Geospatial and Earth System Science
An International Triannual Scientific Journal
e-ISSN: 3139-549X | Vol. 1 | No. 1 | Page Nos. 1 – 18 | June 2026
Original Research Paper
https://www.maned.org/journals
Open Access Journal

Assessment of Groundwater Quality and Non-Carcinogenic Health Risks in Chengalpattu District, Tamil Nadu: A GIS-Based Study

Jesslit Sebastian[1], Surendran D[2] *

[1] Department of Geography, University of Madras, Guindy Campus, Chennai-600025, Tamil Nadu, India

[2] Department of Geography, Central University of Tamil Nadu, Thiruvarur, Tamil Nadu – 610005, India

*Corresponding Author: D. Surendran; surendran@cutn.ac.in

Abbreviation: GESS
Website: www.maned.org/journals

Received: 10-03-2026
Revised: 02-05-2026
Accepted: 09-05-2026

Key Words:

Water Quality Index, Hazard Quotient, Hazard Index, Nitrate, Fluoride, Non-carcinogenic

ABSTRACT

This study integrates Water Quality Index (WQI) and non-carcinogenic health risk assessment (Hazard Quotient and Total Hazard Index) within a GIS framework to evaluate groundwater quality in Chengalpattu District, Tamil Nadu. Analysis of 51 samples across pre- and post- monsoon seasons reveals that groundwater quality ranges from good to poor, with post-monsoon deterioration driven by contaminant leaching. Nitrate emerges as the dominant risk factor, frequently exceeding permissible limits, whereas fluoride remains within safe thresholds. THI values surpass unity in several locations, indicating potential health risks, particularly for infants and children. Spatial patterns identify northern peri-urban and central agricultural zones as critical hotspots influenced by anthropogenic activities. The findings highlight the need for targeted groundwater management and safe drinking water interventions in vulnerable regions.

INTRODUCTION

Groundwater is a significant resource for drinking and irrigation, especially in dry and semi-arid regions where precipitation and surface water are scarce (Patel et al., 2020).

Groundwater is one of the most important sources of freshwater for drinking purposes, particularly in developing countries like India, where a significant proportion of the population depends on it for daily consumption. In rural and semi-urban regions, groundwater often serves as the primary source of potable water. However, rapid urbanization, industrialization, and intensive agricultural practices have led to the deterioration of groundwater quality, posing serious threats to human health and water security (Lapworth et al., 2021; World Health Organization, 2017).

Among various contaminants, nitrate (NO_3^-) and fluoride (F^-) are of major concern due to their widespread occurrence and adverse health impacts. Nitrate contamination in groundwater is mainly associated with anthropogenic activities such as excessive application of fertilizers, leakage from septic systems, and improper waste disposal. Elevated nitrate levels in drinking water can cause methemoglobinemia and other chronic health disorders, particularly in infants (Ward et al., 2018). Fluoride, on the other hand, is primarily geogenic in origin and is released into groundwater through rock–water interactions; however, excessive concentrations can lead to dental and skeletal fluorosis (World Health Organization, 2017). Several studies conducted across India have reported that groundwater frequently exceeds permissible limits for nitrate and fluoride, rendering it unsuitable for drinking purposes (Ali et al., 2022). To assess the suitability of groundwater for drinking, the Water Quality Index (WQI) has been widely used as an effective tool that integrates multiple physico-chemical parameters into a single value, providing an overall assessment of water quality. In addition, non-carcinogenic health risk assessment methods such as Hazard Quotient (HQ) and Hazard Index (HI) are commonly employed to evaluate potential health risks associated with the ingestion of contaminated groundwater (Wu et al., 2020). These indices are particularly useful in identifying vulnerable population groups, especially children, who are more susceptible to health risks due to higher intake rates relative to body weight (Subba Rao et al., 2023).

The application of Geographic Information Systems (GIS) has further enhanced groundwater quality studies by enabling spatial analysis and visualization of contamination patterns. GIS-based approaches help in identifying high-risk zones and understanding the spatial variability of groundwater quality parameters, thereby supporting effective water resource management (Srinivasamoorthy et al., 2014).

Tamil Nadu, particularly rapidly developing districts such as Chengalpattu, has been experiencing increasing pressure on groundwater resources due to urban expansion, industrial activities, and changing land-use patterns. Despite the growing reliance on groundwater for drinking purposes, comprehensive studies integrating water quality assessment, health risk analysis, and spatial evaluation remain limited in this region. Therefore, the present study aims to assess groundwater quality using the Water Quality Index (WQI) and to evaluate non-carcinogenic health risks associated with nitrate and fluoride through the estimation of Hazard Quotient (HQ) and Hazard Index (HI). Furthermore, GIS-based spatial analysis is employed to identify high-risk areas and to provide a scientific basis for sustainable groundwater management and safe drinking water supply in Chengalpattu district, Tamil Nadu, in accordance with standards prescribed by the Bureau of Indian Standards and guidelines of the United States Environmental Protection Agency.

STUDY AREA

The study area, Chengalpattu District, is located in the southeastern part of India and covers an area of approximately 2659.4 km². It lies between latitudes 12°13′41″N to 13°01′42″N and longitudes 79°38′32″E to 80°15′19″E. The district is bounded by Chennai to the north, Kanchipuram District to the northwest, Tiruvannamalai District to the west, Villupuram District to the south, and the Bay of Bengal to the east. The region has an average elevation of about 30 m above mean sea level and shows a general west-to-east slope, influencing groundwater movement.

Geologically, the area consists of sedimentary and crystalline formations, including alluvium, Gondwana sandstones, and weathered rocks, forming multi-layered aquifer systems. Groundwater occurs mainly under unconfined conditions at shallow depths ranging from 5 to 10 m below ground level. The drainage network includes rivers such as the Palar River, along with Adyar and Ongur rivers, which are mostly seasonal and flow during monsoon periods. The district contains a large number of irrigation tanks and recharge structures that support groundwater replenishment.

The climate is tropical, with an average annual temperature of about 27.8°C and an average annual rainfall of approximately 1236.8 mm, mainly received during the northeast monsoon. Groundwater is the primary source of drinking water in the region. However, rapid urbanization, agricultural activities, and improper waste

disposal have increased the risk of groundwater contamination. These conditions make the study area suitable for groundwater quality assessment and human health risk analysis (Nagarathinam et al., 2025).

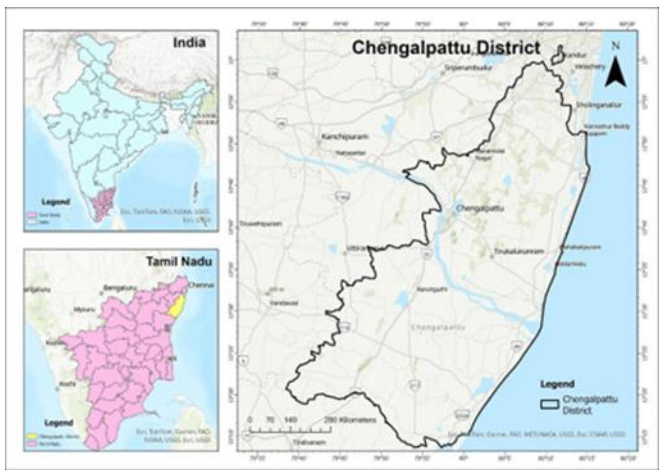

Fig .1: Study area Map of Chengalpattu District

METHODOLOGY

Data Source and Pre-processing

The groundwater quality data used in this study were obtained from the Tamil Nadu State Ground and Surface Water Resources Data Centre. Initially, the dataset was screened and pre-processed to remove incomplete and inconsistent records, resulting in a total of 51 valid groundwater samples for further analysis. The dataset includes key physico-chemical parameters such as pH, Total Dissolved Solids (TDS), nitrate, calcium, magnesium, chloride, sulphate, total hardness, and fluoride, which are essential for evaluating groundwater suitability for drinking purposes.

For the human health risk assessment, specific attention was given to nitrate and fluoride concentrations due to their significant impact on public health. These parameters were extracted from the dataset and used to compute the Hazard Quotient (HQ) and Hazard Index (HI). The data processing and analysis were carried out to ensure consistency and reliability in the estimation of Water Quality Index (WQI) and associated health risk indices. The administrative boundary of the study area was obtained from the Survey of India and used for spatial analysis and map preparation. The processed groundwater data were integrated with the boundary shapefile in a GIS environment to generate spatial distribution maps of water quality parameters and health risk indices.

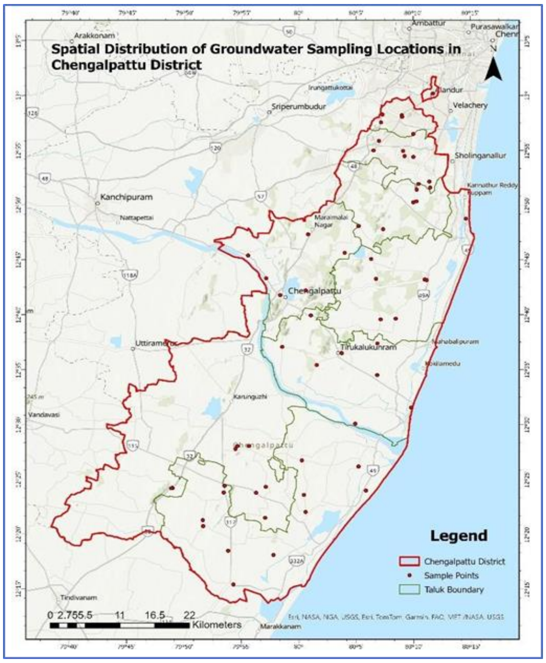

Fig .2: Sampling Locations

The Water Quality Index (WQI) was used to evaluate the suitability of groundwater for drinking purposes by integrating multiple physico-chemical parameters into a single value. Nine parameters, namely pH, Total Dissolved Solids (TDS), nitrate (NO_3^-), calcium (Ca^{2+}), magnesium (Mg^{2+}), chloride (Cl^-), sulphate (SO_4^{2-}), total hardness (TH), and fluoride (F^-), were selected based on their importance in drinking water quality assessment. The standard permissible limits (S_n) were obtained from the Bureau of Indian Standards (BIS, 2012). The WQI was calculated using the weighted arithmetic method proposed by Horton (1965) and later developed by Brown et al. (1972). The unit weight for each parameter was calculated as:

$$W_i = 1 / S_n$$

This ensures that parameters with lower permissible limits receive higher weight. The quality rating (Q_i) was calculated using:

$$Q_i = 100 (V_o - V_i) / (S_n - V_i)$$

where V_o is the observed value, V_i is the ideal value (0 for most parameters and 7 for pH), and S_n is the standard permissible limit. The overall WQI was computed using:

$$WQI = (\Sigma W_iQ_i) / (\Sigma W_i)$$

The calculated WQI values were spatially interpolated using the Inverse Distance Weighting (IDW) method in ArcGIS Pro to generate spatial distribution maps. The WQI values were classified into five categories—excellent (0–25), good (26–50), poor (51–75), very poor (76–100), and unsuitable for drinking (>100)—based on the classification proposed by Mishra and Patel (2001), which helps in evaluating groundwater suitability for drinking purposes (Srinivasamoorthy et al., 2014).

