



Evaluation of hydrogeochemical studies to assess groundwater quality in the Chennai urban region, Tamil Nadu, India

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Received: 4 October 2024 / Accepted: 11 February 2025 / Published online: 26 February 2025
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Abstract

This study investigates the quantity and quality of groundwater in Chennai city, focusing on the hydro-geochemical parameters that determine its suitability for domestic purposes. The primary research question examines whether groundwater in the region meets the standards for potable and domestic use, with the hypothesis suggesting that variations in groundwater quality are influenced by both natural geochemical processes and anthropogenic activities. Groundwater quality was assessed through the analysis of 20 samples, revealing predominantly acidic pH values (below 6) and total dissolved solids (TDS) ranging from 383 to 2350 mg/L, with one sample exceeding the permissible limit of 2000 mg/L (BIS in Specification for drinking water IS 10500: 2012, New Delhi, India, 2012). Electrical conductivity (EC) values ranged from 764 to 4690 $\mu\text{S}/\text{cm}$, with the eastern region exhibiting the highest levels. The study identified sodium (Na^+), calcium (Ca^{2+}), potassium (K^+), and magnesium (Mg^{2+}) as the dominant cations, while bicarbonate (HCO_3^-), chloride (Cl^-), and sulfate (SO_4^{2-}) were the major anions, generally within acceptable limits. Elevated EC values correlated with high TDS, indicating salinity issues. Ionic ratios, such as Na^+/Cl^- and $\text{Mg}^{2+}/\text{Ca}^{2+}$, suggested influences from seawater intrusion to carbonate weathering in certain locations. Approximately 50% of the groundwater samples were classified as potable based on the Bureau of Indian Standards (BIS), while further analysis using USSS, Wilcox, and Gibb's plots suggested moderate salt concentrations and predominantly alkaline water types. Although some locations were deemed suitable for domestic purposes, the findings indicate that much of the groundwater in Chennai is unsuitable for drinking due to poor physico-chemical quality. This study underscores the need for regular monitoring and sustainable management of groundwater resources to ensure long-term availability and usability.

Keywords Hydrogeochemistry · Water quality · Ground water · Water contamination · Chennai

Introduction

The present study includes a geological and geochemical analysis of groundwater samples collected in and around Chennai region, as well as a tabulation and listing of the results. The increased contribution of Na^+ and K^+ as TDS rise shows that these ions are created by silicate weathering or soil salt dissolution. Rapid urbanization, industrial

discharges, agricultural runoff, and seawater intrusion leads groundwater quality at risk in metropolitan coastal areas like Chennai region. While earlier research has investigated groundwater contamination in general, which thoroughly examined the geochemical processes and anthropogenic factors unique to Chennai's complex environmental surroundings. Existing research frequently lacks extensive spatial analysis of groundwater parameters, does not use advanced tools such as the USSS, Wilcox, and Gibb's plots, and does not sufficiently connect these findings to practical implications for irrigation and drinking water management. This study fills these gaps by conducting a thorough geochemical investigation of groundwater, including geographical mapping, and analyzing its appropriateness for diverse uses, with a focus on sustainable resource management. The plot of $\text{Na}^+ + \text{K}^+$ over Cl^- displays the causes of silicate weathering. Assessment and monitoring of water quality and hydrogeochemistry at various locations provide critical

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information about environmental sustainability and human health. Selvam et al. (2024) studied water quality patterns in the Thamirabarani River, concentrating on anthropogenic impacts and hydrological parameters. Shirke et al. (2020) investigated temporal changes in groundwater chemistry in semi-arid regions, with an emphasis on potential health concerns. Srinivasamoorthy et al. (2011) and Thilagavathi et al. (2012) conducted groundwater geochemical studies in Tamil Nadu, focusing on layered aquifer systems and coastal locations, respectively. Several studies have examined the hydrochemical characteristics and quality of groundwater in coastal regions. Ajami (2020) discusses the geological and hydrogeological processes influencing groundwater systems. Khan et al. (2020) assessed groundwater quality along the coastal tracts of Tamil Nadu and Puducherry, highlighting variations in hydrochemical parameters. Majumder et al. (2013) conducted hydrochemical and isotopic studies to evaluate river–groundwater interactions in southern Bangladesh, emphasizing the role of riverbank infiltration. Sakthivel et al. (2016) studied groundwater quality in the South Chennai Coastal Aquifer to determine its suitability for drinking and irrigation. These studies provide valuable insights into groundwater dynamics in coastal environments.

Groundwater contamination research in industrial zones, such as those carried out by Reddy et al. (2012) and Mahmood et al. (2019), have revealed significant chemical pollutants that damage both the environment and human health. Similarly, Sajil Kumar et al. (2014) and Kanagaraj et al. (2018, 2015) investigated seawater intrusion and its consequences for coastal aquifers in South Chennai and Kalpakkam, Tamil Nadu. Alam et al.'s (2020) inquiry in Manipur, India, and Jalali's (2011) study in Western Iran provide different perspectives on water quality for agricultural and drinking purposes. Dávila Pórcel et al. (2012) in Mexico and Akoto et al. (2019) in Ghana have emphasized the challenges of heavy metal contamination in shallow aquifers. Furthermore, regional studies such as Berhe (2020) in Ethiopia and Ayogu et al. (2020) in Nigeria increased understanding of hydrochemistry in surface and groundwater systems, while Chiamsathit et al. (2020) in Thailand assessed seasonal groundwater supplies using heavy metal contamination indices. Ramachandran Muthulakshmi (2020) demonstrates how geospatial techniques increase precision in irrigation water quality measurements. Mondal et al. (2011) explored how seawater affects important hydrochemical ions in Sadras, near Kalpakkam, Tamil Nadu. Groundwater networks in the east and west along the Buckingham Canal and the Bay of Bengal include Na^+ and Cl^- ions. Representative ionic ratios, such as $\text{Mg}^{2+}/\text{Ca}^{2+}$, $\text{HCO}_3^-/\text{Cl}^-$, $\text{Ca}^{2+}/\text{Na}^+$, and TDS levels, separated groundwater that had been heavily impacted by saline or seawater intrusion from less affected areas. Prasanna et al. (2011) studied the hydrochemical parameters of surface and subsurface water

