

Hydro Chemical Characteristics and Heavy Metal Analysis for Quality Assessment of Groundwater in Chengalpattu District of Tamil Nadu

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Abstract: This research investigates groundwater quality in Chengalpattu district, Tamil Nadu. Fifty-one samples were collected from bore wells distributed across the study area. The hydrogeochemical characteristics and heavy metal concentrations of groundwater samples were examined to confirm their quality and their suitability for use. The hydrogeochemical parameters, including pH, electrical conductivity (EC), total dissolved solids (TDS), Alkalinity, and Turbidity, are assessed using the Lovibond potable water quality meter, while the cations (Na^+ , K^+ , Ca^{2+} , Mg^{2+}) and anions (F^- , Br^- , Cl^- , NO_2^- , NO_3^- , PO_4^{3-} , SO_4^{2-}) are analyzed via ion chromatography (IC) measurement. The mean values of the hydrogeochemical parameters, including pH, electrical conductivity (EC), alkalinity, and turbidity, are 7.45 ± 0.35 , 1121 ± 690 ($\mu\text{S}/\text{cm}$), 208.45 ± 80 (mg/l as CaCO_3), and 0.3 ± 0.9 (NTU), respectively. The general order of abundance of cations in the groundwater of this study area is $\text{K}^+ < \text{Mg}^{2+} < \text{Na}^+ < \text{Ca}^{2+}$, while that for anions is $\text{NO}_2^- < \text{F}^- < \text{PO}_4^{3-} < \text{Br}^- < \text{NO}_3^- < \text{SO}_4^{2-} < \text{Cl}^-$. Concentrations of heavy metals were quantified via inductively coupled plasma mass spectrometry (ICP-MS). $\text{Zn} > \text{Cu} > \text{Pb} > \text{Cd}$ levels in drinkable groundwater were found to be significantly lower than WHO recommended limits. Pearson correlation, factor analysis, and cluster analysis were mostly used to clarify the relationship between the groundwater sample's physical, chemical, and heavy metal characteristics and the examined parameters. Water quality was evaluated by comparing the measured parameters against Bureau of Indian Standards (BIS) and World Health Organization (WHO) guidelines.

Keywords: Groundwater quality, Hydro geochemistry, Spatial distribution, Multivariate statistical analyses.

1 Introduction

One of nature's greatest gifts to all forms of life, water is also the most essential fluid for maintaining an organism's survival. A recent study found that freshwater accounts for just 3% of the world's overall water supply, whereas saline water accounts for an estimated 97%. Only one percent of this 3% is actually used by humans. Nearly all drinkable water comes from underground sources, and groundwater makes up nearly all freshwater as well. Groundwater is being degraded and polluted in many ways as a result of human activities, including farming, household chores, and industry [1]. Most of the world's arid and semi-arid regions depend on groundwater for drinking and irrigation due to the scarcity and poor quality of surface water [2] the middle of the twentieth century. This is because of human activities such as industrialization,

population growth, poor sanitation, pollutant runoff, insufficient water quality monitoring, seasonal patterns of precipitation, and other human-made constraints [3].

It is said that over 1 billion cases of diarrhea are reported annually in underdeveloped nations due to contaminated drinking water, which impacts their health [4]. Both urban and rural areas depend on groundwater for their drinking water needs. Investigated heavy metal contamination of groundwater in the Tripura district. Significant health problems, including waterborne illnesses, skeletal fluorosis, and arsenicosis, are caused by groundwater [5].

One of the primary issues in India is the excessive use or degradation of groundwater [6]. The pH scale is the accepted norm for determining the alkalinity of water. An important component in determining the pH of a certain

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sample is the concentration of bicarbonates, calcium, and carbonate in the water [7]. Human excrement is the most reliable indicator for determining the quantity of chloride that humans consume. Water is usually regarded as unfit for human consumption due to its saltiness caused by excessive chloride levels [8].

Many people throughout the world suffer from chronic and acute diseases due to water which isn't fit for human consumption. For a number of people, the aforementioned health issues rank high among the leading causes of death. The need to enhance the management, monitoring, and evaluation of water resource quality has grown in together with the population because of increased demand for water for various purposes, such as domestic, industrial, agricultural, and recreational uses [9].

Representing spatial and temporal variations in groundwater quality parameters, determining groundwater quality between distant sampling points, and depicting the overall status of groundwater quality in a region covered by a source of water can all be accomplished with the help of geostatistical techniques, geographic information systems (GIS), and useful GIS software like ArcGIS [10].

Numerous studies have documented groundwater quality degradation attributed to effluent releases from septic tanks, soak pits, pit latrines, leaky domestic wastewater drains, and leachate originating from solid waste dumpsites [11,12].

Heavy metal concentrations in pre-monsoon groundwater samples were lower compared to post-monsoon levels in the arid regions surrounding Hyderabad, Sindh by [13].

The absence of comprehensive groundwater quality assessments for drinking purposes in Chengalpattu District, Tamil Nadu, India, exposes local populations to various health risks associated with consuming contaminated water. The main objective of this work is to assess the groundwater and surface water quality for drinking and irrigation purposes. In this work a baseline data on anion, cation and heavy metal in the study area is presented and multi variate statistical methods, including Pearson's correlation, factor analysis, and cluster analysis, were performed to to know the factors governing groundwater chemistry as well as water quality data [14].

Consequently, this systematic investigation was conducted to assess groundwater quality and its suitability for various uses. The collected data were documented for archival purposes and potential applications in future studies.

2 Description of the study area

The study area is situated in the southeastern part of India, covering a total area of 2659.4 square kilometers. It spans from latitude $12^{\circ} 13' 41''$ N to $13^{\circ} 1' 42''$ N and from longitude $79^{\circ} 38' 32''$ E to $80^{\circ} 15' 19''$ E (Fig 1). The study area is bordered by Chennai in the North, Kancheepuram district in the Northwest, Tiruvannamalai district in the West, Villupuram district in the south, and the Bay of Bengal to the East. This district is divided into eight taluks. As of the 2011 census, the population of this area is 2,556, 244, with a population density of 1123 people per square kilometer. The mean elevation is 30.36 m. Fig 1. shows Geology map of Chengalpattu. The district has sedimentary and fissured formations, with aquifer systems consisting of unconsolidated, semi-consolidated, Charnokite Gneissic complex and weathered crystalline rocks. Gondwana sandstones, shales, and Tertiary mottled clays act as porous, semi- consolidated sediments, with groundwater found under water table conditions in sandstones, sands, and thin shale fractures, typically at depths of 5 to 10-m bgl.

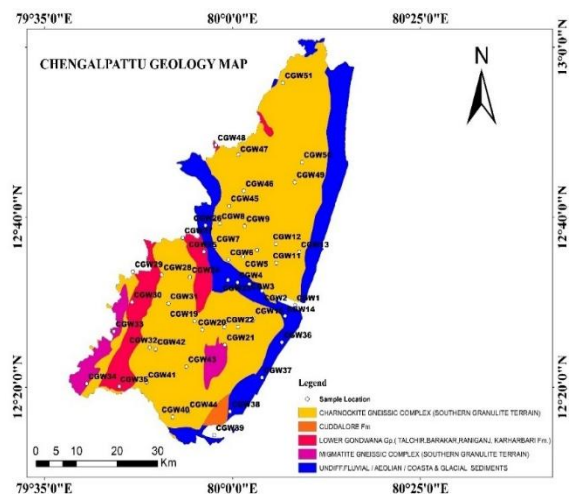


Fig. 1 :Geological map of Chengalpattu District.

Agriculture is the primary occupation in the district, which is well connected by an efficient transportation network. Chengalpattu District experiences a tropical wet-and-dry climate, with an average annual temperature of 27.8°C . The 57 km coastline along the Bay of Bengal moderates the regional climate. According to the India Meteorological Department (IMD), the district receives an average annual rainfall of 1236.8 mm, mainly during the Northeast monsoon (October–November), which serves as the primary source of groundwater recharge [15]. Groundwater quality in Chengalpattu District is influenced by geological formations, land-use practices, and anthropogenic activities. The study area comprises diverse lithological units that control groundwater occurrence and hydrogeochemical characteristics. The lithological map and groundwater sampling locations are shown in Fig 2.

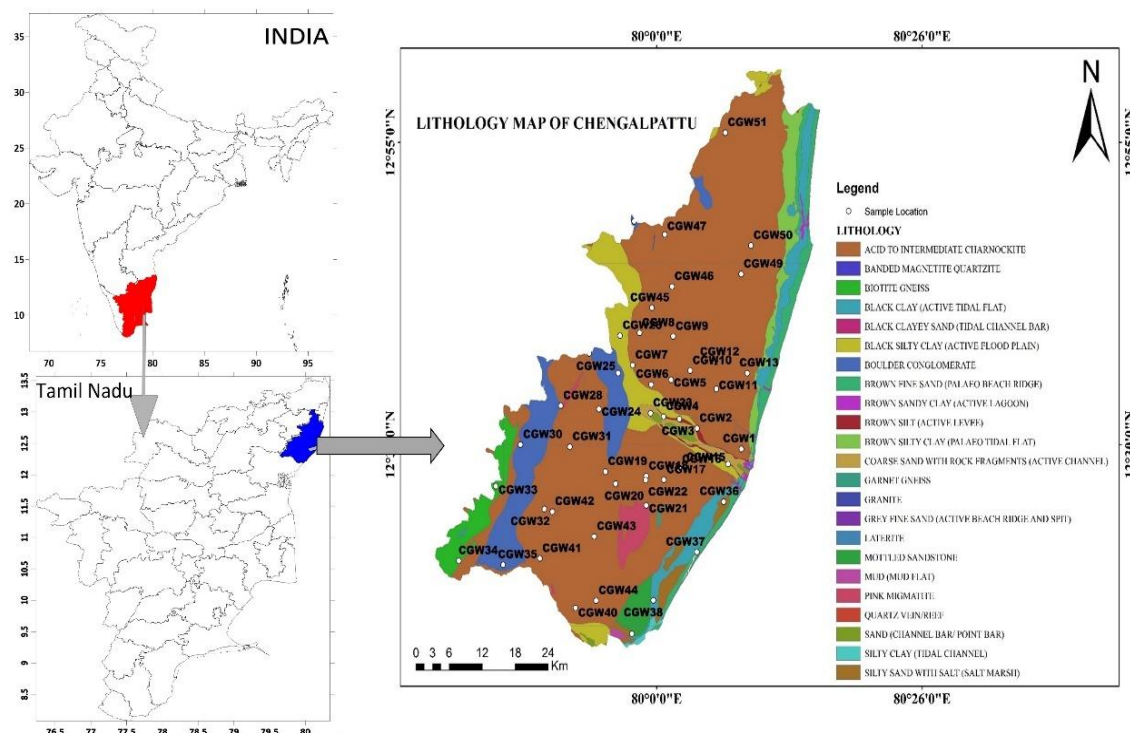


Fig. 2: Lithological map of Chengalpattu District showing the groundwater sampling locations.

3 Sample Collection

The study area was divided into grids using QGIS software, and groundwater samples were collected from representative locations within each grid to ensure uniform spatial coverage [16]. A lithological map obtained from the Geological Survey of India's Bhuvan portal was used to identify the underlying geological formations and sampling locations [17]. Groundwater samples were collected in pre-cleaned 1-L polyethylene bottles following standard sampling protocols [18]. Bore wells were purged for 5 min prior to sampling, and the bottles were rinsed with the sample water before collection. Temperature and GPS coordinates were recorded in situ, and the samples were transported to the laboratory under appropriate conditions for analysis. A total of 51 groundwater samples were collected from Chengalpattu District, Tamil Nadu.

4 Material and methods

All chemicals and reagents used in this study were of analytical grade (Merck, Germany).

Standard metal ion solutions (Merck, Germany) and deionized water were used for sample preparation and analysis. Samples for trace metal analysis were filtered through a 0.45 μm membrane filter, and all glassware and

sample containers were acid-cleaned following standard laboratory procedures [19]. Physicochemical parameters, including pH, electrical conductivity (EC), total dissolved solids (TDS), alkalinity, and turbidity, were measured using a Lovibond potable water quality meter according to standard analytical procedures [20]. Major anions and cations were determined using an ion chromatograph (Metrohm 930, Switzerland), while trace metal concentrations were determined using an inductively coupled plasma mass spectrometer (ICP-MS; ELAN DRC-e, PerkinElmer, USA). Histograms were used to examine the frequency distribution of groundwater quality parameters and to identify data distribution patterns, variability, and potential outliers. Spatial analysis was performed to evaluate the distribution patterns of groundwater quality parameters across the study area. Spatial interpolation techniques were applied to generate contour maps and identify areas with low and high concentrations of the measured parameters.

5 Result and Discussion.

5.1 pH

The pH of the groundwater samples ranged from 6.6 (CGW39) to 8.1 (CGW7), with a mean value of 7.45, indicating slightly alkaline groundwater. All measured pH

values were within the WHO (2011) recommended range (6.5–8.5), confirming the suitability of the groundwater for drinking purposes [21]. The spatial distribution of pH is presented in Fig 3(a), while the corresponding frequency distribution is shown in Fig 3(b).