Hazard Quotient

The non-carcinogenic health risk associated with nitrate and fluoride was assessed using the Human Health Risk Assessment framework recommended by the United States Environmental Protection Agency (USEPA, 2005). Table 1 summarises the parameter values used to estimate the chronic daily intake.

The Chronic Daily Intake (CDI) was calculated as:

$$CDI = (C \times IR \times F \times ED) / (BW \times AT)$$

where C is contaminant concentration (mg/L), IR is ingestion rate (L/day), F is exposure frequency (days/year), ED is exposure duration (years), BW is body weight (kg), and AT is averaging time (days). The Hazard Quotient (HQ) was determined using:

$$HQ = CDI / RfD$$

where RfD is the reference dose (1.6 mg/kg/day for nitrate and 0.04 mg/kg/day for fluoride). The overall non-carcinogenic risk was expressed as the Total Hazard Index (THI), calculated as:

$$THI = HQ (fluoride) + HQ (nitrate)$$

A THI value less than or equal to 1 indicates no significant health risk, whereas a value greater than 1 indicates potential adverse health effects (USEPA, 2005).

Table 1: Parameters and input assumptions for the evaluation of non-carcinogenic health risk. (Kom et al., 2022)

Parameter	Unit	Infants (<2 years)	Children (2–16 years)	Adults (≥16 year
Ingestion rate (IR)	L/day	0.65	1.5	2
Exposure frequency (F)	days/year	365	365	365
Exposure duration (ED)	year	0.5	6	30
Average body weight (BW)	kg	6.94	25.9	64.7
Averaging time (AT)	day	182.5	2190	10950

RESULT AND DISCUSSION

Physico-Chemical Parameters of Groundwater

The physicochemical analysis of groundwater samples collected during pre- and post-monsoon seasons revealed considerable spatial and temporal variations across the study area. The pH values ranged from 7.44 to 8.24 (mean = 7.79) during pre-monsoon and 7.78 to 8.42 (mean = 8.10) during post-monsoon, indicating a slightly alkaline nature of groundwater in both seasons, with no samples exceeding the BIS (2012) permissible limit of 6.5–8.5. The alkaline nature of groundwater may be attributed to the dissolution of carbonate and silicate minerals in the aquifer matrix (Subba Rao, 2021). Total dissolved solids (TDS) ranged from 223 to 1325.2 mg/L (mean = 532.74 mg/L) during pre-monsoon and 231.4 to 848.6 mg/L (mean = 504.41 mg/L) during post-monsoon, with exceedance rates of 52.94% and 49.02%, respectively, surpassing the BIS (2012) desirable limit of 500 mg/L. The relatively higher TDS during pre-monsoon may be attributed to increased evaporation and prolonged water-rock interaction during dry conditions (Wagh et al., 2019). Elevated TDS in drinking water is associated with intestinal irritation, kidney stones, and cardiovascular problems (Karunanidhi et al., 2020). Electrical conductivity (EC) ranged from 408 to 2370 µS/cm (mean = 955.16 µS/cm) in pre-monsoon and 414 to 1478 µS/cm (mean = 901.10 µS/cm) in post-monsoon, with no samples exceeding any prescribed limit, as no standard has been set by BIS (2012) for EC. The higher EC values during pre-monsoon reflect greater ionic concentration due to reduced dilution effect, consistent with findings reported by Wagh et al. (2019).

Calcium (Ca^{2+}) concentrations ranged from 18.8 to 90.8 mg/L (mean = 52.54 mg/L) in pre- monsoon and 26.8 to 99.2 mg/L (mean = 52.19 mg/L) in post-monsoon, with exceedance rates of 9.80% and 7.84%, respectively, above the BIS (2012) desirable limit of 75 mg/L. Calcium in groundwater is commonly derived from the dissolution of calcite, dolomite, and silicate minerals such as feldspar and pyroxene (Kom et al., 2022). Magnesium (Mg^{2+}) showed comparatively higher exceedance rates of 68.63% during pre-monsoon and 47.06% during post-monsoon, with mean values of 39.64 mg/L and 31.82 mg/L, respectively, against the BIS (2012) desirable limit of 30 mg/L. The notable decline in exceedance rate from pre- to post-monsoon suggests a dilution effect due to recharge from rainfall (Marghade et al., 2021). Sodium (Na^{+}) concentrations ranged from 17.6 to 341 mg/L (mean = 82.26 mg/L) in pre-monsoon and 13.2 to 208.8 mg/L (mean = 84 mg/L) in post-monsoon, with no prescribed BIS limit, though elevated sodium intake has been linked to hypertension and cardiovascular diseases (Gopinath et al., 2019). Potassium (K^{+}) was relatively low in both seasons, ranging from 1.03 to 43.6 mg/L (mean = 8.76 mg/L) in pre-monsoon and 1.4 to 41.8 mg/L (mean = 7.72 mg/L) in post-monsoon, with no BIS standard applicable, and the primary sources are likely silicate mineral dissolution and anthropogenic inputs such as potassium-based fertilizers (Marghade et al., 2021).

Chloride (Cl^{-}) concentrations ranged from 54.2 to 567.4 mg/L (mean = 144.86 mg/L) during pre- monsoon and 30.4 to 281.2 mg/L (mean = 116.71 mg/L) during post-monsoon, with exceedance rates of 3.92% and 1.96%, respectively, above the BIS (2012) limit of 250 mg/L. The reduction in chloride concentrations during post-monsoon indicates dilution by recharge, while elevated values may be attributed to anthropogenic inputs such as sewage, agricultural runoff, and industrial effluents (Marghade, 2020). Sulfate (SO_4^{2-}) ranged from 20.2 to 200.2 mg/L (mean = 64.48 mg/L) in pre-monsoon and 10.2 to 149.12 mg/L (mean = 54.92 mg/L) in post-monsoon, with only 1.96% of pre-monsoon samples exceeding the BIS (2012) limit of 200 mg/L and no exceedances during post-monsoon, suggesting that sulfate levels are largely within safe limits (Dhanasekarapandian et al., 2016). Carbonate (CO_3^{2-}) concentrations were generally low, ranging from 0 to 24 mg/L (mean = 3.78 mg/L) in pre-monsoon and 0 to 33.02 mg/L (mean = 7.04 mg/L) in post-monsoon, with no BIS limit prescribed. The slight increase in carbonate during post-monsoon may be linked to enhanced dissolution of carbonate minerals under elevated recharge conditions (Ben Alaya et al., 2014). Bicarbonate (HCO_3^{-}) ranged from 99.4 to 500.2 mg/L (mean = 211.51 mg/L) during pre-monsoon and 125.02 to 418.95 mg/L (mean = 221.71 mg/L) during post-monsoon, with no samples exceeding any prescribed limit. The relatively higher post-monsoon bicarbonate values may reflect increased carbonate weathering and CO_2 dissolution during the recharge period (Kom et al., 2022).

Nitrate (NO_3^{-}) concentrations ranged from 1.2 to 120.44 mg/L (mean = 22.53 mg/L) during pre- monsoon and 4.61 to 131.95

mg/L (mean = 29.58 mg/L) during post-monsoon, with exceedance rates of 7.84% and 19.61%, respectively, above the BIS (2012) permissible limit of 45 mg/L. The notably higher exceedance rate during post-monsoon is of significant concern, as it suggests that surface runoff from agricultural fields and leaching of nitrogenous fertilizers into the groundwater system is intensified during the monsoon season (Rahman et al., 2021). Elevated nitrate in drinking water is a well-documented health hazard, particularly for infants, where it can cause methemoglobinemia (blue baby syndrome), while long-term exposure in adults is associated with gastric cancer, thyroid dysfunction, and hypertension (Adimalla & Li, 2019). Fluoride (F^-) concentrations remained well within the BIS (2012) permissible limit of 1.5 mg/L in both seasons, ranging from 0.12 to 0.88 mg/L (mean = 0.40 mg/L) during pre-monsoon and 0.12 to 0.76 mg/L (mean = 0.42 mg/L) during post-monsoon, with no samples exceeding the prescribed limit in either season. However, the mean fluoride values in both seasons were below 0.6 mg/L, which raises concern for dental caries risk as per WHO (2011) guidelines (Kom et al., 2022). Total hardness (TH) showed the highest exceedance rates among all parameters, with 92.16% of pre-monsoon samples and 84.31% of post-monsoon samples exceeding the BIS (2012) desirable limit of 200 mg/L, with mean values of 294.5 mg/L and 261.4 mg/L, respectively. The predominantly very hard nature of groundwater in both seasons indicates extensive water-rock interaction with calcium and magnesium-bearing minerals, and prolonged consumption of such hard water has been associated with kidney stones, body tissue calcification, and cardiovascular diseases (Dharmaratne, 2015).

Water Quality Index (WQI)

The spatial distribution of the Water Quality Index (WQI) was assessed for both pre-monsoon and post-monsoon seasons across Chengalpattu District to evaluate the suitability of groundwater for drinking purposes. The WQI values were classified into five categories — excellent (0–25), good (26–50), poor (51–75), very poor (76–100), and unsuitable for drinking (>100) — following the classification proposed by Mishra and Patel (2001).

During the pre-monsoon season, the spatial distribution map reveals that the majority of the study area falls under the good water quality category, predominantly covering the central, western, and southern portions of the district, including areas around Uttiramerur and Tindivanam. Pockets of excellent water quality were identified in the northern region near Ilandur and in isolated zones along the eastern coastal belt near Sholinganallur and Mahabalipuram, suggesting relatively lower ionic concentrations and minimal anthropogenic influence in these localities.