in and around Perumal Lake, Cuddalore District. Tertiary formations show little rock–water interactions in groundwater samples. Brindha et al. (2011) looked into fluoride pollution in groundwater in portions of Nalgonda District, Andhra Pradesh. The high fluoride concentration in this area's groundwater is the result of rock weathering and groundwater evaporation, as well as manmade activity like irrigation, which has hastened rock weathering. Vasanthavignar et al. (2010) used the Water Quality Index to assess groundwater quality in the Thirumanimuttar subbasin. The chemical composition of groundwater in the study area is heavily influenced by the efficient weathering and leaching action of feldspars and magnesium calcite found in litho units, as well as anthropogenic activities such as industrial effluents, automobile emissions, and phosphatic fertilizers in urban environments. The sodium danger against salinity hazard ratio for the full water sample collected over two seasons suggests low alkali hazards and high-quality irrigation water. Makoba and Muzuka (2019) looked at the water quality and hydrogeochemical parameters of groundwater near Mt. Meru in northern Tanzania. It has been established that Mt. Meru is the recharge area. In geology, the duration of water's interaction with rock and climate all have an impact on water chemistry. Major freshwater aquifers have been identified as cracked mafic volcanics, breccia, and tuff. Because of their sensitivity to weathering, lahars have been shown to contain low-quality groundwater. Water was moderately acceptable for domestic and irrigation use, ranging from lakes to boreholes, streams, and springs. Saha et al. (2019) investigated the hydrochemistry and groundwater quality of the Tista floodplain near Rangpur, Bangladesh. The groundwater in the investigated area is appropriate for irrigation. Popoola et al. (2019) studied the natural groundwater physiochemical characteristics in major industrial and residential regions of Lagos. The laboratory investigation found that measured physiochemical parameters were within the allowed ranges stipulated by the WHO and NSDWQ, with the exception of pH, TDS, EC, Pb, Mn, and Fe for industrial groundwater samples and pH, Pb, Mn, and Fe for residential areas. Water quality physiochemical indicators have moderate to significant connection ($p < 0.01$). Wali et al. (2019) studied the hydrochemistry of shallow and deep groundwater in the Basement Complex regions of southern Kebbi State, Sokoto Basin, Nigeria. Most groundwater sources are of intermediate hardness. The quality of groundwater is outstanding for a wide range of applications. However, a groundwater categorization based on nitrate pollution found low water quality. Rock minerals are the fundamental mechanism for regulating water chemistry. Heavy metal concentrations demonstrated Cd and Pd toxicity in some of the wells, above the accepted limit for drinking water by WHO standard 2017. Didar Ul Islam et al. (2017) studied the quality of groundwater in Patuakhali District, on Bangladesh's southern coast.