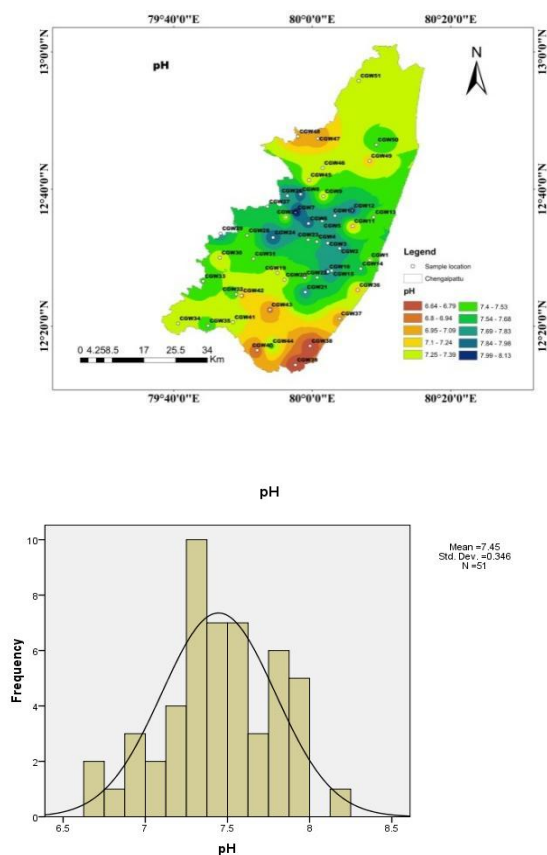
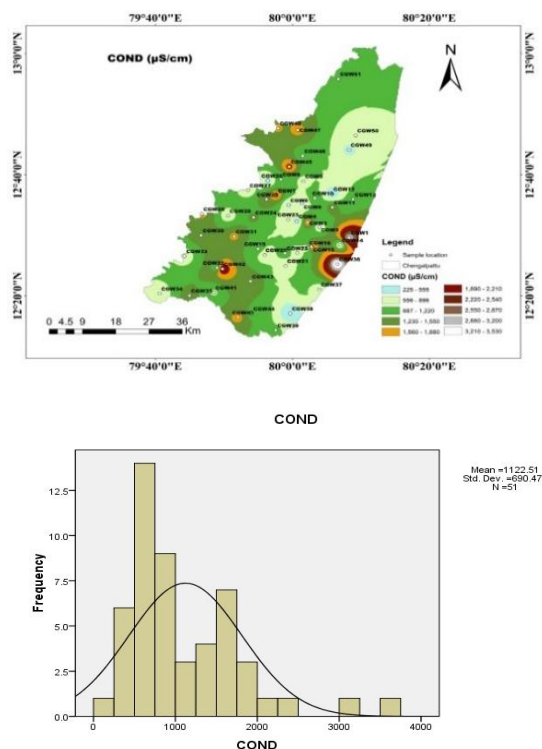


Fig.3: (a) Spatial contour map and (b) histogram of groundwater pH in Chengalpattu District.

5.2 Electrical Conductivity

Electrical conductivity (EC) is an indicator of the dissolved ionic content of groundwater and reflects the degree of mineralization resulting from water–rock interactions. In the present study, EC values ranged from 224.6 $\mu\text{S}/\text{cm}$ (CGW12) to 3535 $\mu\text{S}/\text{cm}$ (CGW36), with a mean value of 1122.5 $\mu\text{S}/\text{cm}$. The elevated EC observed at CGW36,

located near the coastal region, may be attributed to increased salinity and the dissolution of dissolved minerals. Higher EC values indicate greater ionic concentrations, which may affect the suitability of groundwater for drinking if associated with excessive dissolved salts [22]. The spatial distribution of EC across the study area is presented in Fig. 4(a). The histogram (Fig. 4b) exhibits a positively skewed distribution, indicating that only a few sampling locations recorded relatively high EC values.



suspended sediments or localized surface runoff. Increased turbidity can reduce the aesthetic quality of drinking water and may interfere with disinfection processes. The spatial distribution of turbidity is presented in Fig 6(a), while the histogram Fig 6(b), exhibits a positively skewed distribution, indicating that only one sampling location recorded a relatively high turbidity value.

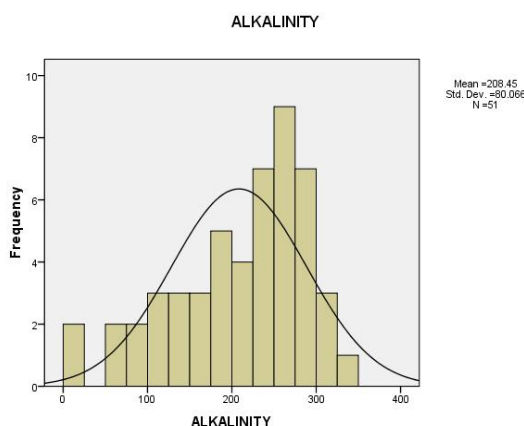
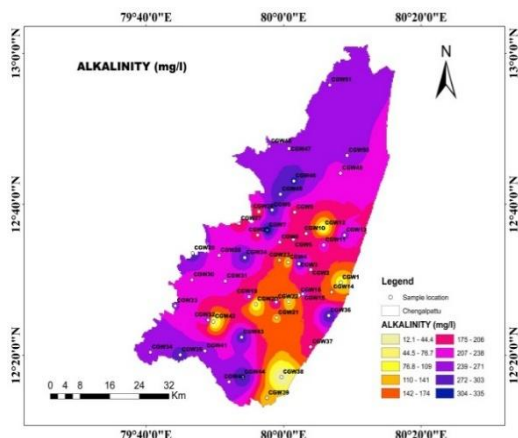


Fig. 5: (a) Spatial contour map and (b) histogram of groundwater Alkalinity in Chengalpattu District.

5.5 Fluoride

Fluoride is an essential trace element for dental health; however, excessive exposure may cause dental and skeletal fluorosis [23,24]. In the present study, fluoride concentrations ranged from 0.04 mg/L (CGW37) to 1.56 mg/L (CGW33), with a mean value of 0.522 mg/L. Most groundwater samples were within the WHO (2011) recommended limit of 1.5 mg/L, while only one sample (CGW33) slightly exceeded this guideline [21]. The elevated fluoride concentration may be attributed to the dissolution of fluoride-bearing minerals from the aquifer matrix. The spatial distribution of fluoride is presented in (Fig. 7 a), and the histogram (Fig. 7b) indicates an approximately normal distribution of fluoride concentrations across the study area.

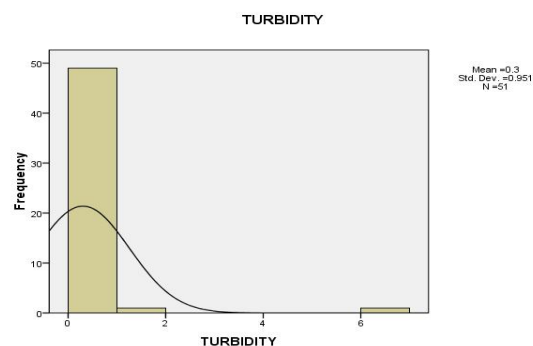
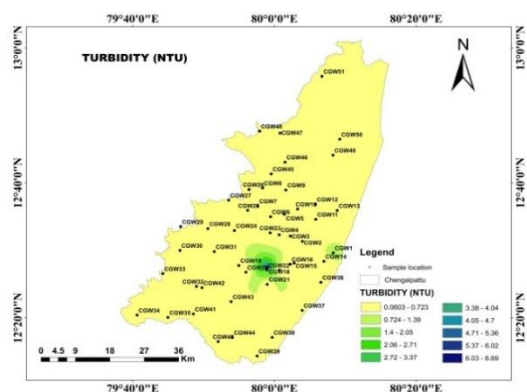


Fig. 6:(a) Spatial contour map and (b) histogram of groundwater Turbidity in Chengalpattu District.

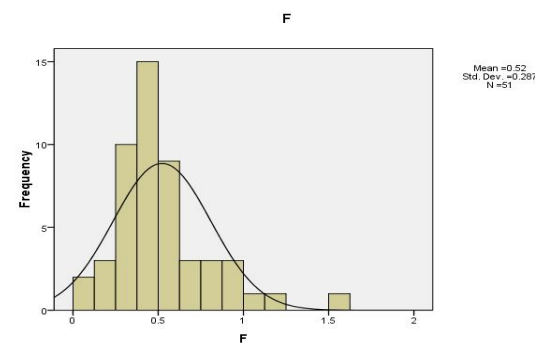
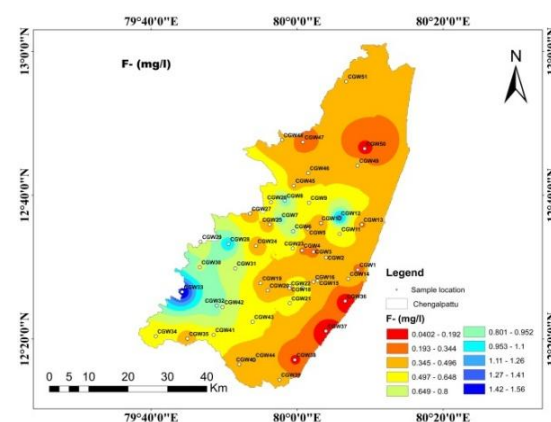


Fig.7: (a) Spatial contour map and (b) histogram of groundwater Fluoride in Chengalpattu District.

5.6 Chloride

Chloride (Cl^-) is a major anion in groundwater and is commonly derived from natural weathering processes as well as anthropogenic activities [25]. In the present study, chloride concentrations ranged from 12.20 mg/L to 918.78 mg/L, with a mean value of 178.89 mg/L. Eleven groundwater samples (CGW1, CGW3, CGW7, CGW14, CGW35, CGW39, CGW41, CGW42, CGW43, CGW45, and CGW47) exceeded the WHO (2011) recommended limit of 250 mg/L [21]. The elevated chloride concentrations may be attributed to seawater intrusion, rock weathering, domestic wastewater, agricultural activities, and industrial effluents. High chloride levels can impair the taste of drinking water and indicate groundwater quality deterioration [26]. The spatial distribution of chloride is presented in (Fig. 8a), while the histogram (Fig. 8b) exhibits a positively skewed distribution, indicating that relatively high chloride concentrations were observed at only a few sampling locations.

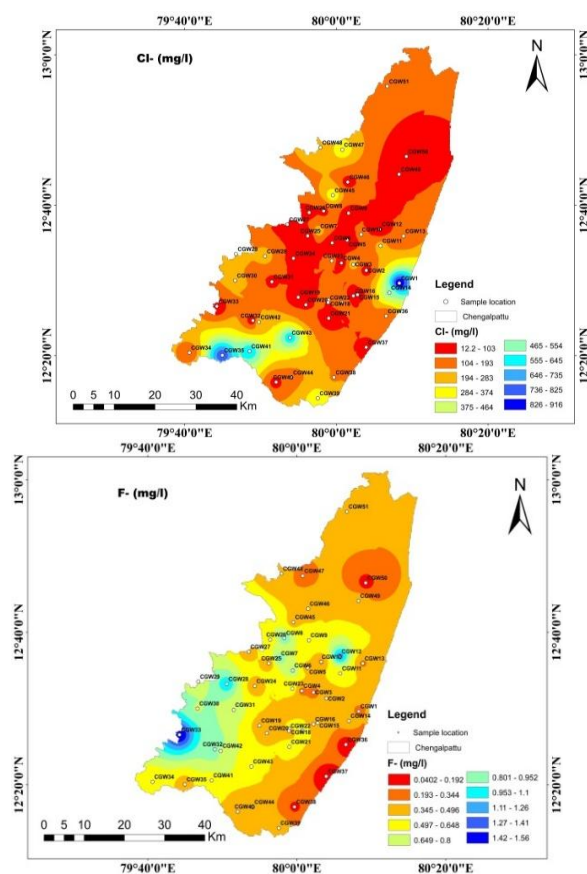


Fig. 8: (a) Spatial contour map and (b) histogram of groundwater Chloride in Chengalpattu District.

5.7 Nitrate

Nitrate (NO_3^-) is one of the major contaminants in groundwater and is commonly associated with agricultural and anthropogenic activities [27]. In the present study, nitrate concentrations ranged from 0.05 mg/L (CGW6) to 136.20 mg/L (CGW11), with a mean value of 27.3 mg/L. Seven groundwater samples (CGW3, CGW11, CGW34, CGW36, CGW39, CGW42, and CGW48) exceeded the WHO (2011) recommended limit of 50 mg/L [21]. The elevated nitrate concentrations may be attributed to the excessive use of fertilizers, domestic wastewater, and agricultural runoff. High nitrate levels in drinking water may pose health risks, particularly methemoglobinemia in infants [28]. The spatial distribution of nitrate is presented in Fig. 9(a), while the histogram (Fig. 9b) exhibits a positively skewed distribution, indicating that elevated nitrate concentrations occurred only at a few sampling locations.