However, zones of poor water quality were observed in the central-eastern and southeastern coastal regions, particularly in areas surrounding Mahabalipuram and Okilamedu, likely attributed to elevated concentrations of total hardness, magnesium, and TDS, which are characteristic of coastal aquifer systems influenced by saltwater intrusion and intense agricultural activities (Srinivasamoorthy et al., 2014). Notably, very poor and unsuitable water quality categories were recorded at two isolated sampling locations — one in the eastern coastal zone near Mahabalipuram (around 12°43'N) and another in the southern part of the district near 12°20'N — indicating localized groundwater contamination possibly driven by elevated nitrate concentrations, high total hardness, or proximity to anthropogenic pollution sources such as agricultural runoff and septic tank leachates (Brown et al., 1972; Karunanidhi et al., 2020).

During the post-monsoon season, a notable shift in the spatial pattern of WQI was observed across the district. The poor water quality zone expanded considerably in comparison to the pre-monsoon season, now covering a larger portion of the central and eastern parts of the district, extending from the northern areas near Sholinganallur southward through Mahabalipuram and Okilamedu. This seasonal expansion of the poor water quality zone may be attributed to the leaching of surface contaminants — particularly nitrates from agricultural fields and organic matter from urban settlements — into the shallow aquifers during the monsoon recharge period, thereby deteriorating groundwater quality (Rahman et al., 2021). The excellent water quality category remained confined to the northern portion of the district near the Chennai boundary and in scattered patches along the eastern coastal belt, consistent with the pre-monsoon observations. The good water quality category, while still dominant in the southern and western parts of the district, showed a slight contraction compared to the pre-monsoon season, suggesting that monsoonal recharge, though beneficial in diluting certain ions, also facilitates the infiltration of surface-derived pollutants into the groundwater system (Wagh et al., 2019). Importantly, the very poor and unsuitable categories were absent in the post-monsoon season, which may reflect the dilution effect of monsoon recharge on the highly concentrated samples previously observed during the dry season (Marghade et al., 2021).

Table 2: The statistical analysis of groundwater samples with reference to BIS Standard

Water Quality Parameter	Season	BIS Limit	Min	Max	Mean	Median	SD	Exceeding	Rate (%)
pH	Pre	6.5 - 8.5	7.44	8.24	7.79	7.78	0.19	0	0.00%
	Post	6.5 - 8.5	7.78	8.42	8.1	8.12	0.14	0	0.00%
TDS (mg/L)	Pre	500	223	1325.2	532.74	507.4	199.55	27	52.94%
	Post	500	231.4	848.6	504.41	481	161.17	25	49.02%
EC (µS/cm)	Pre	NS	408	2370	955.16	892	356.41	0	0.00%
	Post	NS	414	1478	901.1	894	278.14	0	0.00%
Calcium (mg/L)	Pre	75	18.8	90.8	52.54	52	16.69	5	9.80%
	Post	75	26.8	99.2	52.19	50	15.35	4	7.84%
Magnesium (mg/L)	Pre	30	20.66	87.72	39.64	37.54	14.8	35	68.63%
	Post	30	13.61	81.89	31.82	29.04	12.44	24	47.06%
Sodium (mg/L)	Pre	NS	17.6	341	82.26	75.4	56.72	0	0.00%
	Post	NS	13.2	208.8	84	75.2	42.62	0	0.00%
Potassium (mg/L)	Pre	NS	1.03	43.6	8.76	5.2	9.81	0	0.00%
	Post	NS	1.4	41.8	7.72	5.2	7.46	0	0.00%
Chloride (mg/L)	Pre	250	54.2	567.4	144.86	130.86	80.01	2	3.92%
	Post	250	30.4	281.2	116.71	107.2	51.3	1	1.96%
Sulfate (mg/L)	Pre	200	20.2	200.2	64.48	57	34.25	1	1.96%
	Post	200	10.2	149.12	54.92	46	31.84	0	0.00%
Carbonate (mg/L)	Pre	NS	0	24	3.78	1.58	4.75	0	0.00%

The seasonal comparison of WQI spatial distribution clearly indicates that pre-monsoon groundwater quality is relatively better in terms of extreme contamination spots, while post- monsoon conditions lead to a broader spatial expansion of poor water quality zones due to enhanced recharge-driven contaminant transport. These findings are consistent with similar studies conducted in southern India, where seasonal variability in WQI was attributed to the combined influence of hydrogeological processes, anthropogenic pressures, and monsoonal recharge dynamics (Karunanidhi et al., 2020; Srinivasamoorthy et al., 2014).

The spatial maps further highlight that the eastern coastal belt of Chengalpattu District, particularly the areas around Mahabalipuram and Okilamedu, are persistently vulnerable zones requiring immediate attention for water quality management and regular monitoring (Horton, 1965; Brown et al., 1972).