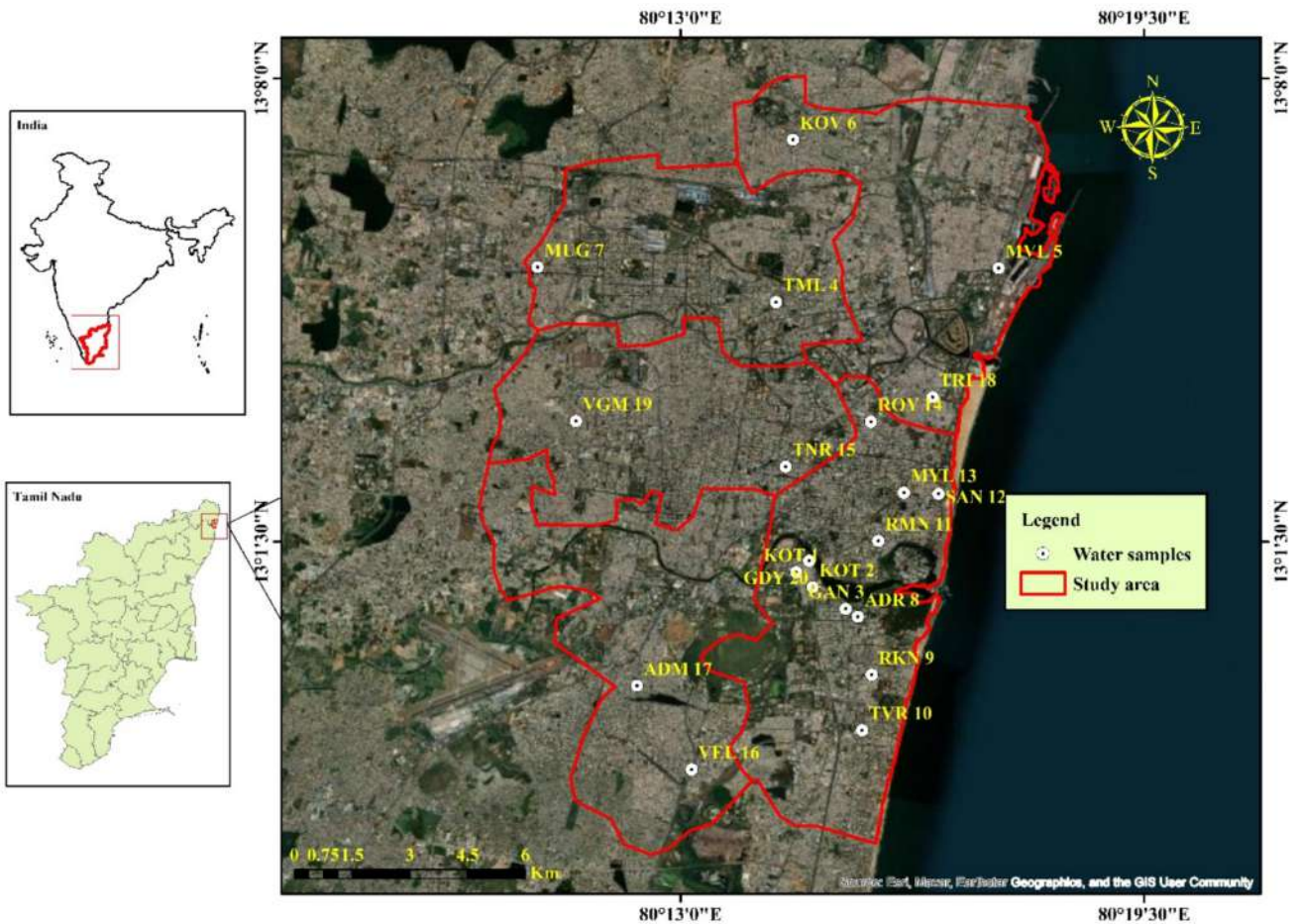


Fig. 1 Location map of the water sampling in the study area

The majority of samples are deemed “unsafe” by the EC, SSP, SAR, RSC, MR, and KR. Salifu et al. (2017) assessed groundwater suitability for irrigation in Ghana’s Upper West region. The EC readings shows that the groundwater is good and acceptable for irrigation.

Abdalla (2016) discovered the seawater intrusion in a shallow coastal aquifer near Jazan, on Saudi Arabia’s southern Red Sea coastline. The geochemical facies of the groundwater indicated Na-Cl to be the major water type, followed by Ca/Mg-Cl, indicating saltwater intrusion and inverse cation exchange processes in the aquifer. Furthermore, greater EC and seawater fraction readings indicate seawater intrusion into the aquifer. The Chennai region has substantial groundwater quality concerns as a result of increased urbanization, industrial activity, and seawater intrusion. These causes lead to the contamination and salinization of groundwater, making it unfit for drinking and irrigation. Poor groundwater management exacerbates the problem, putting the region’s health, livelihood, and agricultural

output at risk. Despite being an important resource, little is known about the geochemical processes and anthropogenic variables that influence groundwater quality in the region. This study seeks to close the gap by assessing the chemical composition of groundwater and its suitability for consumption and irrigation. The primary objective of this research is to assess the physicochemical properties of groundwater in the Chennai region, including pH, TDS, EC, and significant ion concentrations, in order to establish its appropriateness for drinking and irrigation. The study uses analytical techniques including the USSS and Wilcox diagrams to identify groundwater based on salinity and alkalinity concerns. The study also uses Gibb’s plot to determine the primary geochemical processes, such as evaporation, anthropogenic effects, and rock-water interactions. Finally, the study includes a detailed assessment of groundwater quality and spatial distribution, as well as insights to help the region manage its water resources sustainably.



Table 1 Geographical location of the water samples in the study area

S. No	Latitude	Longitude
1	13.017865	80.243725
2	13.014375	80.247549
3	13.0093	80.255281
4	13.146288	80.137813
5	13.0656	80.1608
6	13.13667	80.22111
7	13.089211	80.18323
8	13.007454	80.258093
9	12.993864	80.261379
10	12.980897	80.259102
11	13.025174	80.262918
12	13.036177	80.276991
13	13.036441	80.268884
14	13.053053	80.261195
15	13.042555	80.24126
16	12.9717	80.219232
17	12.991322	80.206494
18	13.0588	80.2756
19	13.0532	80.1922
20	13.0205374	80.2467577

Study area

The study area is located in Chennai, Tamil Nadu, and is bounded by latitudes N 13° 0' 0" to 13° 8' 0" and longitudes E 80° 8' 0" to 80° 18' 0", totaling roughly 20.26 square kilometers shown in the Fig. 1. The Adyar and Cooum rivers predominantly drain the region, having a considerable impact on its hydrology. The area contains urban areas such as Guindy, Adyar, Velachery, Kovilambakkam, and Madhuravoyal, which is distinguished by diverse land use patterns and rapid urbanization. The geological study area geology includes formations from the Archaean epoch to present alluvium deposits, which are classified into three fundamental units: Archean crystalline rocks, Gondwana and tertiary cemented sediments, and modern alluvium. The Archean crystalline rocks are mostly composed of charnockite, gneiss, and associated basic and ultrabasic intrusions, which provide the district's bedrock structure. Gondwana and Tertiary strata reflect past depositional settings, but alluvium formation found in the Adyar and Cooum river floodplains, promotes groundwater recharging and utilization. Hydrologically, the area is influenced by shallow aquifers that are prone to saline intrusion and contamination, with seasonal rainfall from the northeast monsoon providing a significant source of recharge. Proximity to the Bay of Bengal increases vulnerability to seawater intrusion, particularly in the eastern sections, while growing urbanization, unregulated industrial discharge, and poor waste disposal contributes to pollution of surface and groundwater resources.

These variables, together with diminished green cover and increasing impermeable surfaces, have had an impact on natural drainage, groundwater recharge, and overall water quality, creating significant problems for sustainable water management (Kanagaraj et al. 2018).

