52	13.82	13.3	13.53	13.58	0.74	0.82	1.02	0.60	0.67	0.73
3.	Kannadiyan anaicut	13.52	13.61	13.91	13.39	13.62	13.67	0.86	0.94	1.14	0.72	0.79	0.85
4.	Ambasamudram	14.02	14.11	14.41	13.89	14.12	14.17	0.85	0.93	1.13	0.71	0.78	0.84
5.	Cheranmahadevi	12.78	12.87	13.17	12.65	12.88	12.93	0.76	0.84	1.04	0.62	0.69	0.75
6.	Suthamalli	12.84	12.93	13.23	12.71	12.91	12.96	0.66	0.74	0.94	0.52	0.59	0.65
7.	Kurukuthurai	12.89	12.98	13.28	12.76	12.96	13.01	0.55	0.63	0.83	0.41	0.47	0.51
8.	Tirunelveli	10.52	10.61	10.91	10.39	10.59	10.64	0.61	0.70	0.90	0.47	0.53	0.57
9.	Vellakovil	11.27	11.34	11.64	11.14	11.34	11.38	0.81	0.90	1.10	0.67	0.73	0.77
10.	Manapadai Veedu	11.56	11.63	11.93	11.43	11.63	11.67	0.76	0.85	1.05	0.62	0.68	0.72
11.	Sivalaperi	11.62	11.69	11.99	11.49	11.69	11.73	0.66	0.75	0.95	0.52	0.58	0.62
12.	Maruthur anaicut	11.97	12.04	12.34	11.84	12.04	12.08	0.81	0.90	1.10	0.67	0.73	0.77
13.	Karungulam	11.72	11.79	12.09	11.59	11.79	11.83	0.55	0.64	0.84	0.41	0.47	0.51
14.	Srivaikundam	11.66	11.73	12.03	11.53	11.73	11.77	0.61	0.70	0.90	0.47	0.53	0.57
15.	Eral	11.36	11.43	11.73	11.23	11.43	11.47	0.94	1.03	1.23	0.80	0.86	0.90
16.	Authoor	10.66	10.73	11.03	10.53	10.73	10.77	1.14	1.23	1.43	1.00	1.06	1.10
Min		10.52	10.61	10.91	10.39	10.59	10.64	0.55	0.63	0.83	0.41	0.47	0.51
Max		14.02	14.11	14.41	13.89	14.12	14.17	1.14	1.23	1.43	1.00	1.06	1.10
Mean		12.20	12.28	12.58	12.07	12.28	12.32	0.74	0.83	1.03	0.60	0.67	0.71

Table 2. Variations of Cu (ppm) and Mn (ppm) in Tamiraparani River water (2021-22)

S.No	Sampling sites	Cu (ppm)						Mn (ppm)					
		S1	S2	S3	S4	S5	S6	S1	S2	S3	S4	S5	S6
1.	Agasthiyar falls	0.59	0.69	0.93	0.46	0.52	0.59	0.15	0.17	0.23	0.12	0.13	0.15
2.	Vickramasingapuram	0.51	0.61	0.85	0.38	0.44	0.51	0.13	0.15	0.21	0.10	0.11	0.13
3.	Kannadiyan anaicut	0.89	0.99	1.23	0.76	0.82	0.89	0.22	0.25	0.31	0.19	0.21	0.22
4.	Ambasamudram	1.31	1.41	1.65	1.18	1.24	1.31	0.33	0.35	0.41	0.30	0.31	0.33
5.	Cheranmahadevi	1.34	1.44	1.68	1.21	1.27	1.34	0.34	0.36	0.42	0.30	0.32	0.34
6.	Suthamalli	0.85	0.95	1.19	0.72	0.78	0.83	0.21	0.24	0.30	0.18	0.20	0.21
7.	Kurukuthurai	0.96	1.06	1.30	0.83	0.87	0.92	0.24	0.27	0.33	0.21	0.22	0.23
8.	Tirunelveli	0.78	0.87	1.11	0.65	0.69	0.74	0.20	0.22	0.28	0.16	0.17	0.19
9.	Vellakovil	0.83	0.92	1.16	0.70	0.74	0.79	0.21	0.23	0.29	0.18	0.19	0.20