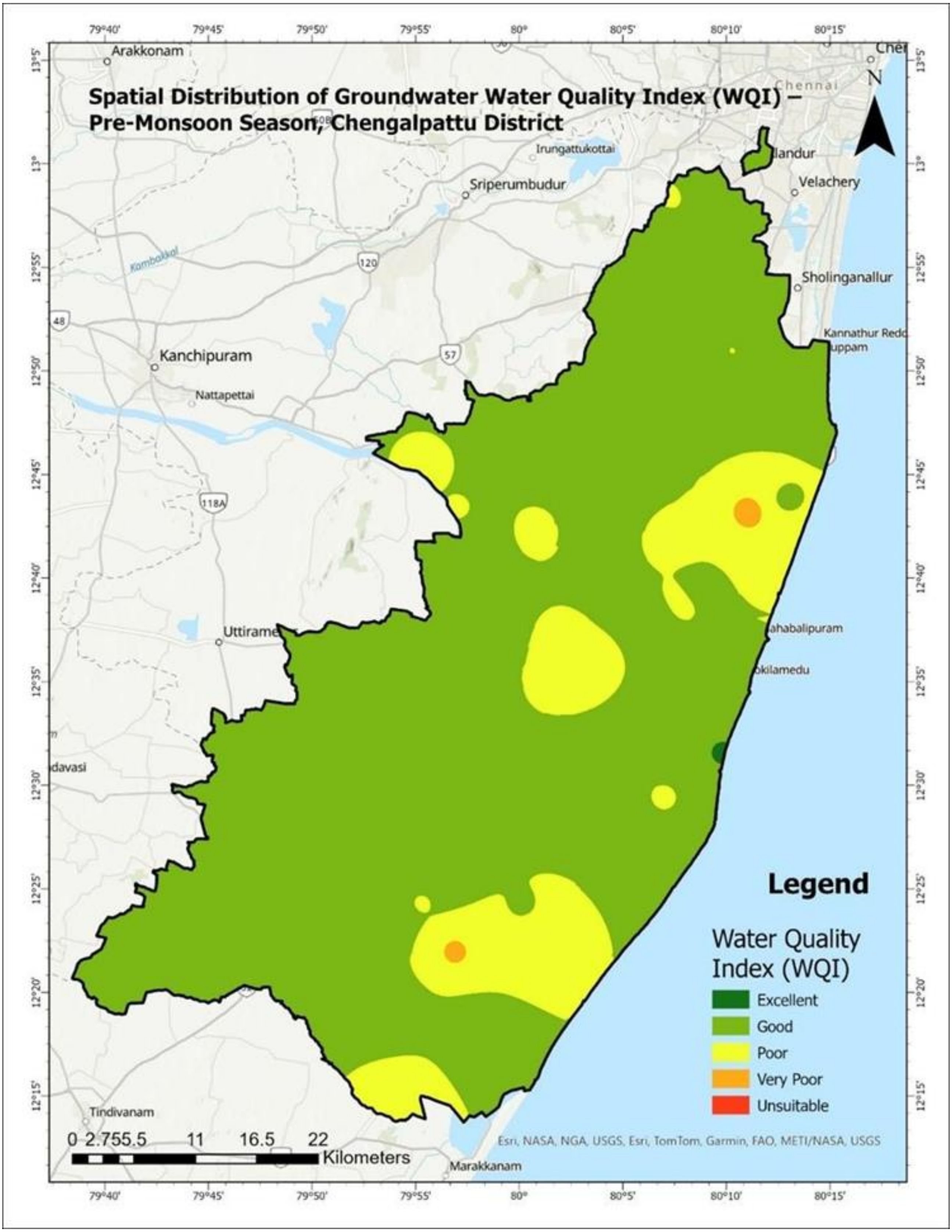

Fig .3: Spatial distribution of GWQI during Pre-monsoon

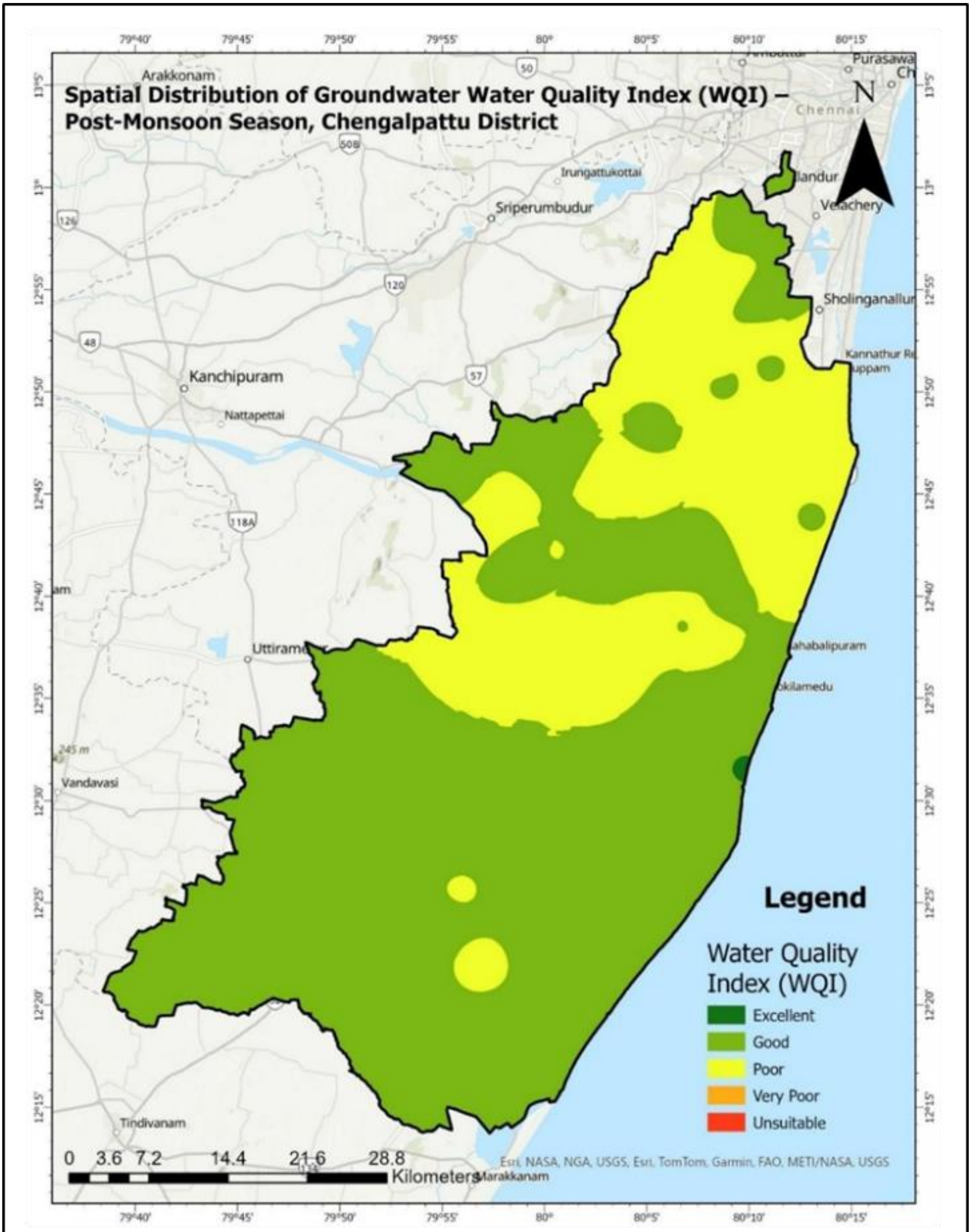

Fig .4: Spatial distribution of GWQI during Post-monsoon

NON-CARCINOGENIC HEALTH RISK *ASSESSMENT VIA HAZARD QUOTIENT (HQ) AND TOTAL HAZARD INDEX (THI)*

Fluoride Hazard Quotient (HQ) — Spatial Distribution

➢ **Adults**

The spatial distribution of fluoride Hazard Quotient (HQ) for adults during both pre-monsoon (as shown in Fig. 5) and post-monsoon seasons reveals a predominantly low-risk scenario across most of Chengalpattu District. During pre-monsoon, nearly the entire district — spanning from the northern coastal fringe near Sholinganallur and Velachery southward through Mahabalipuram to Marakkanam — falls within the low-risk category (HQ < 1), with only a negligible safe-category point visible near the central-eastern coastal belt around the 12°30' latitude zone. Similarly, the post-monsoon fluoride HQ for adults shows an identical spatial pattern, with the district remaining predominantly in the low-risk zone and a single moderate-risk point discernible near the same coastal area. These findings are consistent with the observation that adults have a higher tolerable daily intake for fluoride compared to children and infants, and therefore exhibit lower hazard quotients for the same exposure levels (Adimalla & Venkatayogi, 2017). The relative stability of fluoride risk between seasons for adults suggests that seasonal recharge does not significantly alter fluoride concentrations beyond adult tolerance thresholds in this district.

➢ **Children**

Children exhibit a notably higher vulnerability to fluoride exposure than adults, which is reflected in the spatial maps. During pre-monsoon, the fluoride HQ for children across Chengalpattu District reveals moderate-risk zones (HQ 1–2) appearing as distinct clusters — particularly near the eastern coastal belt around the 12°42' latitude (near Mahabalipuram direction), a central zone around 12°35', and a southern cluster near the 12°20' zone. The dominant background risk for the district, however, remains low risk. During post-monsoon, a single, well-defined moderate-risk cluster is observed near the eastern coastal area around 12°42'N, with the rest of the district remaining in the low-risk zone. The concentration of risk near the coastal belt is noteworthy; coastal aquifers in Tamil Nadu are known to have elevated dissolved mineral loads owing to geogenic processes and salt-water intrusion influences, which can elevate fluoride concentrations (Brindha & Elango, 2011). The greater spatial extent of moderate-risk zones during pre-monsoon compared to post-monsoon for children aligns with the dilution effect of monsoonal recharge, which lowers contaminant concentrations in groundwater (Ravikumar et al., 2015).

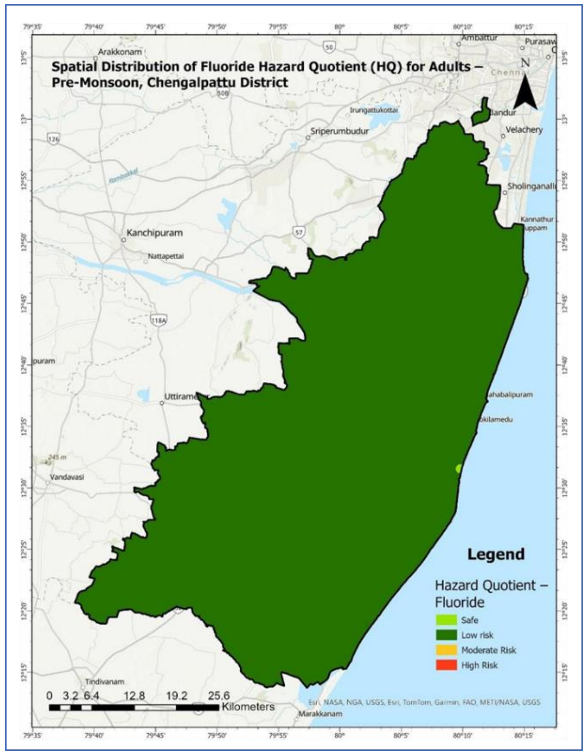

Fig .5: Spatial distribution of Fluoride HQ for Adults

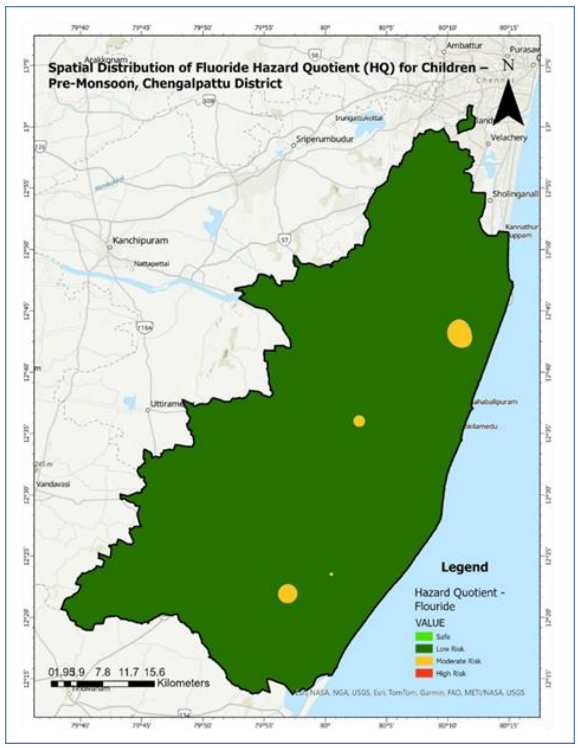

Fig .6: Spatial distribution of Fluoride HQ for Children

- **Infants**

Infants present the most spatially extensive fluoride risk among the three age groups studied. During pre-monsoon, the fluoride HQ map for infants shows substantial areas of moderate risk (HQ 1–2) distributed across the central and southeastern parts of the district, including zones around the Uttiramerur–Mahabalipuram corridor (12°35'–12°44'N), the southern coastal strip near Marakkanam, and clusters near the 12°20'–12°25' latitudinal belt in the southwestern interior. The northern sector and western interior retain low-risk classification. During post-monsoon, the pattern shifts somewhat: moderate-risk zones remain extensive in the central-to- south-eastern areas but show some spatial reorganization, with notable patches persisting around the Okilamedu–Mahabalipuram coastal stretch and the southern tip near Marakkanam. The higher susceptibility of infants arises from their lower body weight, higher water consumption per unit body weight, and developing physiological systems, which amplify the effective dose received relative to adults and children (Fawell et al., 2006; WHO, 2017). This is corroborated by similar findings from other parts of Tamil Nadu and peninsular India, where infant populations consistently show the highest fluoride HQ values in health risk assessments of groundwater (Adimalla & Venkatayogi, 2017; Selvakumar et al., 2017).