Methodologies

Field technique

Twenty groundwater samples were collected from hand pumps, drilled wells, and excavated wells across the study area, ensuring diverse and representative sampling (Table 1). Samples were collected in sterilized polyethylene bottles, transported to the laboratory under controlled conditions, and stored at 4 °C to preserve their integrity for analysis (Fig. 2). The chemical and physical properties of the samples were analysed using standard laboratory techniques and instruments.

Cations (Ca^{2+} , Mg^{2+} , Na^+ , K^+) and anions (Cl^- , SO_4^{2-} , CO_3^{2-} , HCO_3^-) were analysed using volumetric methods, spectrophotometry, and flame photometry, following protocols from the American Public Health Association (APHA 2017).

Physical parameters, including pH, total dissolved solids (TDS), electrical conductivity (EC), and salinity, were measured using a calibrated digital pH meter, conductivity meter, and TDS meter, adhering to BIS (2012) standards for water quality assessment.

To evaluate groundwater quality, the concentrations of these ions were compared against permissible limits set by BIS (2012) and WHO (2017) guidelines. Graphical tools, including the USSSL diagram, Wilcox diagram, and Gibb's plot, were employed to classify the water's suitability for irrigation and to identify the geochemical processes influencing groundwater quality. Spatial distribution maps for various parameters were generated using ArcGIS software, providing a visual interpretation of the geochemical data and highlighting areas of concern. The main cations and anions were analyzed to assess the quality of groundwater for domestic purposes, comparing the results with specific standards and using graphical representation methods (Tables 2 and 3).

Results and discussion

Physical parameters

The pH value of water reflects its ability to react with acidic or alkaline substances. Based on the pH values, we can see that 20 samples had a value of less than 6.5 (BIS 2012).



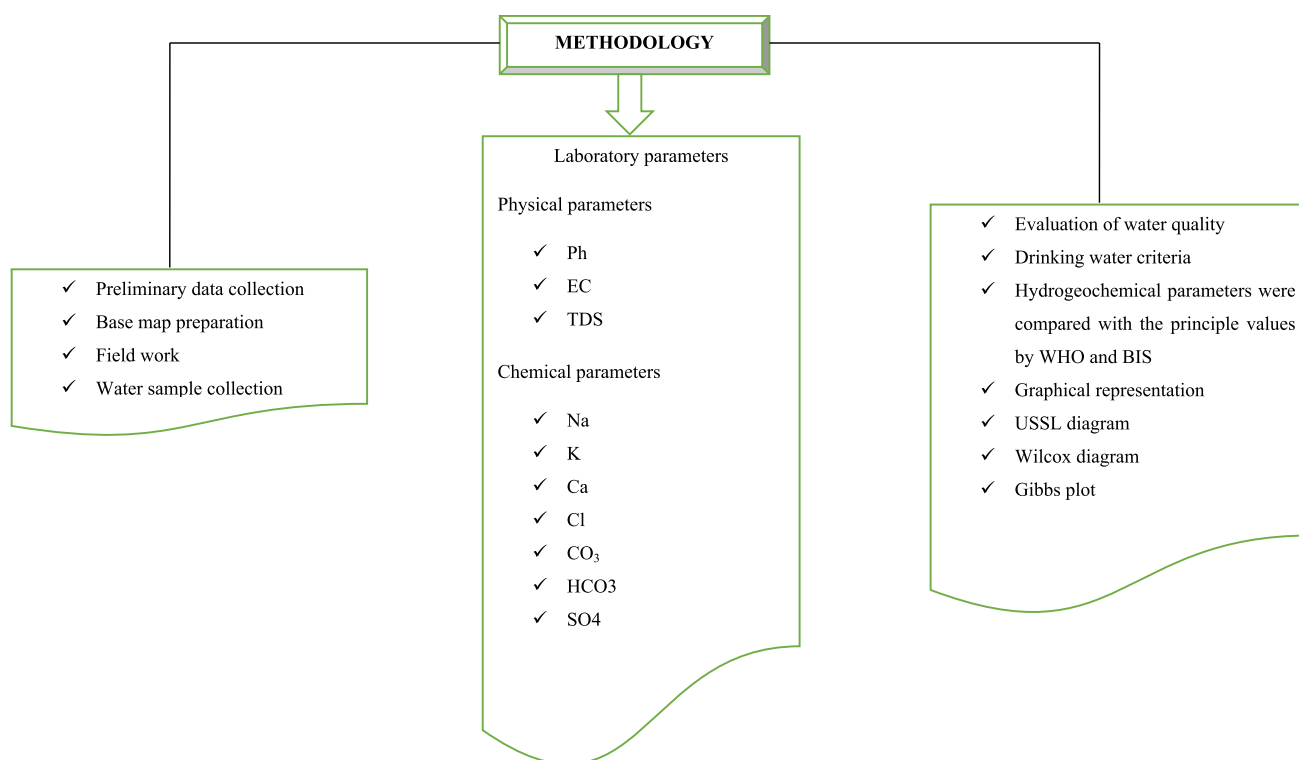


Fig. 2 The flow chart describes from the methodology for water geochemistry analysis