10.	Manapadai Veedu	0.64	0.73	0.97	0.51	0.55	0.60	0.16	0.18	0.24	0.13	0.14	0.15
11.	Sivalaperi	0.89	0.98	1.22	0.76	0.80	0.85	0.22	0.25	0.31	0.19	0.20	0.21
12.	Maruthur anaicut	0.81	0.90	1.14	0.68	0.72	0.77	0.20	0.23	0.29	0.17	0.18	0.19
13.	Karungulam	0.94	1.03	1.27	0.81	0.85	0.90	0.24	0.26	0.32	0.20	0.21	0.23
14.	Srivaikundam	1.02	1.11	1.35	0.89	0.93	0.98	0.26	0.28	0.34	0.22	0.23	0.25
15.	Eral	0.78	0.87	1.11	0.65	0.69	0.74	0.20	0.22	0.28	0.16	0.17	0.19
16.	Authoor	0.59	0.69	0.46	0.46	0.52	0.59	0.15	0.17	0.23	0.12	0.13	0.15
Min		0.51	0.61	0.85	0.38	0.38	0.44	0.51	0.13	0.15	0.21	0.10	0.11
Max		1.34	1.44	1.68	1.21	1.21	1.27	1.34	0.34	0.36	0.42	0.30	0.32
Mean		0.86	0.95	1.19	0.73	0.73	0.78	0.83	0.22	0.24	0.30	0.18	0.20

Table 3. Spatial and temporal variation of micronutrient status of water samples in Tamiraparani river basin

Parameters	Nov-I Fortnight 2020 to Feb-II Fortnight 2021		Nov-I Fortnight 2021 to Feb-II Fortnight 2022	
	Spatial Variation (%)	Temporal Variation (%)	Spatial Variation (%)	Temporal Variation (%)
Fe (ppm)	62	70	32	40
Zn (ppm)	55	75	51	60
Cu (ppm)	45	68	45	52
Mn (ppm)	56	60	36	50

Table 4. Interpretation of water samples for micronutrient status in Tamiraparani river basin

Parameter (ppm)	Upstream	Midstream	Downstream	WHO Standards (ppm)	Interpretation
Copper	0.35-1.68	0.48-1.30	0.40-1.35	2.0 ppm	Safe limit
Manganese	0.09-0.40	0.12-0.33	0.10-0.34	0.4 ppm	Safe limit
Zinc	0.40-1.14	0.29-1.10	0.35-1.43	5 ppm	Safe limit
Iron	11.55- 14.80	9.23-13.67	9.37-12.42	No issue	Safe limit