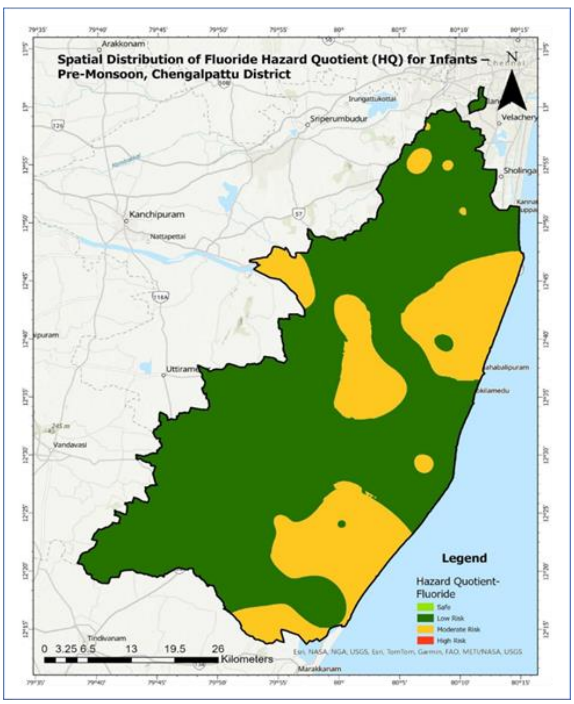

Fig .7: Spatial distribution of Fluoride HQ for Infants during Pre-monsoon

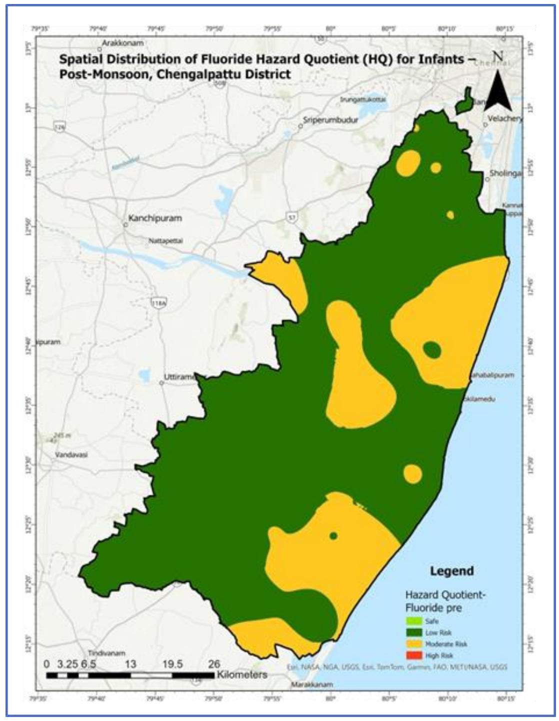

Fig .8: Spatial distribution of Fluoride HQ for Infants during Post-monsoon

Nitrate Hazard Quotient (HQ) — Spatial Distribution

- **Adults**

The spatial distribution of nitrate HQ for adults reveals a more heterogeneous pattern compared to fluoride, with clear evidence of moderate-risk pockets even for adults, who are the least sensitive population. During pre-monsoon, the nitrate HQ map for adults shows the majority of the district classified as low risk; however, moderate-risk zones (HQ 1–2) are identifiable at several discrete locations: a significant cluster in the northern district near the Ilandur–Velachery interface (approximately 12°57'–13°00'N, 80°13'E), a smaller cluster near 12°40'N in the west- central zone, and a few scattered safe-category points in the central belt. During post-monsoon, the moderate-risk pattern intensifies and expands considerably in the northern zone — with a large contiguous moderate-risk area covering the region around Sholinganallur, Ilandur, and extending southward toward Kannathur Reddyuppam (approximately 12°52'–13°00'N).

Additional moderate-risk clusters appear near the central-west interior (around 12°40'N) and southern areas around 12°17'N. The expansion of nitrate risk during post-monsoon is consistent with the well-documented phenomenon of agricultural and urban runoff-driven nitrate loading into shallow aquifers during and after the monsoon season (Suthar et al., 2009; Vasanthavigar et al., 2012). The northern cluster, coinciding with the peri-urban fringe of Chennai near Sholinganallur and Velachery, likely reflects anthropogenic contamination from urban wastewater, septic systems, and intensified land use in this rapidly urbanising corridor (Srinivasamoorthy et al., 2014).

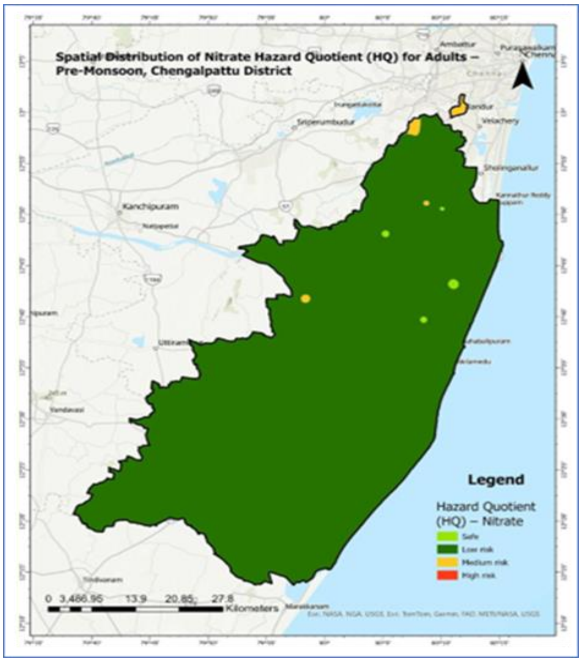

Fig .9: Spatial distribution of Nitrate HQ for Adults

➢ Children

The nitrate HQ maps for children reveal a substantially elevated spatial extent of risk compared to adults. During pre-monsoon, the northern zone (around the Ilandur–Velachery–Sholinganallur area, ~12°57'–13°00'N) continues to show moderate-to-high risk, with a high-risk point (HQ > 2) visible near the Ilandur area. The central-western portion of the district — encompassing the Uttiramerur block area (~12°35'–12°42'N, 79°55') — displays a broad zone of moderate risk, and additional moderate-risk clusters are observed in the southwestern coastal belt near 12°18'– 12°22'N. A large portion of the southern district (Marakkanam–Tindivanam corridor) also shows moderate risk. During post-monsoon, the risk pattern for children shows marked intensification: the northern peri-urban zone exhibits a high-risk point near Ilandur, and a much larger contiguous area across the northeastern district (Sholinganallur–Kannathur direction, ~12°53'– 13°00'N) shows moderate risk. Additionally, a substantial moderate-risk zone expands across the central belt (around 12°40'–12°44'N, 79°55'–80°00'), and the southwestern interior continues to show scattered moderate risk. The elevated vulnerability of children to nitrate is attributable to their higher water intake per body weight, and the particular concern over methemoglobinemia (blue baby syndrome) in younger populations (Manassaram et al., 2006; WHO, 2017). These findings parallel research from agricultural districts of southern India where nitrate contamination disproportionately affects child populations due to exposure through drinking water (Suthar et al., 2009).

➢ Infants

The nitrate HQ maps for infants illustrate the most critical risk scenario among all population groups and contaminants studied. During pre-monsoon, nearly the entire district is classified under moderate risk (HQ 1–2), with the exception of the eastern coastal strip (Mahabalipuram– Marakkanam belt, ~12°15'–12°50'N, 80°08'–80°15'E) and isolated interior pockets that retain low-risk status. A high-risk point (HQ > 2) is distinctly visible at the northern tip near Ilandur (13°00'N, 80°14'E). This pattern is stark: virtually the entire western, central, and southern interior of Chengalpattu District presents a moderate-to-high nitrate health risk for infants in the pre-monsoon period.

During post-monsoon, the spatial risk for infants remains severe, with most of the district still showing moderate risk, though the eastern coastal belt (Mahabalipuram–Okilamedu–Marakkanam) shifts to low risk. A high-risk cluster persists prominently in the northern zone near Ilandur–Velachery. The omnipresence of moderate nitrate risk for infants across both seasons underscores the serious groundwater quality concern for this age group throughout the district. This aligns with established literature documenting that infants relying on formula prepared with nitrate-contaminated groundwater are at the greatest risk of methemoglobinemia (Knobeloch et al., 2000; Fewtrell, 2004). The persistence of risk even post-monsoon — despite dilution — indicates diffuse contamination sources including agricultural fertilizers, animal waste, and septic seepage that continuously reload the aquifer system (Shukla & Saxena, 2020).