Table 2 Physical parameters of the water sampling data of the study area

SAMPLE ID	PH	TDS (ppm)	EC (micro ohms)	SALINITY
KOT 1	6.2	726	1445	865
KOT 2	6.4	694	1387	793
GAN 3	6.6	646	1291	764
TML 4	7.2	383	764	445
MVL 5	6.1	1190	2390	1110
KOV 6	6.2	820	1641	923
MUG 7	7.3	634	1269	679
ADR 8	6.2	798	1595	922
RKN 9	6.8	605	1209	688
TVR 10	6.4	675	1349	769
RMN 11	7.9	398	796	445
SAN 12	6	1120	2240	1023
MYL 13	7.1	604	1207	681
ROY 14	7.2	580	1162	658
TNR 15	6.9	585	1169	670
VEL 16	8.1	388	769	450
ADM 17	6.5	812	1624	844
TRI 18	6.1	2350	4690	1950
VGM 19	8.1	408	812	456
GDY 20	6.2	861	1690	973
minimum value	6	383	764	445
maximum value	8.1	2350	4690	1950
Average value	6.77	763.85	1524.95	805.4

Consequently, the groundwater in the study area appears to have an acidic character. A pH value below 7 is acidic, while a pH value above 7 is alkaline (basic). Normal precipitation has a pH of about 5.6, which is somewhat acidic due to atmospheric carbon dioxide. The total amount of dissolved salts (solids) in the groundwater is between 383 and 2350 mg/L. Only one sample exceeded the permissible limit of 2000 mg/L (BIS 2012). Seventeen sample points are within the permissible range (500–2000 mg/L). A higher TDS value indicates the dissolution of minerals. However, excess wastewater from sewers and unprotected drains can also lead to elevated TDS values in groundwater. The EC value evaluates the ability of a material to conduct electricity; a higher EC value indicates the salt content in the groundwater. Pure water is a poor conductor of electricity. The EC values ranged from 1612 $\mu\text{S}/\text{cm}$ at site 4, Thiruvanamayal, to 4690 $\mu\text{S}/\text{cm}$ at site 18, Triplicane. The 20 samples had an average value of 1524.95 $\mu\text{S}/\text{cm}$. The eastern part of the study area has the highest value, while the central region has the lowest. The EC value is between 764 and 4690 $\mu\text{S}/\text{cm}$. The lowest reported salinity in location 4, Thiruvanamayal, is 445 ppm, while the highest value is 1950 ppm in location 18, Triplicane. The average result of all 20 samples is 805.4 ppm. The southern half of the study region has the lowest value, while the eastern part has the highest (Figs. 3A–D).



Table 3 Major cation and anion of the study area

Major Sample ID	Cation (mg/l)				Anion (mg/l)			
	Ca	Mg	Na	K	SO ₄ ⁻	CO ₃	HCO ₃ ⁻	Cl
KOT 1	34	15.6	190	7	935	0	0	150.6625
KOT2	26	10.8	180	5	165	6.1	0	124.075
GAN 3	30	10.8	143	3	115	61	0	212.7
TML 4	36	46.8	163	2	155	– 6.1	6	168.3875
MVL 5	64	79.2	180	19	205	6.1	0	407.675
KOV 6	50	151.2	132	12	175	6.1	0	327.9125
MUG 7	24	187.2	135	21	135	18.3	0	203.8375
ADR 8	30	214.8	224	35	265	6.1	0	354.5
RKN 9	32	242.4	158	28	155	– 12.2	6	150.6625
TVR 10	40	279.6	111	37	210	6.1	0	336.775
RMN 11	30	304.8	135	24	150	6.1	0	150.6625
SAN 12	56	337.2	158	27	95	– 12.2	6	389.95
MYL 13	50	379.2	165	6	175	6.1	0	159.525
ROY 14	16	405.6	160	6	200	– 12.2	6	97.4875
TNR 15	22	436.8	126	27	305	12.2	0	124.075
VEL 16	10	438	97	9	235	6.1	0	159.525
ADM 17	30	466.8	145	4	230	– 12.2	6	239.2875
TRI 18	36	495.6	156	9	300	12.2	0	877.3875
VGM 19	26	525.6	124	14	335	12.2	0	106.35
GDY20	38	574.8	184	8	250	12.2	0	186.1125
Minimum	10	10.8	97	2	95	– 12.2	0	97.4875
Maximum	64	574.8	190	37	935	18.3	6	877.3875
Average	34	280.14	153.3	15.15	239.5	6.1	1.5	246.3775

Major ions

The acceptable limit for calcium was 75, while the permissible limit was 200. Calcium levels in the study region varied between 10 and 64 mg/l. All samples were below the acceptable limit. Calcium is the major component of many types of rock. Calcium causes brittle water and incrustations in boilers. The magnesium concentration in the study area varies between 10 and 574.8 mg/l. According to BIS 2012, only three samples are below the required limit of 30 mg/l, while 15 samples exceed the maximum permissible value of 100 mg/l. It also enters the ecosystem through the use of fertilizers and animal feed (Anwar and Aggarwal 2014). The Na values in the study region are between 97 and 190 mg/l. Only one sample exceeds the permissible value of 200 mg/l (BIS 2012). The most likely reasons for increased sodium concentrations in groundwater include seawater intrusion, salt pan deposition, and the ion exchange process (Chidambaram et al. 2010). The K content in the study area ranges from 2 to 37 mg/L. All groundwater tests were within the permissible limit of 40 mg/L (BIS 2012). Potassium in groundwater is mainly caused by the weathering of potassium plagioclase in the host rock, which is abundant in silicate rock (Chidambaram et al. 2009) (Fig. 4A–D).

The Cl content in the investigated region ranges from 97.48 to 877.38 mg/liter. The maximum permissible chloride concentration is 250 mg/liter. Five samples exceed the permissible limit. Most of the chloride samples have a salty taste and are associated with the development of hypertension, stroke risk, left ventricular hypertension, osteoporosis, kidney stones, and asthma in humans. The SO₄²⁻ content in the study area ranges from 95 to 935 mg/l.