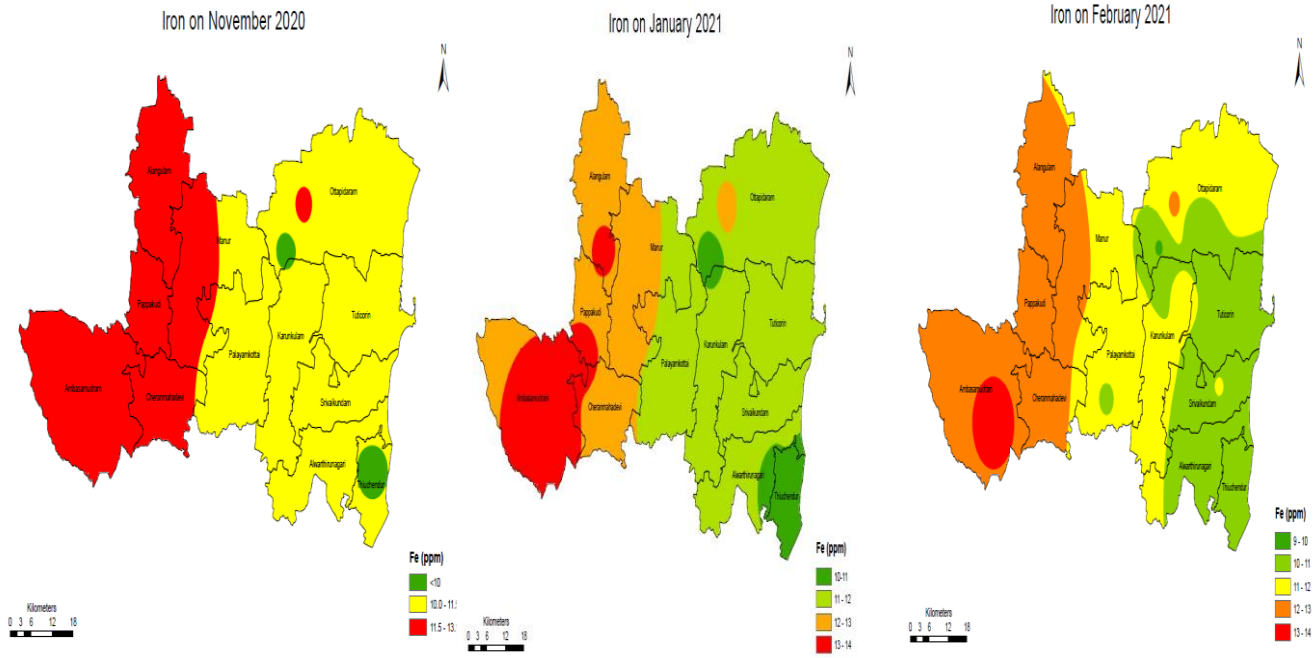


Figure 1. Variation of Fe (ppm) in ground water near Tamiraparani river

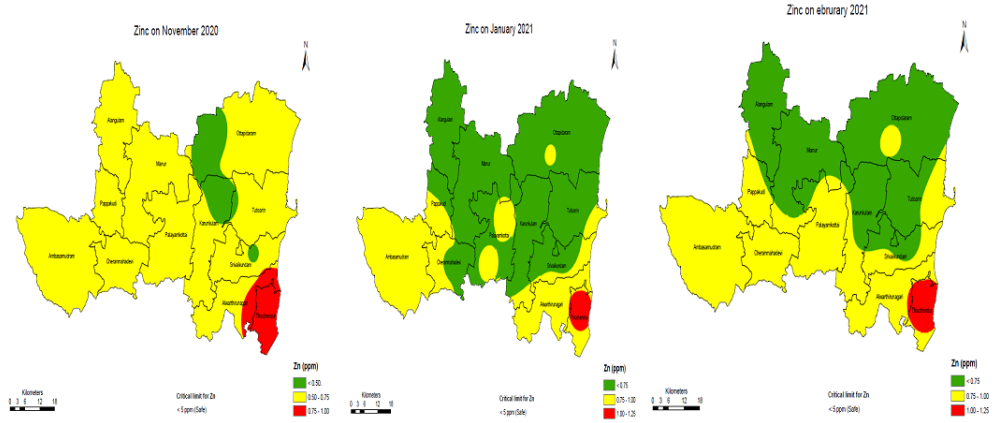


Figure 2. Variation of Zn (ppm) in ground water near Tamiraparani river

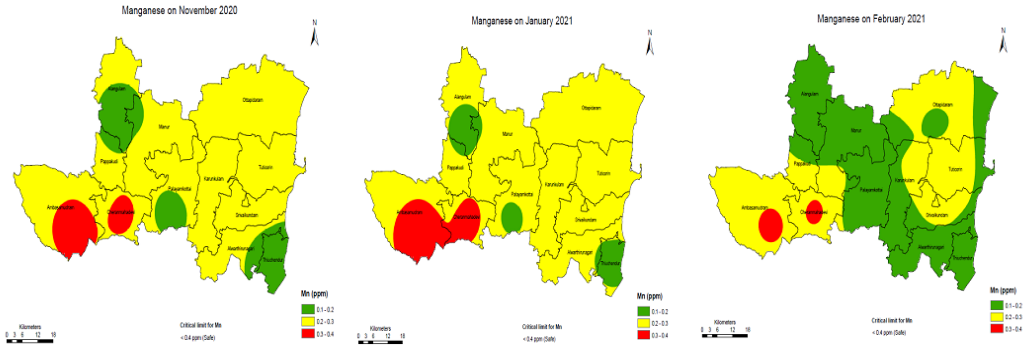