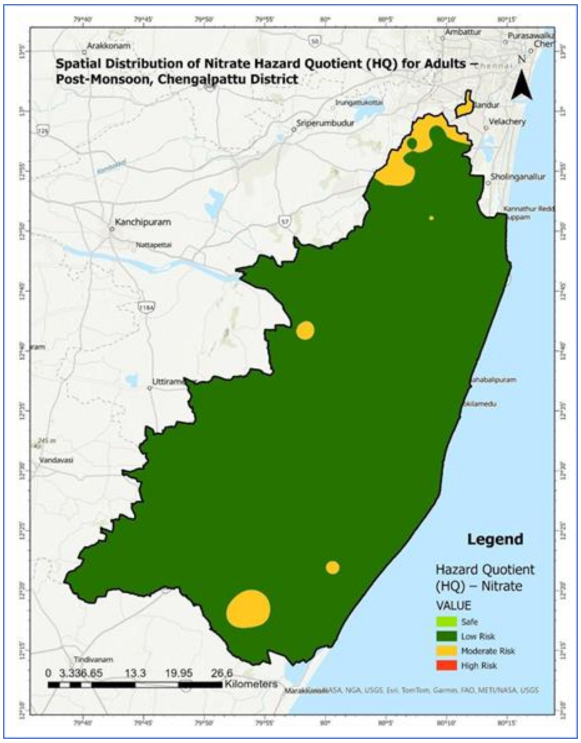

Fig .10: Spatial distribution of Nitrate HQ for Adults during post monsoon

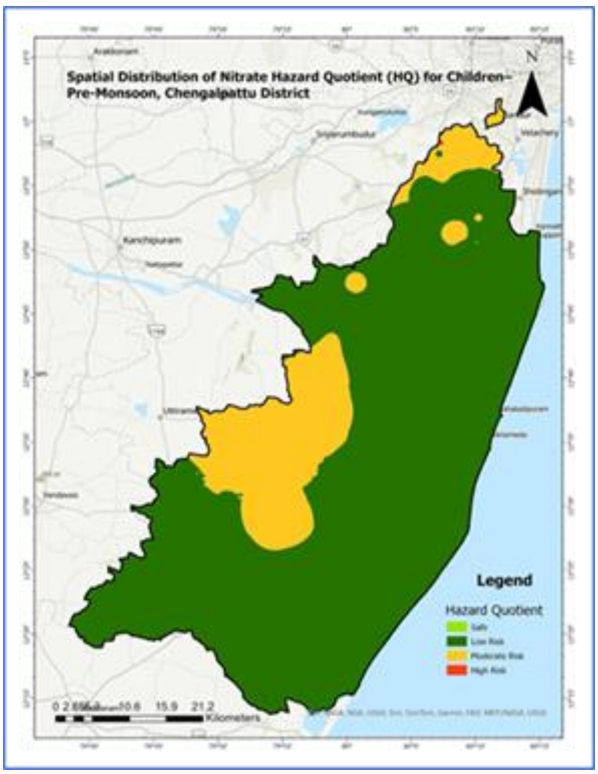

Fig .11: Spatial distribution of Nitrate HQ for children during pre-monsoon

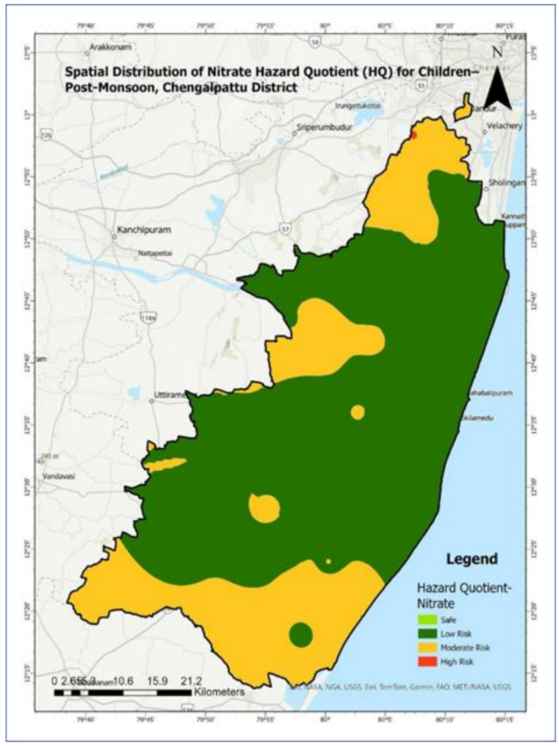

Fig .12: Spatial distribution of Nitrate HQ for children during post-monsoon

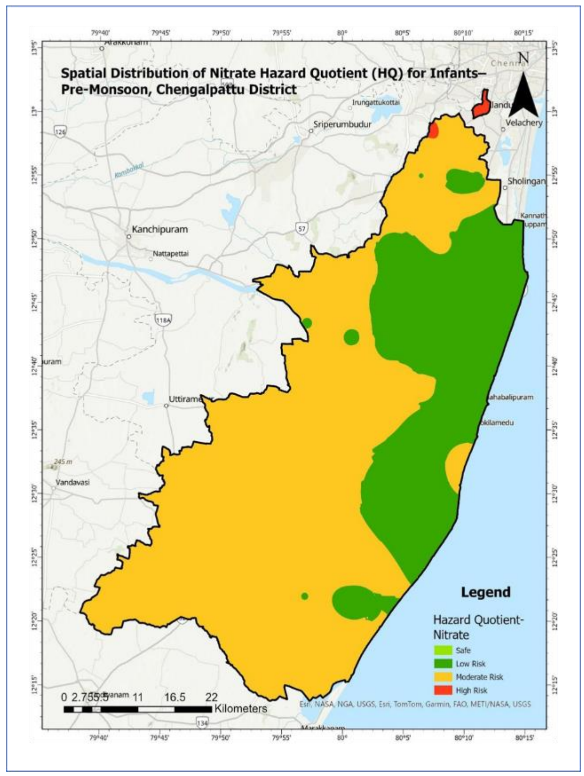

Fig .13: Spatial distribution of Nitrate HQ for Infants during pre-monsoon

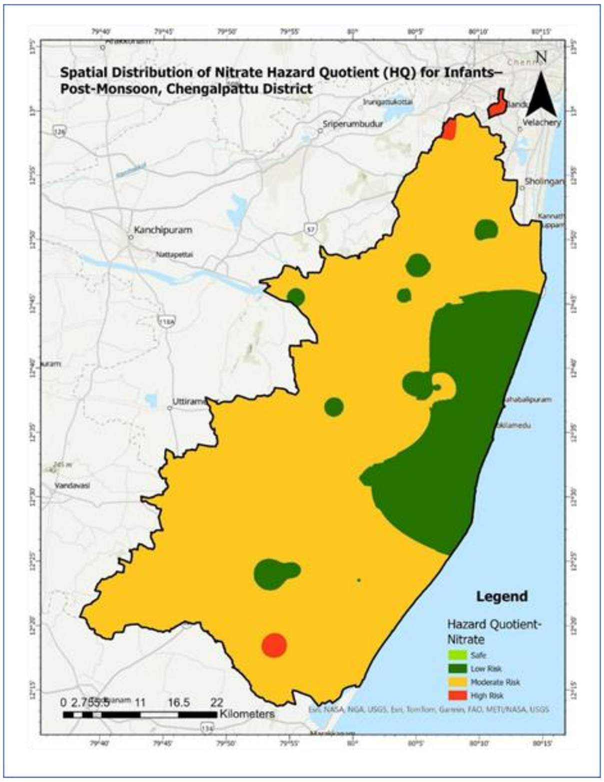

Fig .14: Spatial distribution of Nitrate HQ for Infants during post-monsoon

Total Hazard Index (THI) — Combined Risk Assessment

➢ Adults

The Total Hazard Index (THI), which aggregates the combined non-carcinogenic risk from both fluoride and nitrate via ingestion, provides a holistic picture of drinking water health risk. For adults during pre-monsoon, the THI map presents an overall picture where the majority of the district shows no risk (THI < 1), coloured in light green — spanning most of the southern, central, and western portions of Chengalpattu. Low-risk zones (THI 1–2, dark green) appear as discrete clusters in the central interior near Uttiramerur (12°40'N), with a small moderate-risk zone (THI 2–4, orange) visible in the northern area. The relatively benign THI for adults reflects the lower sensitivity of this population to both fluoride and nitrate at prevailing concentrations. During post-monsoon, the THI spatial pattern for adults shifts considerably: the district transitions from predominantly no-risk to predominantly low risk (dark green), covering nearly the entire district. Small zones of low risk appear in the central area around Uttiramerur and the southern region near Marakkanam. A moderate-risk zone is distinctly visible in the northern district near the Sholinganallur–Ilandur corridor. This post-monsoon escalation in the combined hazard index — even for adults — underscores the dominant role of nitrate (as also seen in individual HQ maps) in driving combined risk during and after the monsoon season, consistent with findings elsewhere in Tamil Nadu (Vasanthavigar et al., 2012; Srinivasamoorthy et al., 2014).

➢ Children

The THI maps for children reveal a more nuanced and concerning risk landscape than for adults. During pre-monsoon, the district shows a mixed pattern: large areas of low risk dominate the northern and central zones, but several moderate-risk clusters are visible in the north (Sholinganallur–Velachery area), the west-central belt (12°40'N near Uttiramerur), and the southern portion. A small high-risk point appears at the extreme northern tip near Ilandur– Velachery. Interestingly, areas of no risk (light green) appear in the eastern coastal zone between approximately 12°43'–12°48'N and around the 12°29'–12°33'N belt — indicating that some coastal sample locations have very low combined contaminant loads. During post-monsoon, the THI for children becomes more spatially extensive in its moderate-risk zones. Moderate-risk areas are observed in the northern zone (Sholinganallur–Ilandur), in the central-western area near Uttiramerur, and a prominent coastal no-risk zone persists along the east. A high-risk point remains at the northern tip. No-risk patches appear in the southeastern coastal zone (Okilamedu– Mahabalipuram direction). The persistence of moderate-to-high risk zones for children across both seasons, particularly in the northern peri-urban and central agricultural zones, points to overlapping fluoride and nitrate burdens that cumulatively exceed safe thresholds. Studies from comparable hydrogeological settings in Tamil Nadu and Andhra Pradesh have similarly found that children face disproportionate combined risk from co-occurring contaminants (Adimalla & Venkatayogi, 2017; Selvakumar et al., 2017).

➢ Infants

The THI maps for infants present the most alarming combined risk scenario in this study. During pre-monsoon, the THI map reveals that the vast majority of Chengalpattu District falls within the moderate-risk category (THI 2–4), depicted in yellow-orange. This includes the entire northern zone (Sholinganallur, Velachery, Ilandur), the central interior (Uttiramerur belt), and the southern reaches toward Marakkanam and Tindivanam. High-risk zones (THI > 4, red) are visible at the northern tip near Ilandur (13°00'N) and at a discrete interior point south of Uttiramerur (approximately 12°40'N, 79°55'). Low-risk zones (dark green) appear only in localized pockets — primarily in the southeastern coastal corridor between Mahabalipuram and the 12°25'–12°45'N zone, and some southwestern interior pockets. During post-monsoon, the THI for infants remains severe: the northern zone near Ilandur retains a high-risk designation, and moderate risk continues to dominate the western and central interior portions of the district.

However, a notable expansion of low-risk classification is visible in the central eastern coastal belt (Mahabalipuram–Okilamedu–Marakkanam area, 12°15'–12°45'N), suggesting that monsoonal recharge significantly dilutes contaminant loads in the coastal aquifer zones. The extreme combined risk for infants is driven primarily by the elevated nitrate HQ (as shown in Section 3.2.3) compounded by moderate fluoride exposure, resulting in THI values that substantially exceed acceptable thresholds across large parts of the district. This finding is deeply significant from a public health standpoint: groundwater in large portions of Chengalpattu District is unsuitable for infant consumption without treatment.

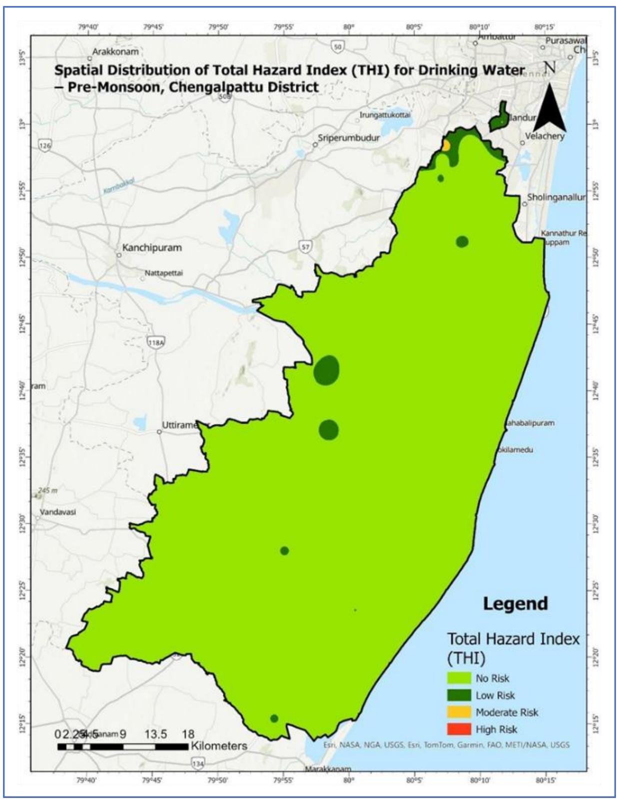

Fig .15: Spatial distribution of THI for Drinking water during pre-monsoon

However, a notable expansion of low-risk classification is visible in the central eastern coastal belt (Mahabalipuram–Okilamedu–Marakkanam area, 12°15'–12°45'N), suggesting that monsoonal recharge significantly dilutes contaminant loads in the coastal aquifer zones.

The extreme combined risk for infants is driven primarily by the elevated nitrate HQ (as shown in Section 3.2.3) compounded by moderate fluoride exposure, resulting in THI values that substantially exceed acceptable thresholds across large parts of the district. This finding is deeply significant from a public health standpoint: groundwater in large portions of Chengalpattu District is unsuitable for infant consumption without treatment. Similar conclusions have been drawn from health risk assessments conducted in Rajasthan (Suthar et al., 2009), Karnataka (Ravikumar et al., 2015), and Andhra Pradesh (Adimalla & Venkatayogi, 2017), all of which highlight infants as the most at- risk population in groundwater-dependent rural communities.