According to BIS (2012), ten samples are within the required value of 200 mg/l, twelve are within the permitted limit of 400 mg/l, and one exceeds the permitted limit of 400 mg/l. Sulfate can enter the groundwater via industrial or anthropogenic sulfate fertilizers (Jameel and Sirajudeen 2006). The HCO₃⁻ content in the study region varies between 0 and 6 mg/l. According to BIS (2012), the minimum value is 200, and the maximum permissible value is 600 mg/l. High values may be due to the seepage of wastewater and industrial waste. The minimum value of HCO₃⁻ is zero mg/l at sites 1, 2, 3, 5, 6, 7, 8, 10, and 11, while the maximum value is 6 mg/l at sites 13 and 15. The 20 samples had an average value of 1.5 mg/l. The western and eastern parts of the study area have the highest values, while the south-northern region has the lowest values (Figs. 5A–C). According to BIS (2012), the minimum value is 200 mg/l, while the allowable limit is 600 mg/l, depending on the BIS



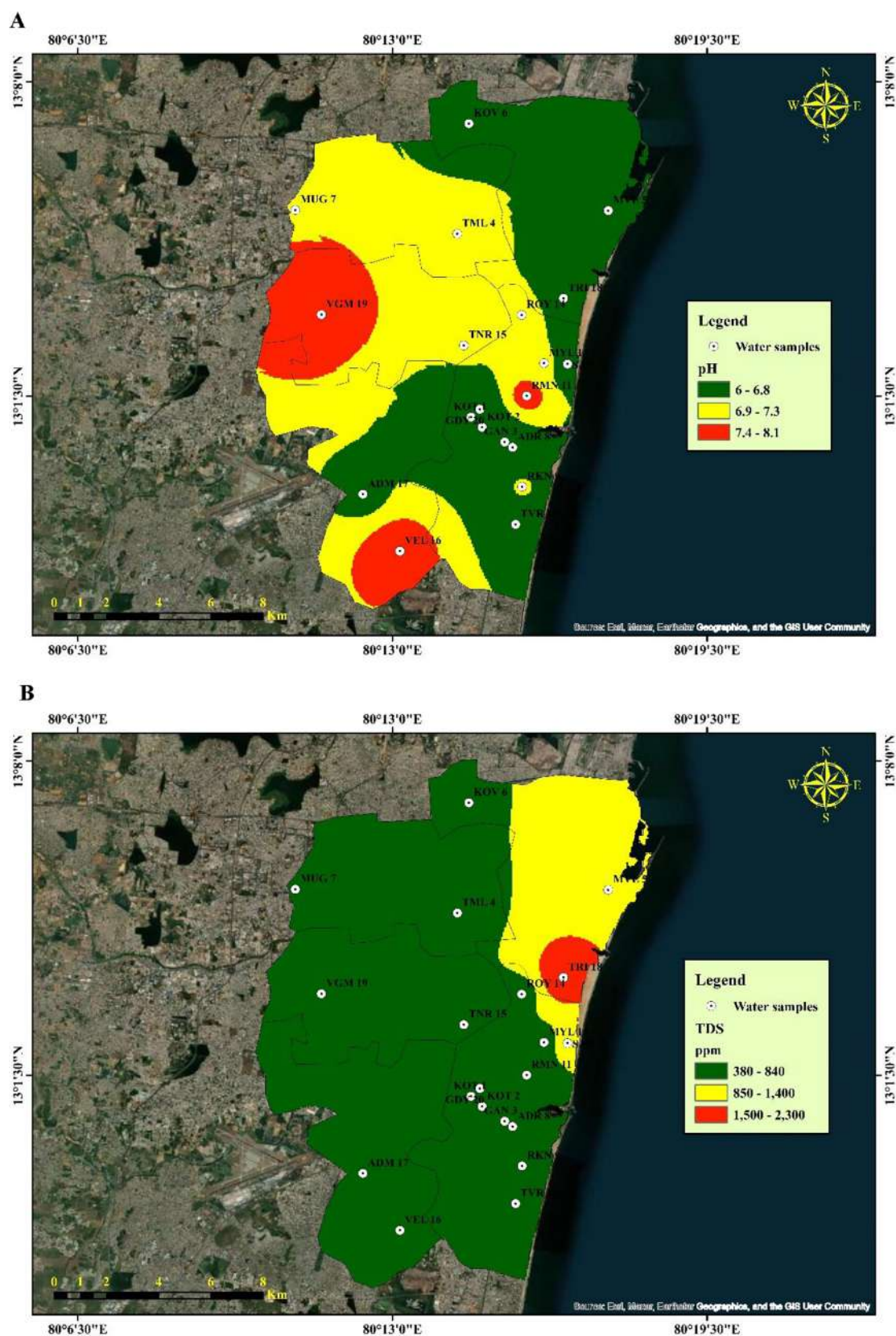


Fig. 3 **A** Spatial diagram of pH in the study area. **B** Spatial diagram of TDS in the study area. **C** Spatial diagram of EC in the study area. **D** Spatial diagram of Salinity in the study area