Figure 3. Variation of Mn (ppm) in ground water near Tamiraparani river

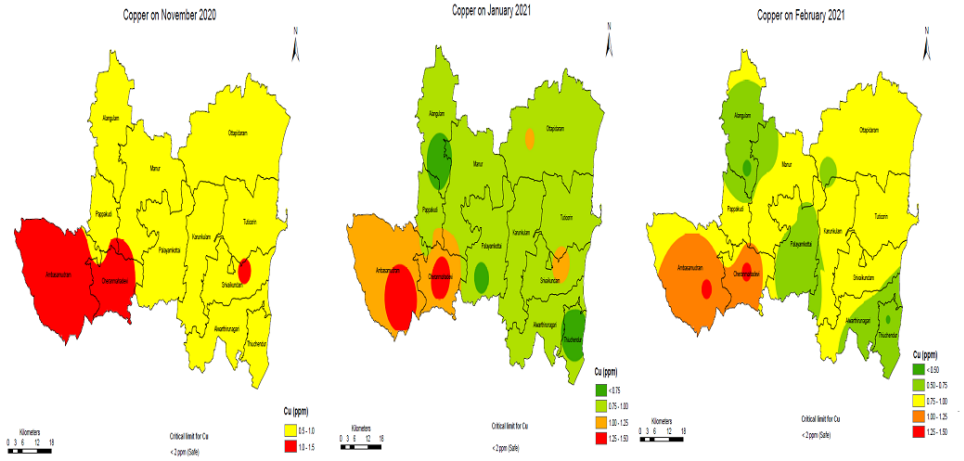


Figure 4. Variation of Cu (ppm) in ground water near Tamiraparani river

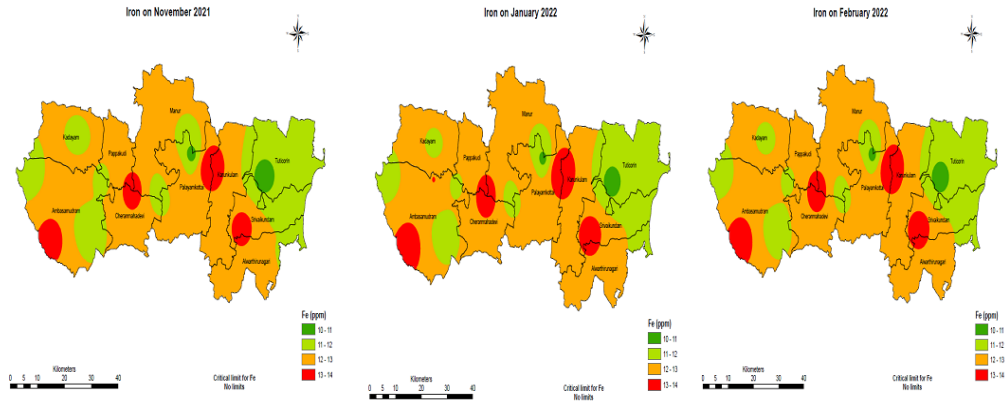


Figure 5. Variation of Fe (ppm) in Tamiraparani river

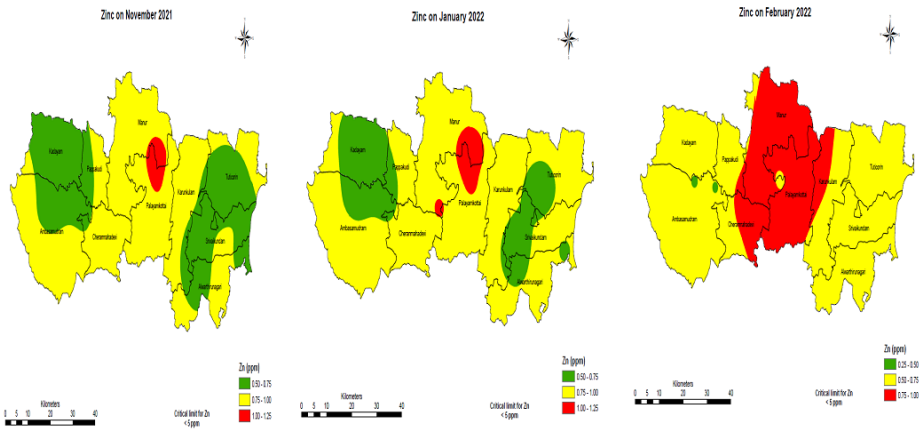