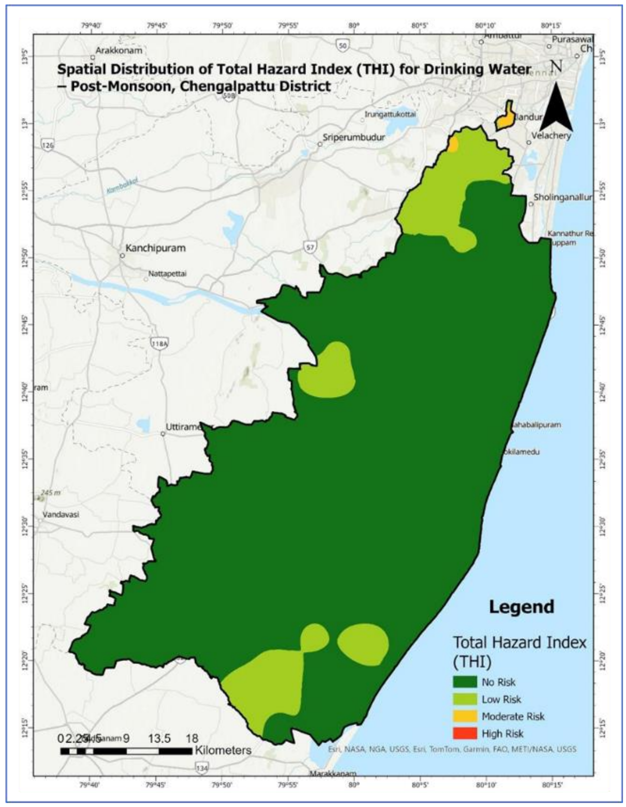

Fig .16: Spatial distribution of THI for Drinking water during post-monsoon

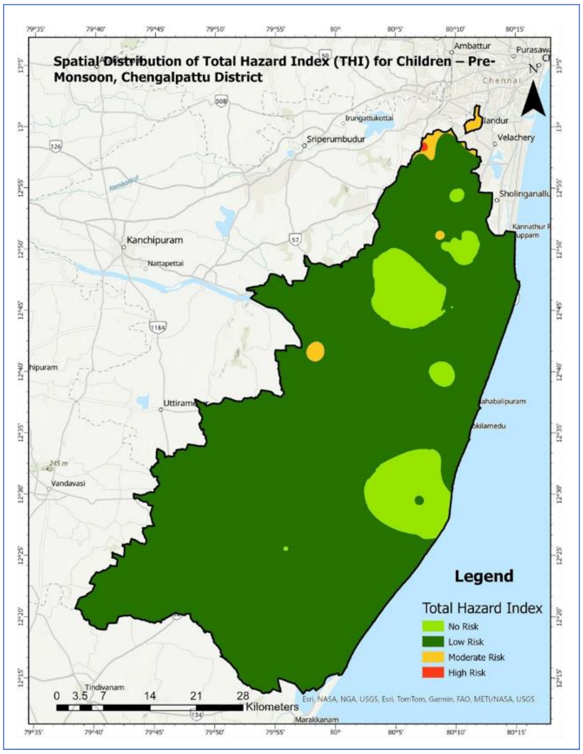

Fig .17: Spatial distribution of THI for children during pre-monsoon

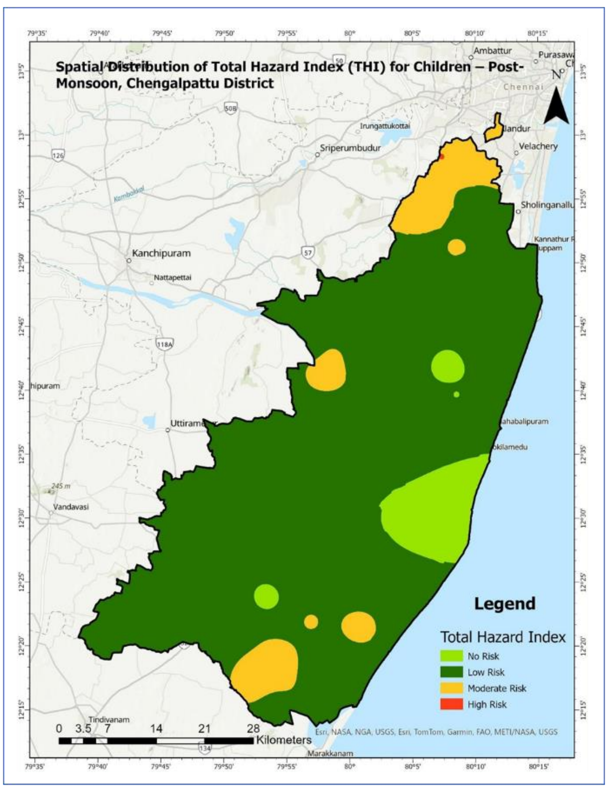

Fig .18: Spatial distribution of THI for children during post-monsoon

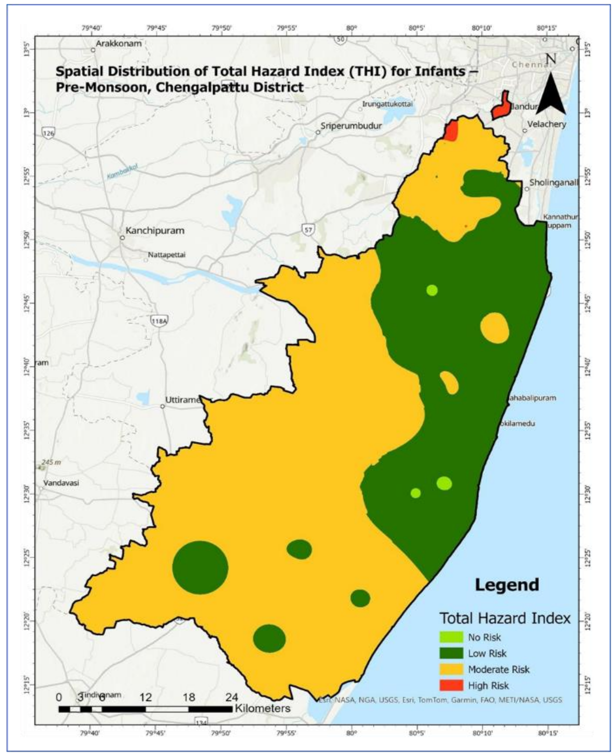

Fig .19: Spatial distribution of THI for Infants during pre-monsoon

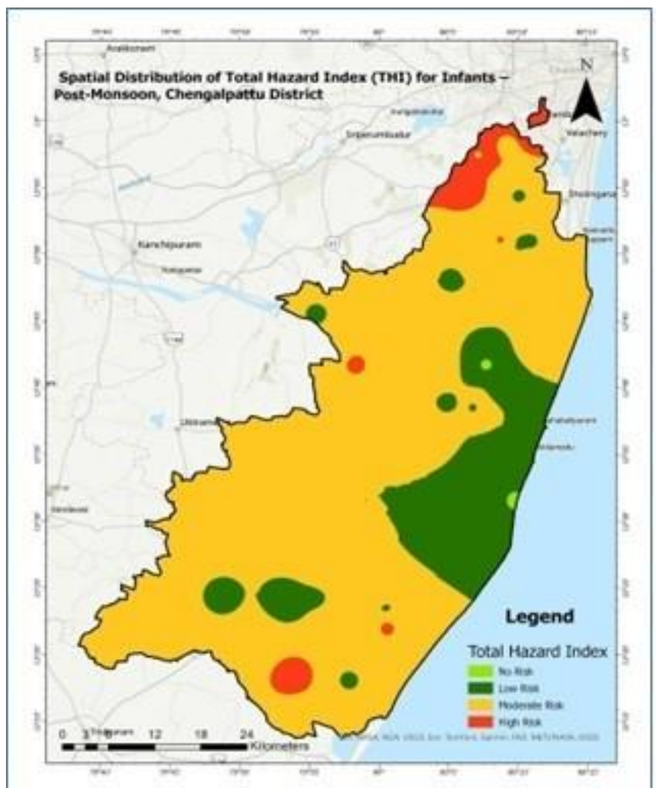

Fig .20: Spatial distribution of THI for Infants during post-monsoon

Key Spatial Hotspots and Management Implications

Northern district (Ilandur–Velachery–Sholinganallur zone, ~12°55'–13°00'N, 80°10'–80°15'E): This peri-urban fringe consistently shows the highest THI and nitrate HQ values across all population groups and both seasons. The proximity to the rapidly urbanising Chennai metropolitan fringe — with associated dense septic infrastructure, urban runoff, and historical industrial effluents — is the most plausible driver (Srinivasamoorthy et al., 2014). This zone requires priority groundwater monitoring and alternative safe water supply.

Central-western belt (Uttiramerur block, ~12°35'–12°42'N, 79°52'–80°00'E): Nitrate HQ shows moderate risk for children and infants in both seasons, likely attributable to intensive agriculture and associated fertilizer use in the Uttiramerur agricultural tract. Nitrate leaching from paddy and other crop cultivation in this region likely constitutes the dominant contamination pathway (Vasanthavigar et al., 2012).

Southern coastal–interior zone (~12°15'–12°22'N): Moderate THI values for children and infants and moderate nitrate risk suggest contamination in this relatively remote southern portion of the district, possibly from agricultural activities around the Tindivanam sub-district fringe.

Eastern coastal belt (Mahabalipuram–Okilamedu–Marakkanam, 12°15'–12°45'N, ~80°12'– 80°15'E): This zone consistently shows lower THI values — and even no-risk classification for some population groups — in post-monsoon conditions, suggesting that coastal aquifer recharge during monsoon effectively dilutes groundwater contaminants here. However, fluoride moderate- risk pockets for infants indicate ongoing geogenic contribution even in this zone.

The seasonal comparison across all maps consistently reveals that pre-monsoon conditions generate higher combined risk for infants and children due to groundwater concentration through evapotranspiration and reduced dilution, while post-monsoon conditions slightly alleviate risk incoastal zones but intensify nitrate risk in peri-urban areas through runoff-driven loading (Ravikumar et al., 2015; Shukla & Saxena, 2020).