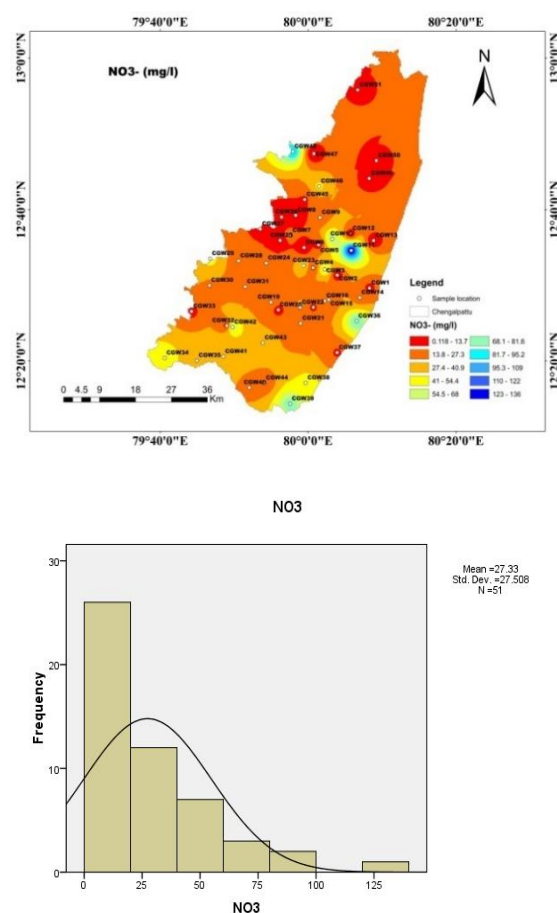


Fig. 9: (a) Spatial contour map and (b) histogram of groundwater Nitrate in Chengalpattu District.

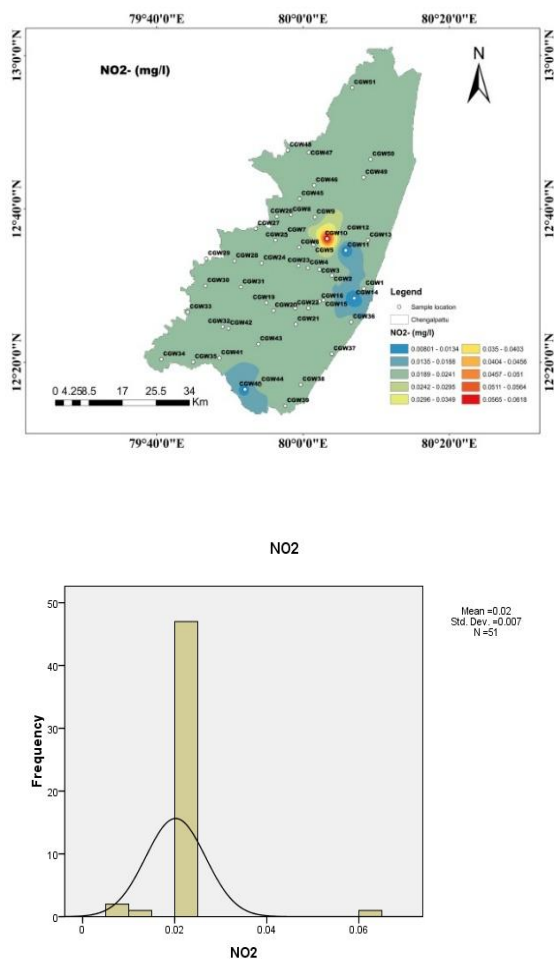


Fig. 10: (a) Spatial contour map and (b) histogram of groundwater Nitrite in Chengalpattu District.

Nitrite (NO_2^-) is an intermediate nitrogen species in groundwater and serves as an indicator of nitrogen transformation processes. In the present study, nitrite concentrations ranged from 0.0080 mg/L (CGW11 and CGW14) to 0.0620 mg/L (CGW10), with a mean value of 0.0202 mg/L. All groundwater samples were well below the WHO (2011) guideline value of 3 mg/L [21] and the BIS (2012) acceptable limit of 1 mg/L [29], indicating no significant nitrite contamination in the study area. The spatial distribution of nitrite is presented in (Fig. 10a), while the histogram (Fig. 10b) indicates an approximately normal distribution of nitrite concentrations across the study area.

5.9 Phosphate

Phosphate (PO_4^{3-}) is an essential nutrient commonly introduced into groundwater through natural processes and anthropogenic activities, particularly agricultural practices [30]. In the present study, phosphate concentrations ranged from 0.05 to 5.20 mg/L, with a mean value of 0.28 mg/L.

Most groundwater samples were within the recommended range of 0.2–1.4 mg/L [30], whereas slightly elevated concentrations were observed at CGW3 and CGW10. The increased phosphate levels at these locations may be attributed to fertilizer application, domestic wastewater, and localized industrial activities. The spatial distribution of phosphate is presented in Fig. 11(a), while the histogram (Fig. 11b) exhibits a positively skewed distribution, indicating that elevated phosphate concentrations were confined to a few sampling locations.

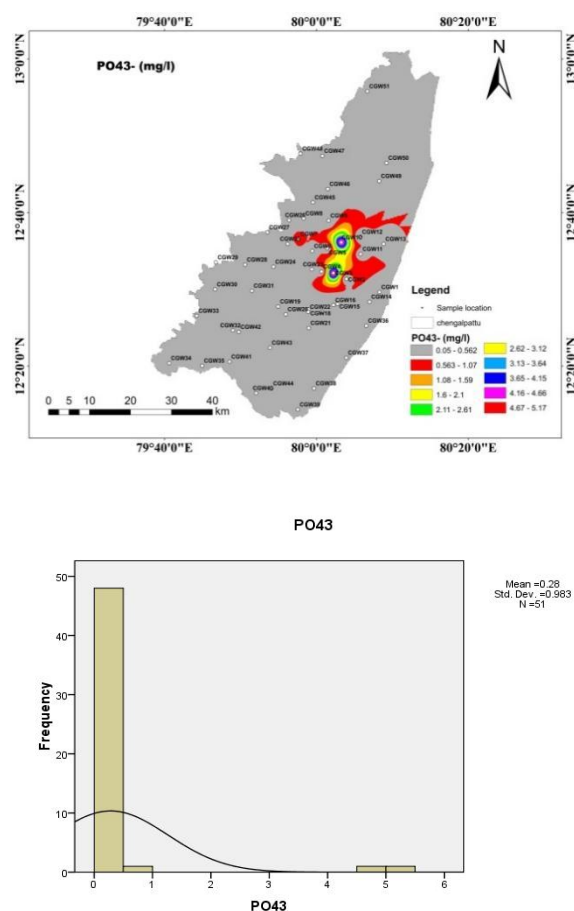


Fig.11: (a) Spatial contour map and (b) histogram of groundwater Phosphate in Chengalpattu District.

5.10 Sulphate

Sulphate (SO_4^{2-}) is a naturally occurring anion in groundwater derived from the weathering of Sulphate - bearing minerals and anthropogenic activities [31]. In the present study, Sulphate concentrations ranged from 4.65 mg/L (CGW6) to 551.20 mg/L (CGW24), with a mean value of 65.05 mg/L. Most groundwater samples were within the WHO (2011) recommended limit of 500 mg/L, while only one sample (CGW24) slightly exceeded this guideline [21]. The elevated Sulphate concentration at CGW24 may be associated with geological formations or localized anthropogenic inputs. High Sulphate

concentrations may impart a bitter taste to water and produce a laxative effect in sensitive individuals [31]. The spatial distribution of Sulphate is presented in (Fig. 12 a), while the histogram (Fig. 12b) exhibits a positively skewed distribution, indicating that elevated Sulphate concentrations occurred at only a few sampling locations.

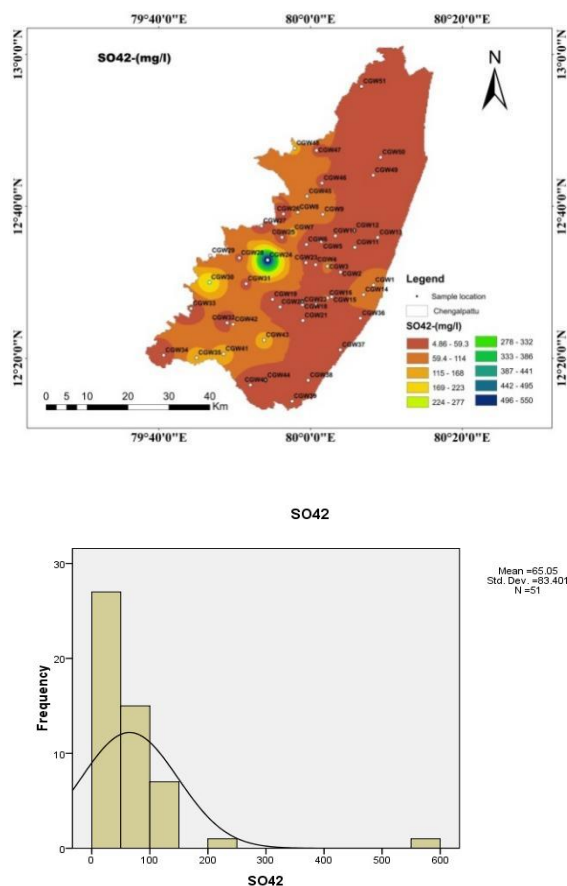


Fig.12: (a) Spatial contour map and (b) histogram of groundwater Sulphate in Chengalpattu District.

5.11 Sodium

Sodium (Na⁺) is one of the major cations in groundwater and is primarily derived from water-rock interactions and anthropogenic activities. In the present study, sodium concentrations ranged from 9.81 mg/L (CGW12) to 370.02 mg/L (CGW1), with a mean value of 90.83 mg/L. Most groundwater samples were within the WHO (2011) recommended limit of 200 mg/L, while only two samples (CGW1 and CGW28) exceeded this guideline [21]. The elevated sodium concentrations may be attributed to seawater intrusion, weathering of sodium-bearing minerals (e.g., feldspar and halite), and agricultural activities. High sodium concentrations may adversely affect drinking water quality and may pose health concerns for individuals with sodium-restricted diets. The spatial distribution of sodium is presented in (Fig. 13a), while the histogram (Fig. 13b) exhibits a positively skewed distribution, indicating that

elevated sodium concentrations occurred at only a few sampling locations.

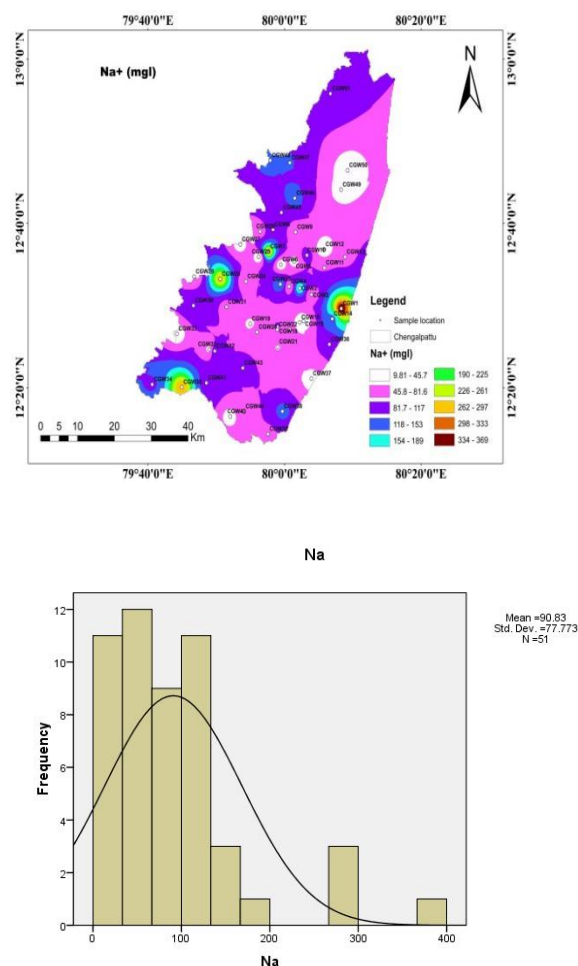


Fig.13: (a) Spatial contour map and (b) histogram of groundwater Sodium in Chengalpattu District.

5.12 Potassium

Potassium (K⁺) is a naturally occurring cation in groundwater, primarily derived from the weathering of potassium-bearing minerals and anthropogenic activities [32,33]. In the present study, potassium concentrations ranged from 0.36 mg/L to 139.02 mg/L, with a mean value of 8.20 mg/L. Four groundwater samples (CGW3, CGW7, CGW10, and CGW35) exceeded the recommended limit of 20 mg/L [21]. The elevated potassium concentrations may be associated with mineral weathering, agricultural practices, and localized industrial activities. Although potassium generally poses minimal health risks at typical concentrations, elevated levels may indicate groundwater quality deterioration. The spatial distribution of potassium is presented in (Fig. 14a), while the histogram (Fig. 14b) exhibits a positively skewed distribution, indicating that elevated potassium concentrations were confined to a few

sampling locations.