Figure 6. Variation of Zn (ppm) in Tamiraparani river

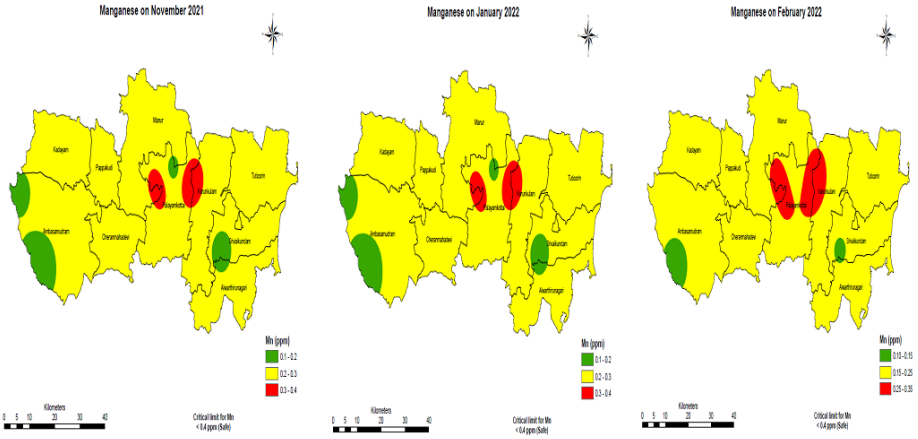


Figure 7. Variation of Mn (ppm) in Tamiraparani river

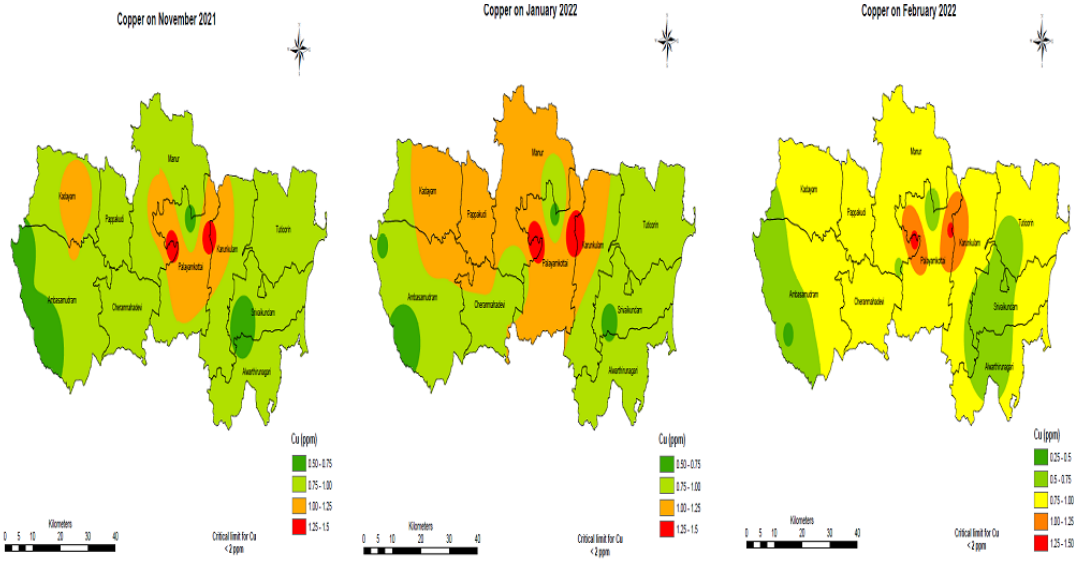


Figure 8. Variation of Cu (ppm) in Tamiraparani river

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