Distribution of Total Hazard Index (THI) Across Age Groups

The boxplot representation of the Total Hazard Index (THI) illustrates the distribution and variability of non-carcinogenic health risk across the study area. The median THI values for all groups lie above the reference threshold (THI = 1), indicating the presence of potential health risk in a significant portion of the samples. Among the groups, the first category exhibits the highest median and wider interquartile range, suggesting greater exposure levels and spatial variability, whereas the subsequent groups show relatively lower median values but still exceed the safe limit. The presence of multiple outliers in the higher range further indicates localized hotspots of elevated risk. The spread of the data above the threshold line highlights that a considerable number of sampling locations fall under moderate to high-risk categories. This pattern confirms that the overall groundwater quality poses non-carcinogenic health concerns, with variability influenced by spatial heterogeneity in contaminant concentration.

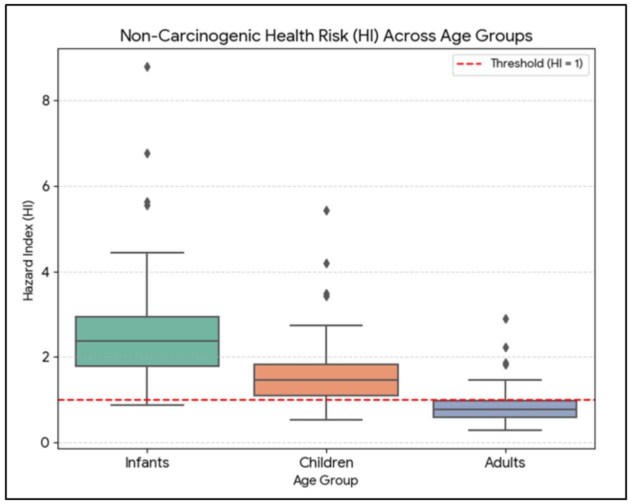

Fig .21: Non- Carcinogenic Health Risk (HI) across age groups

CONCLUSION

The present study provides a comprehensive assessment of groundwater quality and associated non-carcinogenic health risks in Chengalpattu District using integrated WQI, HQ, and THI approaches within a GIS framework. The results indicate that although most physico-chemical parameters fall within permissible limits, significant exceedances in TDS, magnesium, nitrate, and total hardness highlight concerns regarding groundwater suitability for drinking purposes. Seasonal variation plays a crucial role, with pre-monsoon conditions showing higher concentration of dissolved ions due to evaporation, while post-monsoon conditions exhibit increased nitrate contamination due to surface runoff and leaching.

The WQI results reveal that groundwater quality ranges from good to poor, with a noticeable spatial expansion of poor-quality zones during the post-monsoon season. Health risk assessment demonstrates that nitrate is the primary contributor to non-carcinogenic risk, whereas fluoride poses comparatively lower risk. Infants are identified as the most vulnerable population group, followed by children, due to higher intake rates relative to body weight. The THI values exceeding unity across several parts of the district indicate that groundwater is unsuitable for direct consumption without treatment, particularly for infants.

Spatial analysis identifies the northern peri-urban region, central agricultural belt, and southern interior as major risk hotspots influenced by anthropogenic activities such as excessive fertilizer application, septic leakage, and rapid urbanisation. In contrast, the eastern coastal belt shows relatively lower risk due to dilution effects during monsoonal recharge.

Overall, the study highlights the need for continuous groundwater quality monitoring, implementation of sustainable agricultural practices, and provision of safe drinking water alternatives in high-risk zones. The integration of GIS with water quality and health risk assessment proves to be an effective tool for identifying vulnerable regions and supporting evidence-based water resource management.

REFERENCES

1) Adimalla, N., & Li, P. (2019). Occurrence, health risks, and geochemical mechanisms of fluoride and nitrate in groundwater of the semi-arid region of South India. Human and Ecological Risk Assessment, 25(1–2), 81–103. https://doi.org/10.1080/10807039.2018.1482746

2) Adimalla, N., & Venkatayogi, S. (2017). Mechanism of fluoride enrichment in groundwater of hard rock aquifers in South India. Environmental Earth Sciences, 76, 45. https://doi.org/10.1007/s12665-016-6362-8

3) Ali, S., Thakur, S. K., Sarkar, A., & Shekhar, S. (2022). Worldwide contamination of water by fluoride. Environmental Chemistry Letters, 20, 137–151. https://doi.org/10.1007/s10311-021- 01237-9

4) Ben Alaya, M., Saidi, S., Zemni, T., & Zargouni, F. (2014). Suitability assessment of groundwater for drinking and irrigation purposes in the region of Sidi Bouzid, Tunisia. Environmental Earth Sciences, 71, 3387–3421.

5) Brindha, K., & Elango, L. (2011). Fluoride in groundwater: Causes, implications and mitigation measures. International Journal of Environmental Sciences, 1(7), 1680–1694.

6) Brown, R. M., McClelland, N. I., Deininger, R. A., & O'Connor, M. F. (1972). A water quality index—Crossing the psychological barrier. Journal of the Water Pollution Control Federation, 44(10), 173–187.

7) Dhanasekarapandian, M., Chandran, S., Devi, D. S., & Kumar, V. (2016). Spatial analysis of groundwater quality using GIS in Thanjavur district, Tamil Nadu, India. Applied Water Science, 6, 119–131.

8) Dharmaratne, R. W. (2015). Fluoride in drinking water and diet: The causative factor of chronic kidney disease of unknown etiology in Sri Lanka. Environmental Health and Preventive Medicine, 20, 237–242.

9) Fewtrell, L. (2004). Drinking-water nitrate, methemoglobinemia, and global burden of disease: A discussion. Environmental Health Perspectives, 112(14), 1371–1374.

10) Fawell, J., Bailey, K., Chilton, J., Dahi, E., Fewtrell, L., & Magara, Y. (2006). Fluoride in drinking- water. World Health Organization.

11) Gopinath, B., Harris, D. C., Flood, V. M., Burlutsky, G., & Mitchell, P. (2019). Consumption of sodium and risk of chronic kidney disease. Nutrients, 11(3), 545.

12) Horton, R. K. (1965). An index number system for rating water quality. Journal of the Water Pollution Control Federation, 37(3), 300–306.

13) Karunanidhi, D., Subramani, T., & Elango, L. (2020). Groundwater quality assessment using water quality index and GIS in Tamil Nadu. Environmental Monitoring and Assessment, 192, 1–17.

14) Knobeloch, L., Salna, B., Hogan, A., Postle, J., & Anderson, H. (2000). Blue babies and nitrate- contaminated well water. Environmental Health Perspectives, 108(7), 675–678.

15) Kom, K. P., Gurugnanam, B., & Bairavi, S. (2022). Non-carcinogenic health risk assessment of nitrate and fluoride contamination in groundwater of Noyyal basin, India. Environmental Science and Pollution Research.

16) Lapworth, D. J., Nkhuwa, D. C. W., Okotto-Okotto, J., Pedley, S., Stuart, M. E., Tijani, M. N., & Wright, J. (2021). Urban groundwater quality in sub-Saharan Africa. Science of the Total Environment, 565, 130–145.

17) Manassaram, D. M., Backer, L. C., & Moll, D. M. (2006). A review of nitrates in drinking water: Maternal exposure and adverse reproductive outcomes. Environmental Health Perspectives, 114(3), 320–327.

18) Marghade, D. (2020). Hydrogeochemical evaluation of groundwater quality. Applied Water Science, 10, 1–14.

19) Marghade, D., Malpe, D. B., & Subba Rao, N. (2021). Application of water quality index for groundwater assessment. Environmental Geochemistry and Health, 43, 1–15.

20) Mishra, P. C., & Patel, R. K. (2001). Study of water quality index. Indian Journal of Environmental Protection, 21(9), 822–829.

21) Nagarathinam, M., Boss, M., Shylesh, D. S. D., Soundararaj, S., Ramasamy, J., Karunanandan, N., & Ulaganathan, S. (2025). Assessment of land use transformations and its impact on fluctuations in groundwater quality in Chengalpattu district, Tamil Nadu. Geology, Ecology, and Landscapes, 9(3), 1034–1045. https://doi.org/10.1080/24749508.2024.2373487

22) Patel, P. M., Saha, D., & Shah, T. (2020). Sustainability of groundwater through community-driven distributed recharge. Journal of Hydrology: Regional Studies, 29, 100680.

23) Rahman, M. M., Bodrud-Doza, M., Islam, A. R. M. T., & Rakib, M. A. (2021). Hydrochemical evaluation of groundwater quality. Environmental Nanotechnology, Monitoring & Management, 15, 100417.

24) Ravikumar, P., Somashekar, R. K., & Angami, M. (2015). Hydrochemistry and groundwater quality assessment. Environmental

Monitoring and Assessment, 187, 1–17.

25) Selvakumar, S., Chandrasekar, N., & Kumar, G. (2017). Hydrogeochemical characteristics and groundwater contamination. Environmental Earth Sciences, 76, 1–18.

26) Shukla, S., & Saxena, A. (2020). Sources and health effects of groundwater contamination.

27) Groundwater for Sustainable Development, 10, 100306.

28) Srinivasamoorthy, K., Chidambaram, S., Anandhan, P., Vasudevan, S., Vasanthavigar, M., & Manivannan, R. (2014). Hydrochemical characteristics and groundwater quality assessment. Arabian Journal of Geosciences, 7, 429–443.

29) Subba Rao, N. (2021). Hydrogeochemistry of groundwater in India. Environmental Geochemistry and Health, 43, 1–15.

30) Subba Rao, N., et al. (2023). Health risk assessment of groundwater contamination. Environmental Research, 216, 114–125.

31) Suthar, S., Bishnoi, P., Singh, S., Mutiyar, P. K., Nema, A. K., & Patil, N. S. (2009). Nitrate contamination in groundwater. Environmental Monitoring and Assessment, 148, 373–382.

32) Vasanthavigar, M., Srinivasamoorthy, K., Vijayaragavan, K., Rajiv Ganthi, R., Chidambaram, S., Anandhan, P., & Manivannan, R. (2012). Application of water quality index. Environmental Monitoring and Assessment, 184, 405–425.

33) Ward, M. H., Jones, R. R., Brender, J. D., de Kok, T. M., Weyer, P. J., Nolan, B. T., Villanueva, C. M., & van Breda, S. G. (2018). Drinking water nitrate and human health. International Journal of Environmental Research and Public Health, 15(7), 1557.

34) World Health Organization. (2017). Guidelines for drinking-water quality (4th ed.). WHO.

35) United States Environmental Protection Agency. (2005). Guidelines for human health risk assessment. USEP