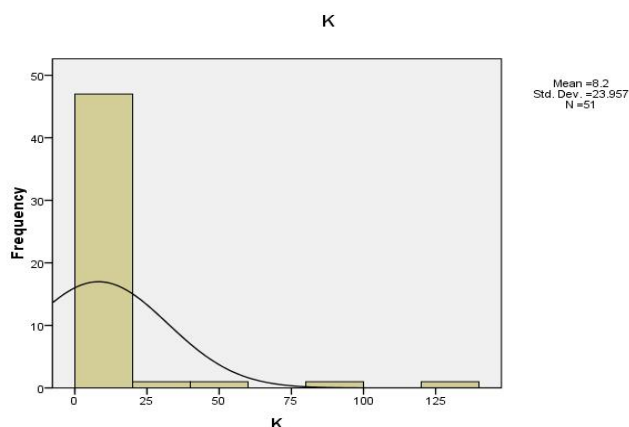
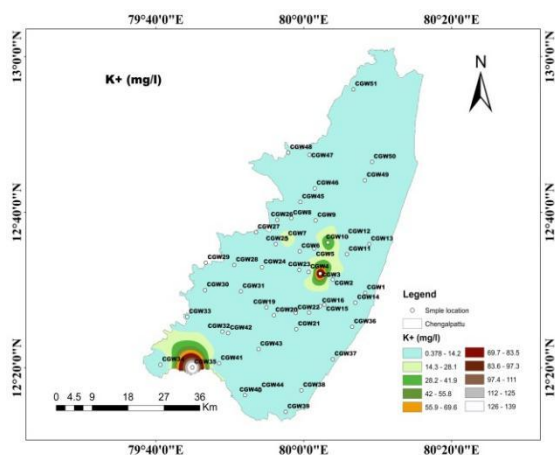


Fig. 14: (a) Spatial contour map and (b) histogram of groundwater Potassium in Chengalpattu District.

5.13 Magnesium

Magnesium (Mg^{2+}) is a naturally occurring cation in groundwater, primarily derived from the weathering of carbonate and silicate minerals, particularly dolomite and calcite [34]. In the present study, magnesium concentrations ranged from 4.18 mg/L (CGW37) to 107.16 mg/L (CGW45), with a mean value of 35.51 mg/L. The WHO (2011) recommends a desirable limit of 50 mg/L and a permissible limit of 150 mg/L for magnesium in drinking water [21]. Most groundwater samples were within the desirable limit, while all samples remained below the permissible limit. The spatial distribution of magnesium is presented in (Fig. 15a), and the histogram (Fig. 15b) indicates an approximately normal distribution of magnesium concentrations across the study area.

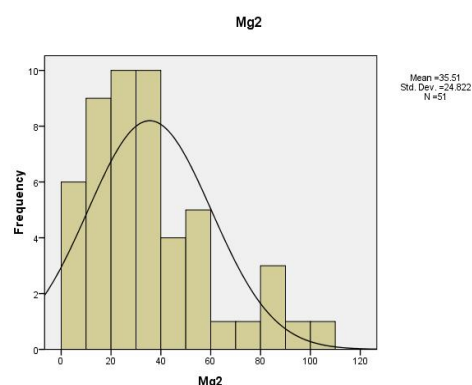
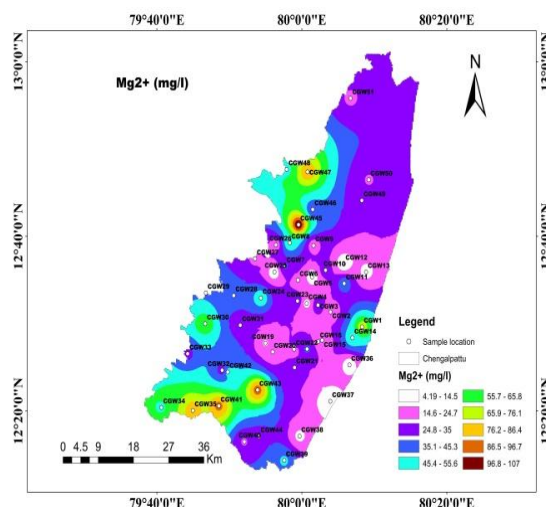


Fig. 15: (a) Spatial contour map and (b) histogram of groundwater Magnesium in Chengalpattu District.

5.14 Calcium

Calcium (Ca^{2+}) is a major cation in groundwater and is primarily derived from the weathering of calcium-bearing minerals, such as limestone, dolomite, and gypsum [34]. In the present study, calcium concentrations ranged from 12.33 mg/L (CGW37) to 327.35 mg/L (CGW43), with a mean value of 91.93 mg/L. Twelve groundwater samples (CGW1, CGW11, CGW16, CGW18, CGW21, CGW24, CGW29, CGW30, CGW39, CGW41, CGW42, and CGW43) exceeded the WHO (2004) recommended limit of 100 mg/L [35]. The elevated calcium concentrations may be attributed to the dissolution of calcium-bearing rocks and localized agricultural activities, including the application of lime and calcium-based fertilizers. High calcium concentrations contribute to water hardness and may affect the aesthetic quality of drinking water [34]. The spatial distribution of calcium is presented in Fig. 16(a),

while the histogram (Fig. 16b) exhibits a positively skewed distribution, indicating that elevated calcium concentrations were observed at only a few sampling locations.

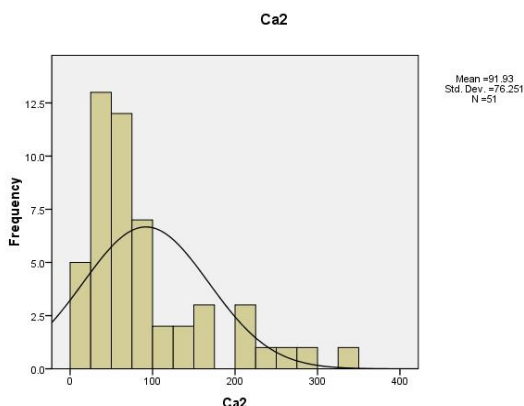
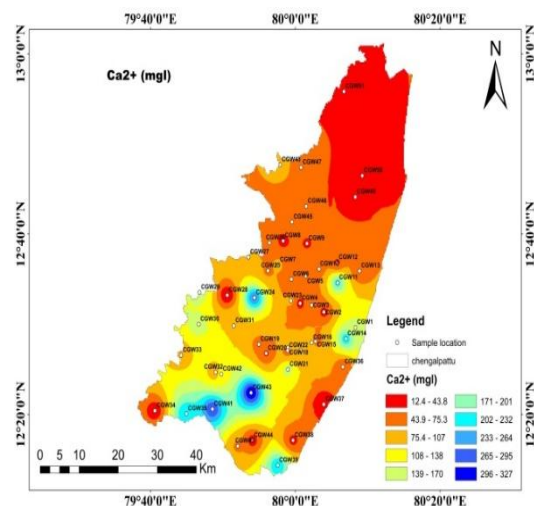


Fig. 16: (a) Spatial contour map and (b) histogram of groundwater Calcium in Chengalpattu District.

5.15 Bromide

Bromide (Br^-) is a naturally occurring anion in groundwater, primarily derived from seawater intrusion, mineral weathering, and anthropogenic activities. In the present study, bromide concentrations ranged from 0.287 mg/L (CGW37) to 5.950 mg/L (CGW1), with a mean value of 1.785 mg/L. The elevated bromide concentrations observed at a few sampling locations may be associated with coastal influence and localized agricultural activities involving bromide-containing compounds. Although bromide itself is generally not considered toxic at environmental concentrations, it is of concern because it can form potentially harmful disinfection by-products

during water treatment. The spatial distribution of bromide is presented in (Fig. 17a), while the histogram (Fig. 17b) exhibits a positively skewed distribution, indicating that elevated bromide concentrations were confined to a few sampling locations.

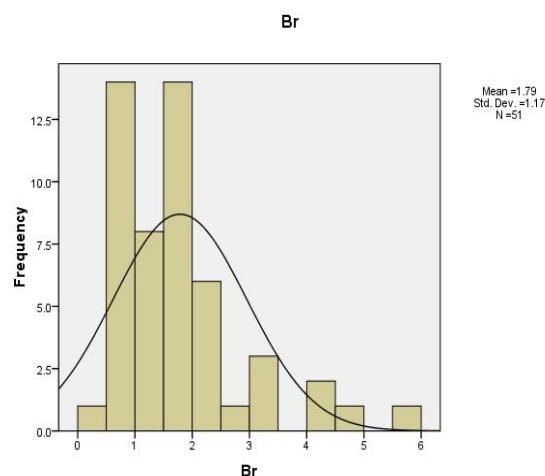
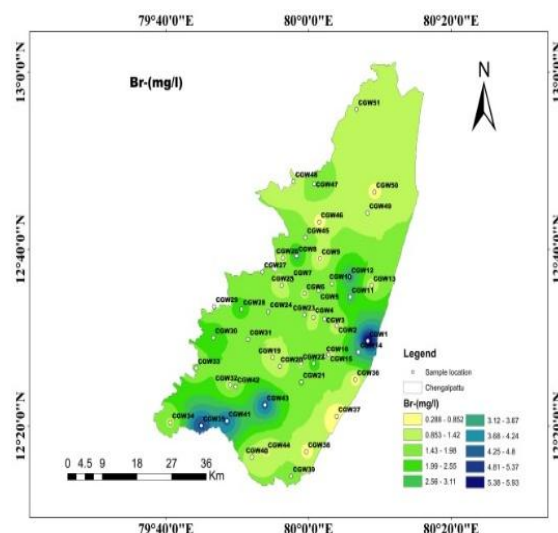


Fig.17: (a) Spatial contour map and (b) histogram of groundwater Bromide in Chengalpattu District.

5.16 Carbonate

Carbonate (CO_3^{2-}) is a naturally occurring constituent of groundwater and contributes to the carbonate equilibrium that influences water chemistry and alkalinity. In the present study, carbonate concentrations ranged from 2.84 mg/L (CGW12) to 90.56 mg/L (CGW40), with a mean value of 22.66 mg/L. All groundwater samples were well below the WHO (2011) reference value of 300 mg/L [21]. The observed carbonate concentrations are primarily attributed to the weathering of carbonate-bearing minerals

and natural geochemical processes within the aquifer. The spatial distribution of carbonate is presented in (Fig. 18a), while the histogram (Fig. 18b) indicates an approximately normal distribution of carbonate concentrations across the study area.

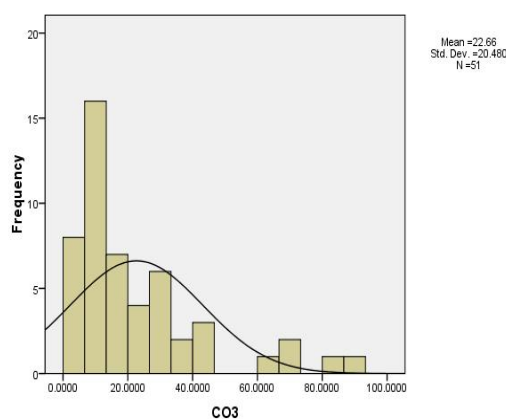
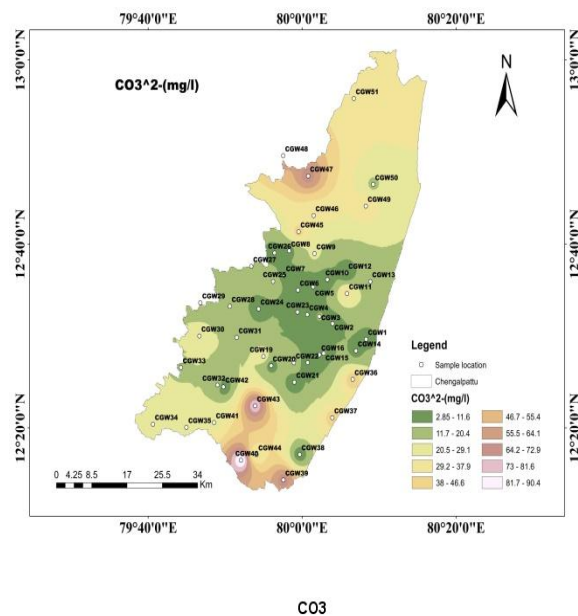


Fig.18: (a) Spatial contour map and (b) histogram of groundwater Carbonate in Chengalpattu District.

5.17 Bicarbonate

Bicarbonate (HCO_3^-) is a major anion in groundwater and plays an important role in the carbonate buffering system that controls water chemistry and alkalinity [36]. In the present study, bicarbonate concentrations ranged from 5.93 mg/L (CGW38) to 329.45 mg/L (CGW7), with a mean value of 185.91 mg/L. Ten groundwater samples (CGW3, CGW7, CGW8, CGW24, CGW29, CGW35, CGW36, CGW44, CGW45, and CGW46) exceeded the reference value of 250 mg/L [37]. The elevated bicarbonate concentrations may be attributed to the dissolution of

carbonate minerals, such as limestone and dolomite, as well as localized anthropogenic influences. High bicarbonate levels can contribute to water hardness and scaling in distribution systems. The spatial distribution of bicarbonate is presented in (Fig. 19a), while the histogram (Fig. 19b) indicates an approximately normal distribution of bicarbonate concentrations across the study area.