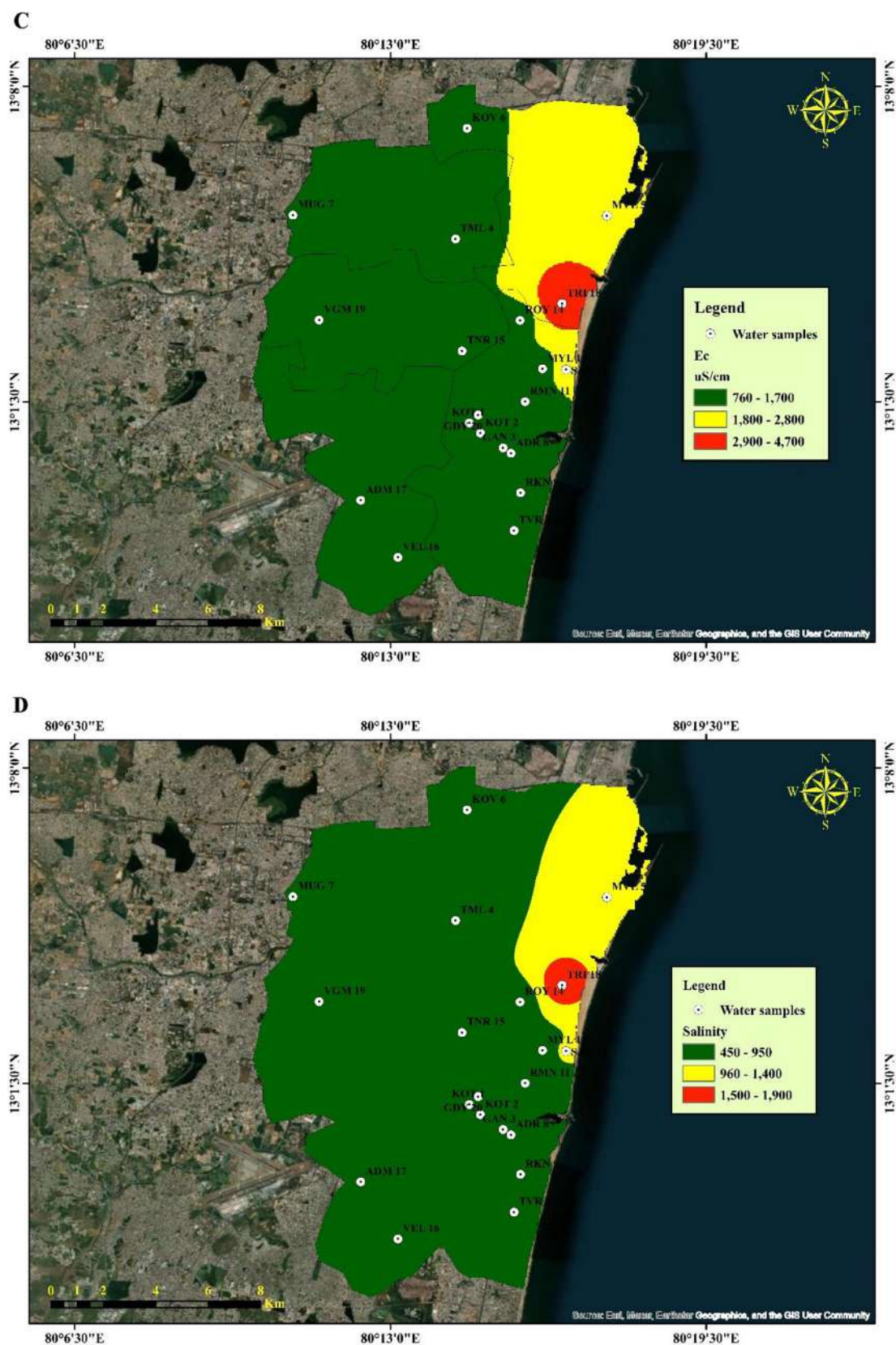


Fig. 3 (continued)