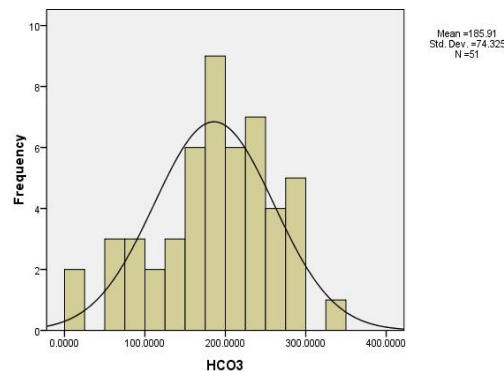
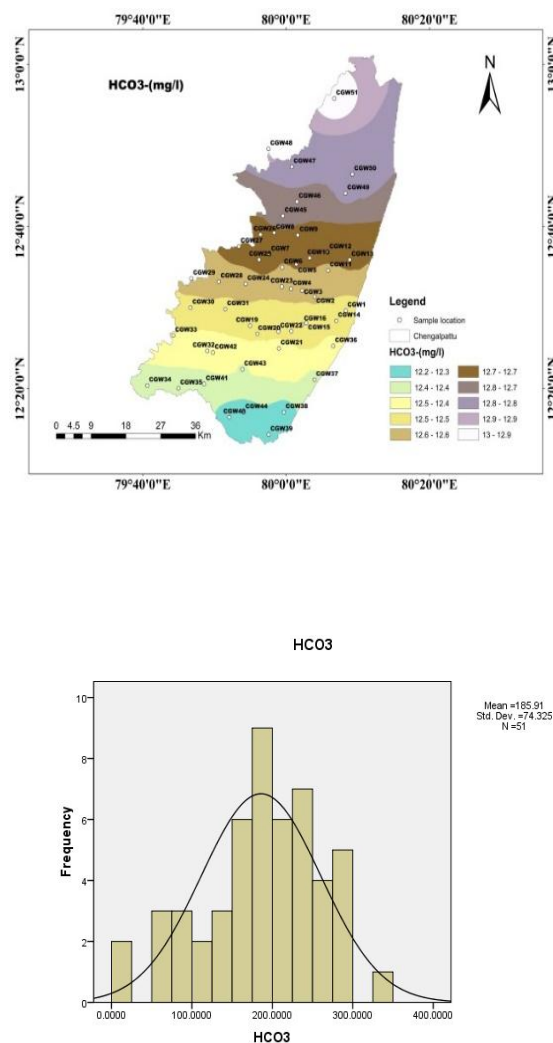


Fig.19: (a) Spatial contour map and (b) histogram of groundwater Bicarbonate in Chengalpattu District.

5.18 Total Dissolved Solids (TDS)

Total dissolved solids (TDS) represent the combined concentration of dissolved inorganic salts and organic substances in groundwater. In the present study, TDS concentrations ranged from 143.74 mg/L (CGW12) to 2262.40 mg/L (CGW36), with a mean value of 718.41 mg/L. Twelve groundwater samples (CGW1, CGW3, CGW7, CGW15, CGW29, CGW31, CGW36, CGW40, CGW42, CGW45, CGW47, and CGW48) exceeded the

recommended limit of 1000 mg/L [21]. The elevated TDS levels may be attributed to mineral dissolution, seawater intrusion, and anthropogenic activities, including agricultural practices and domestic wastewater. High TDS concentrations may affect the palatability of drinking water and indicate reduced groundwater quality [38]. The spatial distribution of TDS is presented in (Fig. 20a), while the histogram (Fig. 20b) exhibits a positively skewed distribution, indicating that elevated TDS concentrations occurred at only a few sampling locations.

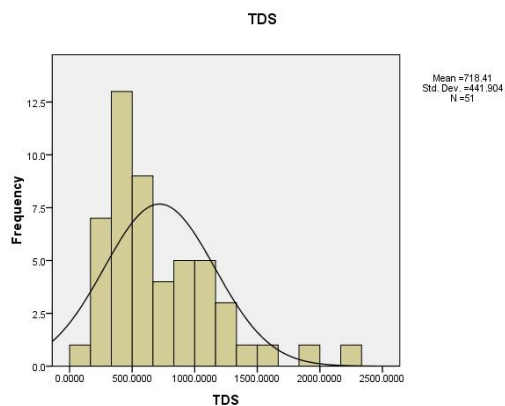
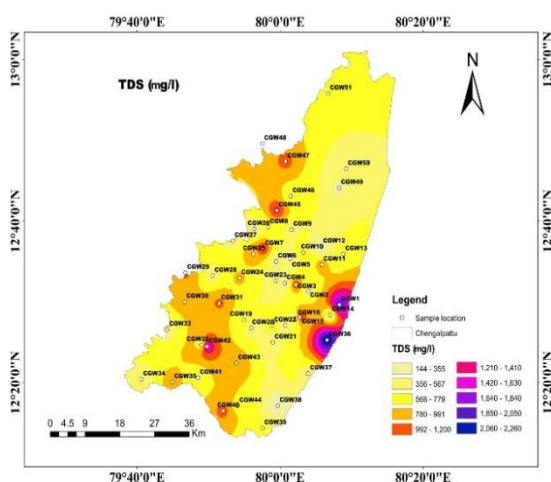
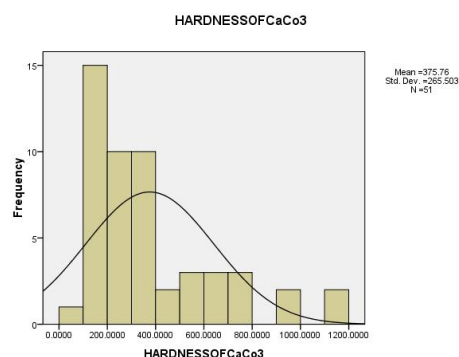
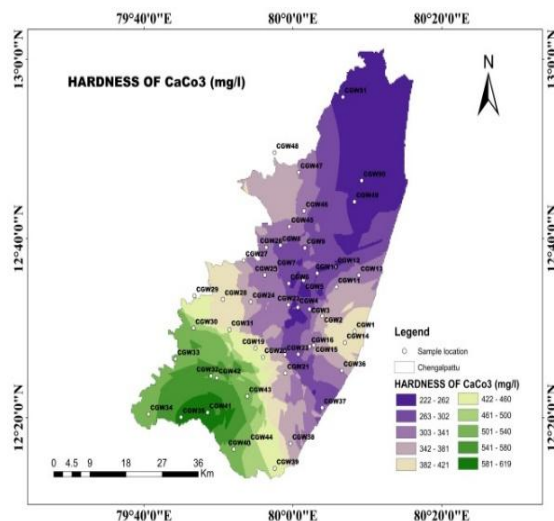


Fig. 20: (a) Spatial contour map and (b) histogram of groundwater TDS in Chengalpattu District.

5.19 Hardness

Hardness (as CaCO_3) is primarily determined by the concentrations of calcium (Ca^{2+}) and magnesium (Mg^{2+}) ions in groundwater and reflects the degree of mineralization [39]. In the present study, total hardness ranged from 48.00 mg/L (CGW37) to 1194.84 mg/L (CGW43), with a mean value of 375.76 mg/L. Thirteen groundwater samples (CGW1, CGW11, CGW14, CGW21,

CGW24, CGW29, CGW30, CGW35, CGW39, CGW41, CGW42, CGW43, and CGW45) exceeded the recommended limit of 500 mg/L [21]. The elevated hardness values are primarily attributed to the dissolution of calcium- and magnesium-bearing minerals within the aquifer. High water hardness may contribute to scaling in water distribution systems and reduce the aesthetic quality of drinking water, although it is not generally considered a direct health risk [40,41]. The spatial distribution of hardness is presented in (Fig. 21a), while the histogram (Fig. 21b) exhibits a positively skewed distribution, indicating that elevated hardness values occurred at only a few sampling locations.



Trace Elements (Pb, Cd, Zn, and Cu)

Fig. 21: (a) Spatial contour map and (b) histogram of groundwater Hardness in Chengalpattu District.

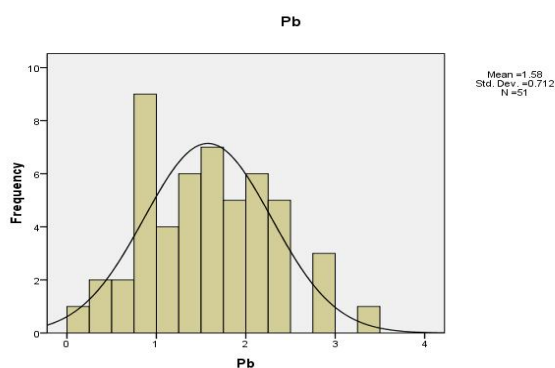
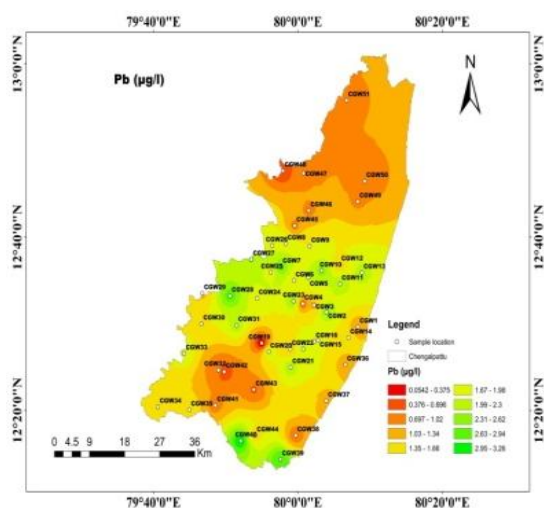


Fig.22: (a) Spatial contour map and (b) histogram of groundwater Lead in Chengalpattu District.

5.20 Lead (Pb)

Lead (Pb) is a toxic trace metal of environmental concern due to its persistence and potential adverse health effects. In the present study, lead concentrations ranged from 0.05 µg/L (CGW19) to 3.26 µg/L (CGW40), with a mean value of 1.57 µg/L. All groundwater samples were well below the WHO (2011) and BIS (2012) guideline value of 10 µg/L [21,29], indicating no significant lead contamination in the study area. The low lead concentrations suggest limited anthropogenic influence and favorable groundwater quality with respect to lead. The spatial distribution of lead is presented in (Fig. 22a), while the histogram (Fig. 22b) indicates an approximately normal distribution of lead concentrations across the study area.

5.21 Cadmium (Cd)

Cadmium (Cd) is a toxic trace metal of environmental concern because of its persistence and potential adverse health effects [42]. In the present study, cadmium concentrations at all sampling locations were well below the WHO (2011) and BIS (2012) guideline value of 3 µg/L [21,29], indicating the absence of significant cadmium contamination in the groundwater. The consistently low cadmium concentrations suggest minimal anthropogenic influence within the study area. The spatial distribution of cadmium is presented in (Fig. 23 a). The histogram (Fig. 23b) shows a uniform distribution, reflecting the negligible variation in cadmium concentrations among the groundwater samples.

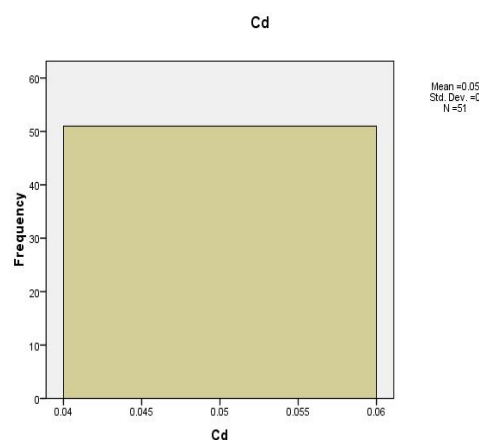


Fig.23: (a) Spatial contour map and (b) histogram of groundwater Cadmium in Chengalpattu District.

5.22 Zinc (Zn)

Zinc (Zn) is an essential trace element that occurs naturally in groundwater through the weathering of zinc-bearing minerals and anthropogenic activities [43]. In the present study, zinc concentrations ranged from 3.40 µg/L (CGW42) to 55.48 µg/L (CGW3), with a mean value of 20.05 µg/L. All groundwater samples were well below the WHO (2011) guideline value of 3000 µg/L and the BIS (2012) acceptable limit of 5000 µg/L [21,29], indicating the absence of significant zinc contamination in the study area. The low zinc concentrations suggest minimal anthropogenic influence on groundwater quality. The spatial distribution of zinc is presented in Fig. 24(a), while the histogram (Fig. 24b) indicates an approximately normal distribution of zinc concentrations across the study area.

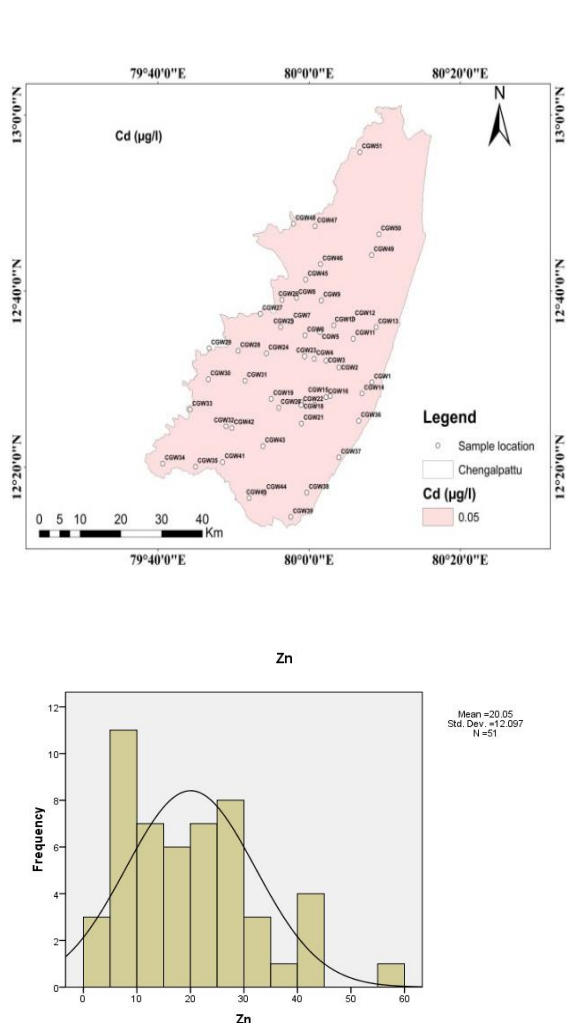


Fig.24:(a) Spatial contour map and (b) histogram of groundwater Zinc in Chengalpattu District.

5.23 Copper (Cu)

Copper (Cu) is an essential trace element that occurs naturally in groundwater through mineral weathering and, to a lesser extent, anthropogenic activities. In the present study, copper concentrations ranged from 0.05 µg/L (CGW43) to 21.82 µg/L (CGW7). All groundwater samples were well below the WHO (2011) guideline value of 2000 µg/L, indicating the absence of significant copper contamination in the study area [21]. The low copper concentrations suggest that groundwater quality has not been adversely affected by copper-related sources. The spatial distribution of copper is presented in Fig. 25(a), while the histogram (Fig. 25b) exhibits a bimodal distribution, indicating the presence of two distinct concentration groups within the dataset.

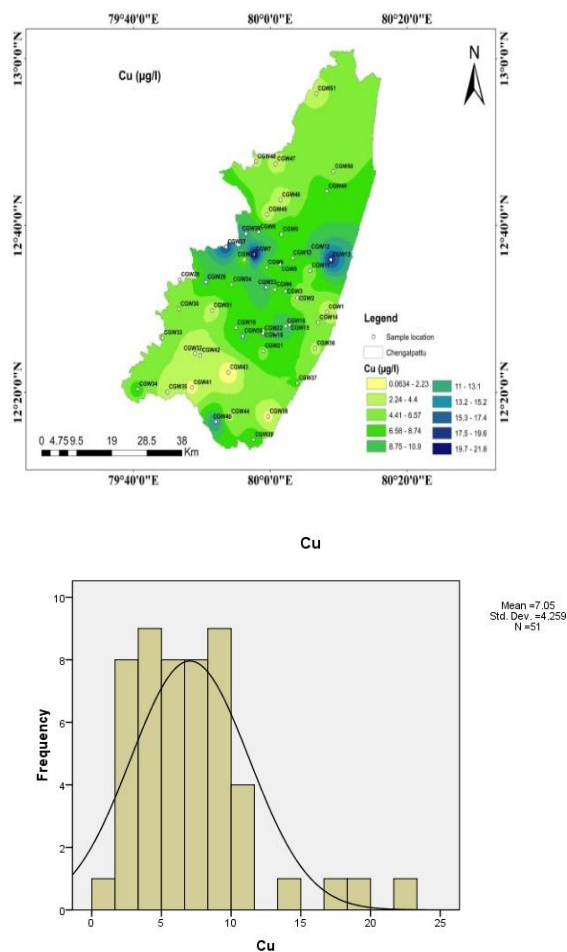


Fig.25: (a) Spatial contour map and (b) histogram of groundwater Copper in Chengalpattu District.

The trace metal concentrations followed the order $Zn > Cu > Pb > Cd$, with all measured values remaining low in groundwater samples collected during the pre-monsoon season in Chengalpattu District. Table 1 summarizes the physicochemical characteristics and trace metal concentrations measured in groundwater samples collected from Chengalpattu District, Tamil Nadu, India. Table 2 compares the concentrations of major cations, anions, and trace metals in groundwater samples from Chengalpattu District with the drinking water guideline values recommended by WHO (2011) and BIS (2012).

6 Multivariate statistical analysis

6.1 Pearson's correlation analysis

Table 3. Presented a strong positive correlation was observed between electrical conductivity (EC) and total dissolved solids (TDS), confirming that dissolved ionic species are the primary contributors to groundwater conductivity [44]. EC also showed strong positive correlations with Cl^- , Na^+ , NO_3^- , Mg^{2+} , and alkalinity,

suggesting that groundwater chemistry is controlled by mineral weathering, ion exchange, and localized anthropogenic inputs. Chloride exhibited strong positive correlations with Br^- , Mg^{2+} , Na^+ , Ca^{2+} , total hardness, and TDS, indicating a common geochemical origin and the influence of dissolved salts. Magnesium showed strong positive correlations with total hardness, Ca^{2+} , CO_3^{2-} , and TDS, reflecting its significant contribution to groundwater hardness and mineralization [45].

Fluoride exhibited a moderate positive correlation with pH ($r = 0.326$), suggesting that alkaline conditions may enhance fluoride mobility in groundwater [46]. Nitrate showed a moderate positive correlation with Ca^{2+} ($r = 0.368$), whereas its correlation with pH was weak and negative ($r = -0.366$), indicating that nitrate occurrence is influenced by multiple hydrogeochemical and anthropogenic factors rather than pH alone. A moderate positive correlation between Cl^- and NO_3^- ($r = 0.210$) suggests the possible influence of domestic waste. Bicarbonate (HCO_3^-) exhibited a strong positive correlation with alkalinity ($r = 0.968$), confirming that bicarbonate is the principal contributor to groundwater alkalinity. Moderate water and agricultural activities [47].

positive correlations were also observed between HCO_3^- and CO_3^{2-} , Mg^{2+} , and TDS. Among the trace metals, Zn, Pb, and Cu exhibited positive correlations, suggesting a possible common source or similar geochemical behavior within the study area.

6.2 The principal component analysis

Principal Component Analysis (PCA) was performed to identify the major factors controlling groundwater chemistry in the study area. The analysis included all measured physicochemical parameters, major ions, and trace metals. Four principal components with eigenvalues greater than 1 were extracted and rotated using the Varimax method with Kaiser normalization to improve the interpretation of factor loadings [48].

The rotated component matrix and the percentage of variance explained by each principal component are presented in Table 4. The scree plot showing the eigenvalues of the extracted components is presented in (Fig. 26a), while the rotated component plot of the first three principal components is shown in (Fig. 26b).

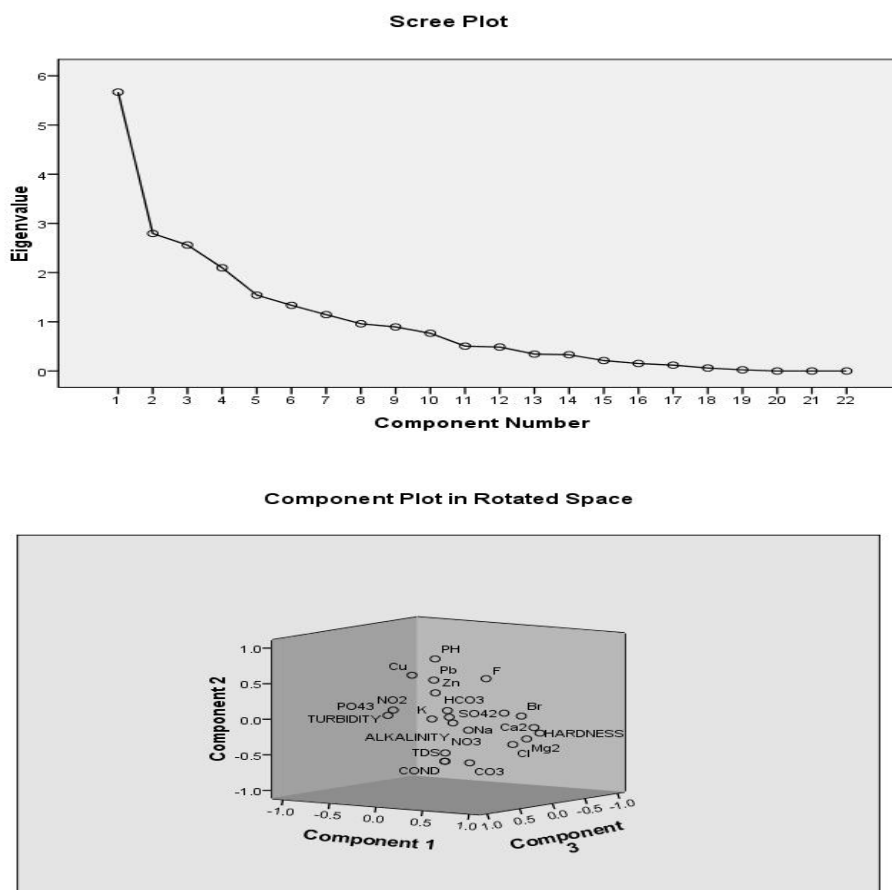


Fig. 26: (a)Scree plot of the eigen values from PCA and (b) Rotated loading plots of first three PCs.

The Principal Component Analysis (PCA) explained 61.34% of the total variance through four principal components (Table 4). Factor 1 accounted for 22.37% of the total variance and showed strong positive loadings for Cl^- , Br^- , SO_4^{2-} , Na^+ , Mg^{2+} , Ca^{2+} , and total hardness, indicating that groundwater chemistry is primarily controlled by mineral dissolution and groundwater mineralization. Factor 2 explained 14.42% of the total variance and exhibited positive loadings for pH, F^- , Pb, and Cu, suggesting the influence of geochemical processes governing trace metal mobility. Factor 3 accounted for 11.68% of the total variance and was characterized by high loadings of PO_4^{3-} , NO_2^- , and K^+ , reflecting the influence of agricultural activities, particularly fertilizer application [49]. Factor 4 explained 11.17% of the total variance and showed strong positive loadings for alkalinity and HCO_3^- , indicating the contribution of carbonate weathering and natural hydrogeochemical processes. In contrast, EC, turbidity, NO_3^- , Zn, and CO_3^{2-} exhibited relatively weak loadings across the extracted components, suggesting that these parameters contributed less to the identified factors.

6.3 Hierarchical Cluster Analysis

Hierarchical Cluster Analysis (HCA) was performed using the average linkage method to classify groundwater quality parameters based on their similarity. The resulting dendrogram is presented in Fig. 27. The analysis revealed three major clusters representing distinct hydrogeochemical associations. The first cluster comprised most of the major ions, trace metals, and physicochemical parameters, indicating their close geochemical relationship. The second cluster consisted of electrical conductivity (EC) and total dissolved solids (TDS), which exhibited the highest similarity, reflecting the dominant contribution of dissolved ions to groundwater mineralization. Overall, the clustering pattern was consistent with the Pearson correlation and Principal Component Analysis (PCA) results, confirming that groundwater chemistry in the study area is primarily controlled by mineral weathering, dissolved salts, and localized anthropogenic influences.

7 Water Quality Index (WQI)

The Water Quality Index (WQI) is a widely used tool for evaluating the overall suitability of groundwater for drinking purposes by integrating multiple water quality parameters into a single numerical value [36,50–57]. In the present study, the Weighted Arithmetic Water Quality Index (WAWQI), National Sanitation Foundation Water Quality Index (NSFWQI), and Canadian Council of Ministers of the Environment Water Quality Index (CCMEWQI) were applied to assess groundwater quality. The WQI was calculated using the WHO (2011) drinking water guideline values as reference standards [21]. The

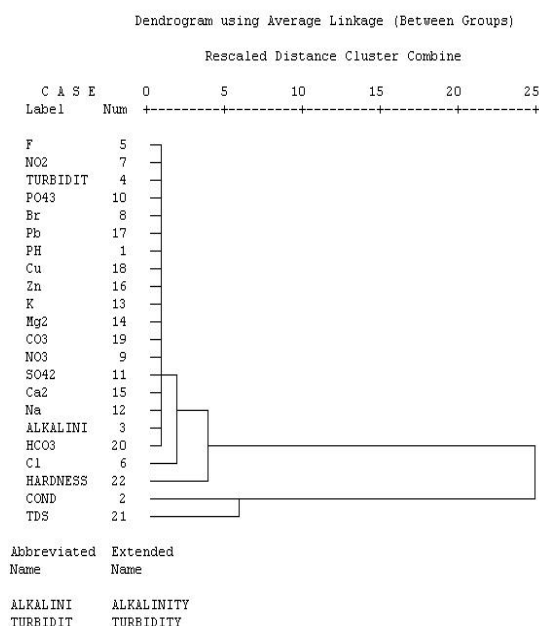


Fig. 27: Dendrogram.

analysis included physicochemical parameters and trace metals, namely pH, electrical conductivity (EC), alkalinity, turbidity, fluoride (F^-), chloride (Cl^-), nitrite (NO_2^-), nitrate (NO_3^-), sulfate (SO_4^{2-}), sodium (Na^+), potassium (K^+), magnesium (Mg^{2+}), calcium (Ca^{2+}), zinc (Zn), cadmium (Cd), lead (Pb), and copper (Cu). The calculation procedure for the weighted arithmetic WQI is described below [56].

Calculation of subindex or quality rating (q_n):

For n water quality parameters, the quality rating or sub-index (q_n) for the n th parameter represents its relative concentration in polluted water compared to the standard permissible limit. This sub-index (q_n) is computed using the following equation.

$$q_n = 100 [(V_n - V_{io}) / (S_n - V_{io})]$$

Where:

q_n = Quality rating for the n th water quality parameter

V_n = Measured concentration of the n th parameter at the sampling site

S_n = Standard permissible limit for the n th parameter

V_{io} = Ideal value of the n th parameter in pure water (pH = 7.0; 0 for all other parameters)

pH calculation through water quality rating evaluation:

For pH, the ideal value in pure water is 7.0, while the permissible limit for polluted water is 8.5. Thus, the quality rating for pH is determined using the following relation:

$$qpH = 100 [(V_{pH} - 7.0) / (8.5 - 7.0)]$$

Where V_{pH} = Observed value of pH

Calculation of unit weight:

Unit weight (W_n) was determined as a value inversely proportional to the recommended standard limit (S_n) of the respective parameter.

$$W_n = K/S_n$$

Where

W_n =Unit weight for the nth parameter

S_n =Standard permissible value for the nth parameter

K = Proportionality constant

The overall Water Quality Index was computed by linearly aggregating the product of quality rating (q_n) and unit weight (W_n) across all parameters.

$$WQI = \sum q_n W_n / \sum W_n$$

The groundwater quality was classified based on the Water Quality Index (WQI) values, as presented in Table 5. The WQI categorizes water into five quality classes ranging from excellent to unfit for drinking, providing a simple and comprehensive assessment of groundwater suitability for potable use.

Table 1. Physicochemical parameters and heavy metal concentrations in groundwater samples from Chengalpattu District.

Sample code	pH	EC ($\mu\text{S}/\text{cm}$)	ALKALINITY (mg/l)	TURBIDITY (NTU)	F- (mg/l)	Cl- (mg/l)	NO ₂ - (mg/l)	Br- (mg/l)	NO ₃ - (mg/l)	PO ₄ - (mg/l)	SO ₄ - (mg/l)	Na+ (mg/l)
CGW1	7.4	3113	85	1.17	0.323	918.78	0.02	5.95	9.73	0.05	85.69	370
CGW2	7.9	662.3	204	0.65	0.45	53.02	0.02	0.893	3.03	0.05	7.2	45.53
CGW3	7.8	1834	294	0.23	0.266	256.3	0.02	1.99	58.7	5.2	90.2	199.1
CGW4	7.6	393.6	100	0.26	0.29	52.7	0.02	0.802	10.1	0.05	17.6	40.87
CGW5	7.8	461.3	174	0.17	0.435	20.56	0.02	1.689	7.2	0.05	13.5	27.04
CGW6	7.9	471.8	206	0.08	0.844	29.25	0.02	1.36	0.05	0.05	4.65	15.58
CGW7	8.1	1972	336	0.06	0.942	264.6	0.02	1.77	20.1	0.98	144.6	290
CGW8	8	984.4	298	0.14	0.945	85.1	0.02	3	0.327	0.05	73.13	106.1
CGW9	7.3	740.1	186	0.08	0.5	64.9	0.02	0.696	19	0.05	76.22	50.76
CGW10	7.8	1180	188	0.17	0.315	125	0.062	1.9	69	4.9	56	97.37
CGW11	7.1	1410	222	0.14	0.6	222	0.008	2.7	136.2	0.25	47.6	81.5
CGW12	7.9	224.6	65	0.09	1.2	19.8	0.02	3.45	4.77	0.05	7.2	9.81
CGW13	7.5	958.6	248	0.11	0.323	114.5	0.02	1.12	3	0.208	12.7	72.06
CGW14	7.6	655.4	143	0.16	0.408	480.2	0.008	3.2	20	0.05	110	139.5
CGW15	7.7	2143	256	0.11	0.357	36.9	0.02	0.944	23.3	0.05	27.8	15.8
CGW16	7.9	425.3	116	0.11	0.437	103.6	0.02	2	24.2	0.05	71.5	37.16
CGW17	7.6	704.6	94	0.12	0.7	126.5	0.02	2.4	10.1	0.05	54.1	50.78
CGW18	7.4	957.8	123	6.86	0.601	155.8	0.02	2.15	40	0.05	62	99.61
CGW19	7.3	1103	228	0.18	0.44	42.2	0.02	1.02	23	0.05	30.8	36.17
CGW20	7.4	598.4	66	0.23	0.42	97	0.02	0.932	9.2	0.25	17.1	67.53
CGW21	7.8	622.7	134	0.11	0.59	55.2	0.02	2.03	19	0.05	50.3	43.9
CGW22	7.5	990.4	250	0.14	0.3	77.5	0.02	1.01	7.1	0.12	28.4	54.1
CGW23	7.6	596.6	163	0.11	0.58	127	0.02	1.72	44	0.232	58.8	161.4
CGW24	8	1270	290	0.08	0.386	85	0.02	1.88	18.6	0.05	551.2	50.9
CGW25	7.3	1545	182	0.13	0.35	12.2	0.02	0.92	6.8	0.05	11	11.45
CGW26	7.8	392.8	164	0.15	0.57	80.4	0.02	1.23	9.5	0.05	28.2	56.37
CGW27	7.6	661.7	186	0.1	0.388	43.1	0.02	1.61	9.6	0.05	19.7	23.88
CGW28	7.5	673.8	216	0.1	1.058	230.1	0.02	2.18	22.8	0.05	48	274.4
CGW29	7.8	1612	294	0.14	0.744	252	0.02	1.79	46.4	0.05	57.5	47.33

CGW30	7.3	1366	234	0.13	0.788	226.6	0.02	2.34	26.6	0.05	233.2	113.7
CGW31	7.5	1610	232	0.1	0.765	84.8	0.02	1.555	20.4	0.05	42.4	66.95
CGW32	7.6	886.1	264	0.12	0.976	23.4	0.02	1.158	7.3	0.05	19.3	31.88
CGW33	7.5	642.6	240	0.13	1.56	29.1	0.02	1.54	10.1	0.05	15.6	18.8
CGW34	7.3	647.2	256	0.11	0.527	134.2	0.02	1.343	50.2	0.05	38.05	114.4
CGW35	7.4	1338	282	0.29	0.4	800	0.02	4.924	33.2	0.05	136.1	295.1
CGW36	7.2	3535	300	0.24	0.08	103.4	0.02	0.618	82.22	0.05	34.02	84.2
CGW37	7	747.1	188	0.15	0.04	67.7	0.02	0.287	12.2	0.05	9	30.75
CGW38	6.7	261.3	12	0.22	0.171	190.3	0.02	0.733	44.2	0.05	34.8	129.7
CGW39	6.6	915.1	130	0.09	0.42	334.4	0.02	1.66	75.4	0.05	43	74.22
CGW40	6.8	1654	268	0.1	0.34	67.1	0.012	1.1	22	0.13	27.4	28.03
CGW41	7.3	841.5	262	0.16	0.6	622	0.02	4.4	39.2	0.05	143.2	104.8
CGW42	7	2449	10	0.12	0.74	280	0.02	1.91	64.6	0.05	78.4	119.6
CGW43	6.9	1559	288	0.18	0.552	616	0.02	4.48	39.5	0.05	143.2	108.3
CGW44	7.4	1136	308	0.14	0.442	147.8	0.02	0.758	16.25	0.05	30.8	72.38
CGW45	7.2	1997	298	0.15	0.43	364.5	0.02	1.81	12.24	0.05	107.2	108.9
CGW46	7.3	987.7	308	0.11	0.35	71.21	0.02	0.62	43.24	0.05	51.74	136.2
CGW47	6.9	1630	262	0.13	0.24	335.3 9	0.02	1.94	0.05	0.05	54.34	118.9
CGW48	7	1568	250	0.25	0.48	236.5 9	0.02	0.87	94.68	0.05	125.2	130.7
CGW49	7.2	500.7	232	0.09	0.41	33.76	0.02	0.93	6.17	0.05	9.02	34.8
CGW50	7.5	618.7	246	0.16	0.14	20.67	0.02	0.79	8.27	0.05	24.91	22.18
CGW51	7.3	999.9	250	0.11	0.41	103.6 5	0.02	0.97	11.03	0.05	54.09	111.7
Min	6.6	224.6	10	0.06	0.04	12.2	0.01	0.29	0.05	0.05	4.65	9.81
Max	8.1	3535	336	6.86	1.56	918.8	0.06	5.95	136.2	5.2	551.2	370
Mean	7.5	1122.5	208	0.3	0.52	178.9	0.02	1.79	27.33	0.28	65.05	90.83
CGW1	7.84	72.34	145.5	29.33	0.05	1.087	2.205	9.16	75.94	1992	661.18	
CGW2	1.6	13.75	32.22	19.01	0.05	2.428	3.917	7.53	196.5	423.9	137.08	
CGW3	97.8	33.34	74.11	6.281	0.05	1.248	8.909	12.36	281.68	1174	322.35	
CGW4	4.85	9.87	30.76	17.16	0.05	0.639	7.026	6.21	93.84	251.9	117.45	
CGW5	0.51	5.39	56.57	35.28	0.05	2.012	7.475	7.19	166.84	295.2	163.45	
CGW6	2.73	23.27	47.2	17.14	0.05	1.623	7.169	6.82	199.21	302	213.68	
CGW7	29.7 4	36.93	81.4	33.73	0.05	2.761	21.83	6.56	329.46	1262	355.33	
CGW8	1.77	56.85	33.39	41.73	0.05	1.902	9.22	8.46	289.57	630	317.48	
CGW9	1	18.32	39.72	43.47	0.05	1.651	8.754	22.21	163.9	473.7	174.62	
CGW10	43.2 8	31.28	66.41	40.51	0.05	2.484	7.012	7.39	180.65	755.2	294.64	
CGW11	4.7	43.38	215.1	25.57	0.05	2.19	4.992	38.1	184.07	902.4	715.64	
CGW12	0.75	4.65	39.11	9.532	0.05	1.364	9.407	2.85	62.18	143.7	116.81	
CGW13	2.09	11.3	45.59	13.89	0.05	2.111	18.46	18.36	229.71	613.5	160.37	
CGW14	2.4	54.05	221.3	20.64	0.05	1.447	5.464	8.68	134.37	419.5	775.16	
CGW15	0.43	13.34	53.9	20.21	0.05	1.734	8.9	12.62	243.42	1372	189.52	
CGW16	0.7	23.48	108	14.5	0.05	1.634	10.86	4.01	112.02	272.2	366.44	
CGW17	4.03	38.6	83.63	29.67	0.05	2.073	9.264	6.29	87.77	450.9	367.78	

CGW18	2.88	30.75	102.5	43.63	0.05	1.587	5.934	12.43	110.67	613	382.57
CGW19	1.1	13.26	64.37	25.06	0.05	0.05	8.374	25.21	202.9	705.9	215.34
CGW20	5.9	15.1	38.3	21.44	0.05	2.023	9.217	7.62	58.48	383	157.82
CGW21	0.55	27.85	157.4	14.77	0.05	2.25	5.881	5.53	128.5	398.5	507.81
CGW22	2.9	16.1	49	6.201	0.05	1.377	10.46	18.58	231.49	633.9	188.65
CGW23	4.4	32.1	81	19.45	0.05	2.471	11.5	9.86	153.2	381.8	334.44
CGW24	0.855	54.4	272.9	27.82	0.05	1.839	6.918	7.71	282.31	812.8	905.38
CGW25	0.46	4.99	70.7	20.73	0.05	1.817	5.444	21.19	160.92	988.8	197.09
CGW26	3.28	17.76	55.47	11.83	0.05	1.888	11.65	7.59	156.45	251.4	211.64
CGW27	2.47	22.53	81.77	25.87	0.05	2.329	17.2	11.9	174.15	423.5	296.96
CGW28	2.92	39.69	14.86	19.92	0.05	2.82	8.929	17.88	198.19	431.2	200.55
CGW29	0.787	45.3	158.7	25.71	0.05	1.255	4.446	11.75	282.29	1032	582.72
CGW30	0.9	64.15	154.7	30.64	0.05	1.634	6.184	27.38	206.74	874.2	650.41
CGW31	2.8	26.45	92.8	12.47	0.05	2.15	3.178	19.47	212.61	1030	340.64
CGW32	1	29.38	74.19	6.265	0.05	0.81	3.267	17.13	246.93	567.1	306.24
CGW33	2.1	32.3	78.9	29.21	0.05	1.977	6.446	18.67	221.4	411.3	330.02
CGW34	0.36	55.26	27.04	20.72	0.05	1.41	6.869	27.81	228.3	414.2	295.08
CGW35	139	82.2	228.2	22.24	0.05	1.584	3.75	24.78	257.3	856.3	908.32
CGW36	5.4	7.9	51.4	17.65	0.05	1.148	3.914	44.97	255.18	2262	160.88
CGW37	2.35	4.18	12.33	55.49	0.05	1.215	6.583	41.1	147.11	478.1	48
CGW38	12.6	12.4	37.45	8.244	0.05	0.779	1.723	6.52	5.94	167.2	144.58
CGW39	1.32	46.6	222.5	33.32	0.05	2.975	8.152	67.52	62.99	585.7	747.48
CGW40	0.36	23.42	70.31	24.54	0.05	3.268	13.44	90.56	177.77	1059	272.01
CGW41	1.47	89.79	292.9	8.266	0.05	0.905	1.701	27.87	234.23	538.6	1101.03
CGW42	1.41	48.77	135.3	3.407	0.05	0.406	2.275	3.21	7.01	1567	538.58
CGW43	1.37	91.66	327.4	10.72	0.05	0.651	0.05	80.69	207.59	997.8	1194.85
CGW44	0.85	30.54	30.19	8.475	0.05	1.479	3.951	26.92	281.17	727	201.15
CGW45	1.66	107.2	71.23	7.801	0.05	0.893	2.324	42.23	255.91	1278	619.15
CGW46	1.5	37.51	44.11	9.358	0.05	0.928	2.97	33.18	274.93	632.1	264.61
CGW47	2.36	84.45	53	3.559	0.05	0.912	3.955	68.5	193.76	1043	480.11
CGW48	1.95	54.14	99.87	4.413	0.05	0.41	4.219	61.11	189.13	1004	472.32
CGW49	0.84	24.64	20.92	7.815	0.05	0.974	8.082	34.85	197.3	320.5	153.7
CGW50	1.21	24.17	23.02	7.035	0.05	0.78	5.442	18.78	227.29	396	157.01
CGW51	0.55	23.84	19.88	10.88	0.05	0.977	4.048	30.17	219.95	639.9	147.81
Min	0.36	4.18	12.33	3.41	0.05	0.05	0.05	2.85	5.94	143.7	48
Max	139	107	327.4	55.49	0.05	3.27	21.83	90.56	329.5	2262	1194.85
Mean	8.2	35.5	91.93	20.05	0.05	1.58	7.05	22.66	185.91	718.4	375.76

Table 2: Shows comparison of all Cation, Anion and Heavy metal of groundwater with WHO and BIS.

Parameters	WHO 2011	BIS 2012	Exceed sample Location (WHO)
PH	6.5-8.5	6.5-8.5	Nil
CONDUCTIVITY			Nil
ALKALINITY	300	200	7,44,46
TURBIDITY	5	1	Nil
F ⁻	1.5	1	Nil
Cl ⁻	250	250	1,3,7,14,35,39,41,42,43,45,47
NO ₂ ⁻ (nitrite)	3	1	Nil
Br ⁻	-	-	Nil
NO ₃ ⁻ (Nitrate)	50	45	3,11,34,36,39,42,48
PO ₄ ³⁻	-	-	Nil
SO ₄ ²⁻	500	200	24
Na ⁺	200	-	1,28
K ⁺	20	50	3,7,10,35
Mg ²⁺	150	30	Nil
Ca ²⁺	100 WHO (2004)	75	1,11,16,18,21,24,29,30,39,41,42,43
CO ₃ ²⁻	300	-	Nil
HCO ₃ ⁻	250 WHO(2017)	-	3,7,8,24,29,35,36,44,45,46
TDS	1000	500	1,3,7,15,29,31,36,40,42,45,47,48
Hardness	500	200	1,11,14,21,24,29,30,35,39,41,42,43,45
Zn	3000	5000	Nil
Cd	3	3	Nil
Pb	10	10	Nil
Cu	2000	50	Nil

Table 3. Pearson's correlation Analysis.

	PH	EC	ALKALINITY	TURBIDITY	F ⁻	Cl ⁻	NO ₂ ⁻	Br ⁻	NO ₃ ⁻	PO ₄ ³⁻	SO ₄ ²⁻	Na ⁺	K ⁺	Mg ²⁺	Ca ²⁺	Zn	Pb	Cu	CO ₃ ⁻	HCO ₃ ⁻	TDS	HARDNESS
PH	1																					
EC	-0.214	1																				
ALKALINITY	0.107	.293*	1																			
TURBIDITY	-0.029	0.029	-0.187	1																		
F ⁻	.326*	-0.19	0.004	0.001	1																	
Cl ⁻	-0.257	.412**	0.026	0.074	-0.086	1																
NO ₂ ⁻	0.199	0.001	-0.027	0	-0.073	-0.085	1															
Br ⁻	0.086	0.211	-0.079	0.118	0.236	.816**	-0.046	1														
NO ₃ ⁻	-.366**	.342*	0.03	0.057	-0.119	0.21	0.064	0.063	1													
PO ₄ ³⁻	0.235	0.135	0.112	-0.03	-0.141	0.018	.621**	0.024	0.275	1												
SO ₄ ²⁻	0.14	0.205	0.245	-0.01	0.002	.298*	-0.015	.307*	0.109	0.032	1											
Na ⁺	-0.049	.401**	0.083	0.098	0.011	.733**	0.012	.552**	0.197	0.202	0.246	1										
K ⁺	0.127	0.155	0.177	-0.008	-0.129	.410**	0.212	.332*	0.176	.550**	0.129	.504**	1									
Mg ²⁺	-0.221	.319*	.297*	0	0.106	.765**	-0.049	.651**	0.18	-0.032	.484**	.502**	0.197	1								
Ca ²⁺	-0.113	0.202	0.057	0.031	0.063	.641**	-0.158	.660**	.368**	-0.06	.598**	0.205	0.163	.611**	1							
Zn	0.142	-0.049	-0.076	.283*	0.066	-0.061	0.191	0.06	-0.003	0.068	0.088	0.01	0.012	-0.14	0.019	1						
Pb	0.264	-0.149	-0.004	-0.022	0.217	-0.181	0.081	-0.014	-0.03	0.126	-0.033	0.018	0.04	-0.199	-0.008	.445**	1					
Cu	.394**	-0.205	0.041	-0.088	0.101	-.354*	-0.006	-0.219	-0.236	0.127	-0.093	-0.051	0.015	-.396**	-.290*	0.271	.562**	1				
CO ₃ ⁻	-.735**	.287*	.396**	-0.089	-0.248	0.219	-0.181	-0.026	.280*	-0.139	0.008	-0.018	-0.089	.354*	0.21	-0.106	-0.065	-0.199	1			
HCO ₃ ⁻	.316*	0.243	.968**	-0.177	0.072	-0.032	0.02	-0.078	-0.047	0.158	0.261	0.094	0.215	0.223	0.004	-0.052	0.014	0.098	0.152	1		
TDS	-0.214	1.000**	.293*	0.029	-0.19	.412**	0.001	0.211	.342*	0.135	0.205	.401**	0.155	.319*	0.202	-0.049	-0.149	-0.205	.287*	0.243	1	
HARDNESS	-0.167	0.267	0.156	0.022	0.086	.754**	-0.133	.728**	.333*	-0.056	.615**	.340*	0.193	.802**	.952**	-0.04	-0.082	-.360**	.287*	0.089	0.267	1

Table 4. Principal Component Analysis PCA.

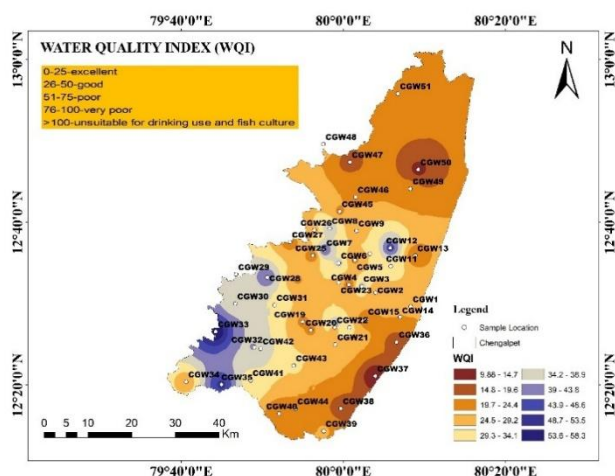
Rotated Component Matrix(a)				
	Component			
	1	2	3	4
PH	-0.022	0.823	0.174	0.207
CONDUCTIVITY	0.267	-0.55	0.437	0.299
ALKALINITY	0.11	-0.076	0.09	0.946
TURBIDITY	0.085	0.005	0.11	-0.362
F ⁺	0.224	0.508	-0.257	0.051
Cl ⁺	0.84	-0.287	0.215	-0.134
NO ₂ ⁻	-0.162	0.154	0.618	-0.087
Br ⁻	0.868	0.102	0.122	-0.204
NO ₃ ⁻	0.197	-0.454	0.332	-0.073
PO ₄ ³⁻	-0.072	0.118	0.826	0.051
SO ₄ ²⁻	0.611	0.102	0.02	0.275
Na ⁺	0.557	-0.076	0.488	-0.033
K ⁺	0.29	0.082	0.667	0.056
Mg ²⁺	0.833	-0.242	-0.009	0.179
Ca ²⁺	0.855	-0.092	-0.09	-0.026
Zn	0.018	0.358	0.227	-0.146
Pb	-0.047	0.521	0.158	0.042
Cu	-0.303	0.559	0.128	0.169
CO ₃ ⁻	0.113	-0.673	-0.162	0.301
HCO ₃ ⁻	0.087	0.103	0.141	0.936
TDS	0.267	-0.55	0.437	0.299
HARDNESS	0.934	-0.159	-0.068	0.05
% of Variance	22.367	14.42	11.68	11.17

Table 5: Water quality rating for drinking purposes

WQI level	Water quality Rating
0-25	Excellent
26-50	Good
51-75	Poor
76-100	Very poor
> 100	Unfit for drinking

Water Quality Index (WQI)

The spatial distribution of the Water Quality Index (WQI) is presented in Fig. 28. The WQI map indicates that groundwater quality in most parts of Chengalpattu District falls within the excellent to good categories, demonstrating its suitability for drinking purposes. Of the 51 groundwater samples, 26 (50.98%) were classified as excellent, 24 (47.06%) as good, and only one sample (1.96%) as poor.

**Fig. 28:** Spatial map of water quality index Chengalpattu district

The poor-quality groundwater is localized at sampling site CGW33 in the southwestern part of the study area, where elevated fluoride concentration contributed to the higher WQI value. No groundwater samples were classified as very poor or unsuitable for drinking. Overall, the spatial distribution confirms that groundwater quality in the study area is generally suitable for potable use, with only localized deterioration requiring periodic monitoring and appropriate management.

8 Conclusion

This study evaluated the groundwater quality of Chengalpattu District, Tamil Nadu, using physicochemical parameters, trace metals, spatial analysis, multivariate statistical techniques, and the Water Quality Index (WQI). The dominant cation sequence was $K^+ < Mg^{2+} < Na^+ < Ca^{2+}$, while the anion sequence followed $NO_2^- < F^- < PO_4^{3-} < Br^-$.

$< NO_3^- < SO_4^{2-} < Cl^-$. The trace metal concentrations decreased in the order $Zn > Cu > Pb > Cd$, with all measured values remaining below the WHO (2011) and BIS (2012) drinking water guideline limits. Most physicochemical parameters were also within the recommended limits, indicating generally good groundwater quality across the study area. Spatial distribution maps revealed localized variations in groundwater chemistry, particularly for fluoride and nitrate, reflecting the influence of both geological conditions and human activities. Pearson correlation, Principal Component Analysis (PCA), and Hierarchical Cluster Analysis (HCA) consistently indicated that groundwater quality is primarily controlled by mineral weathering, groundwater mineralization, and localized anthropogenic inputs. The WQI assessment classified 26 groundwater samples as excellent, 24 as good, and only one sample as poor, confirming that groundwater in most parts of Chengalpattu District is suitable for drinking purposes. Continuous groundwater monitoring and sustainable management practices are recommended to prevent localized deterioration and to ensure the long-term safety of groundwater resources.

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