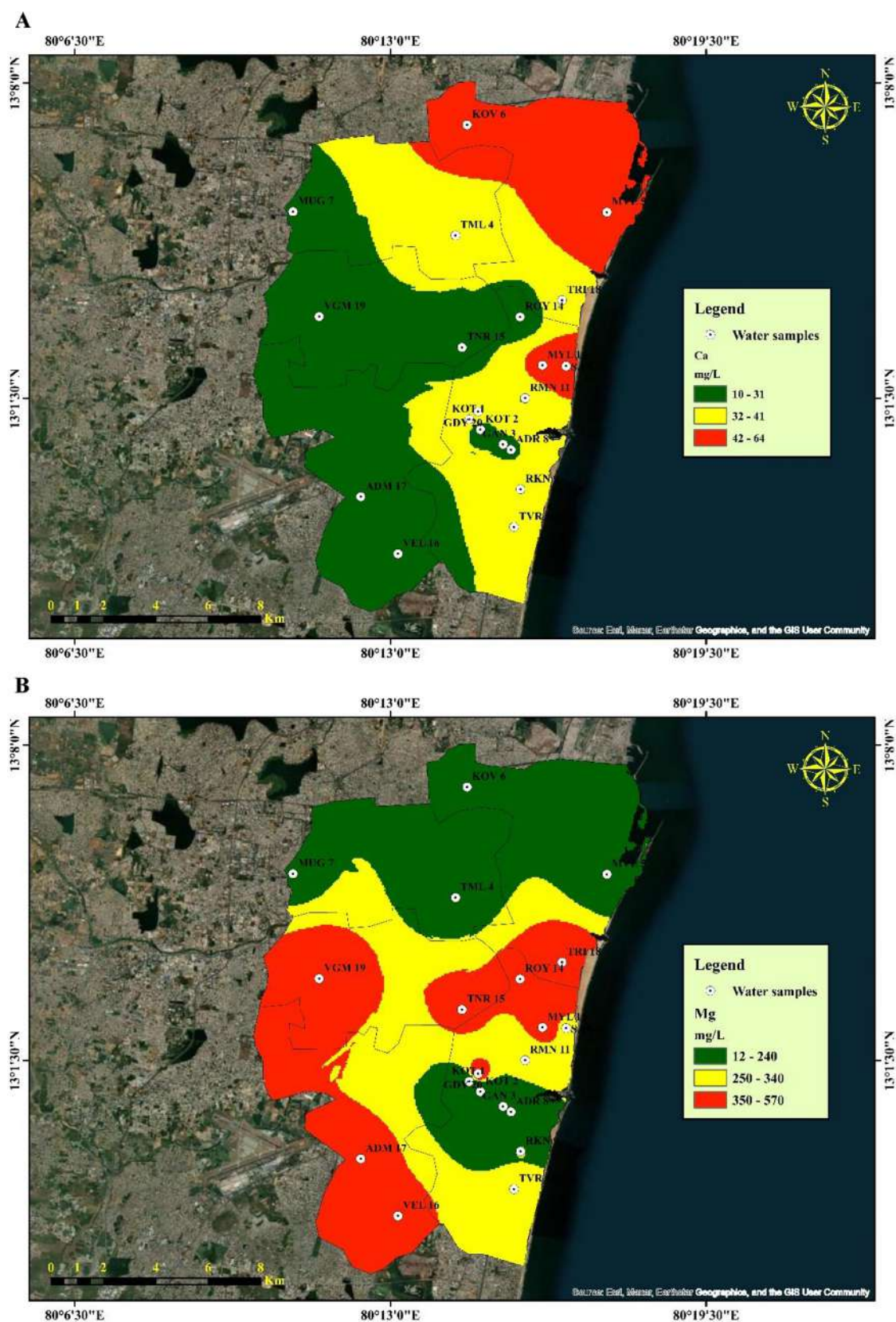


Fig. 4 **A** Spatial diagram of Ca^{2+} in the study area. **B** Spatial diagram of Mg^{2+} in the study area. **C** Spatial diagram of Na^{+} in the study area. **D** Spatial diagram of K^{+} in the study area



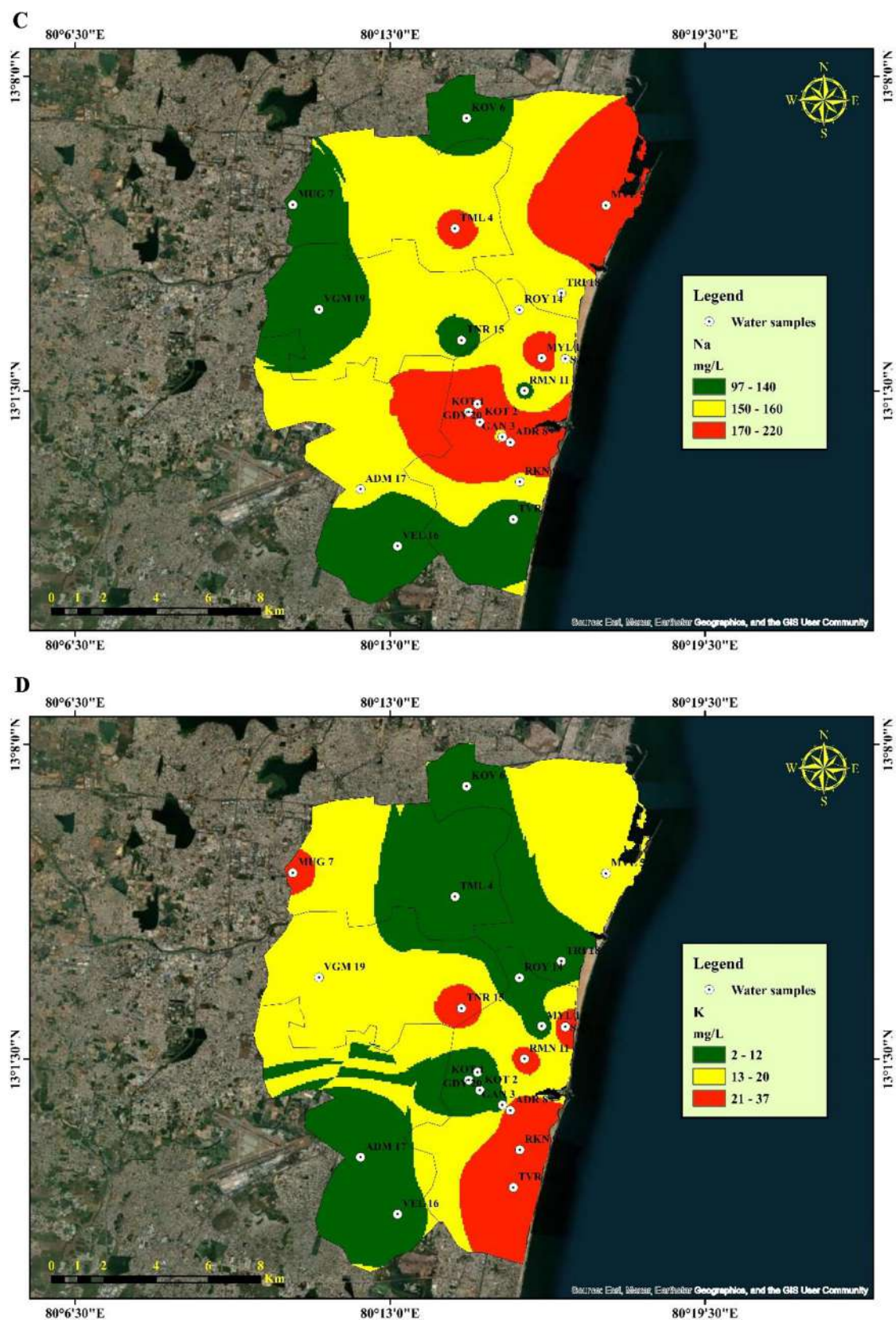


Fig. 4 (continued)



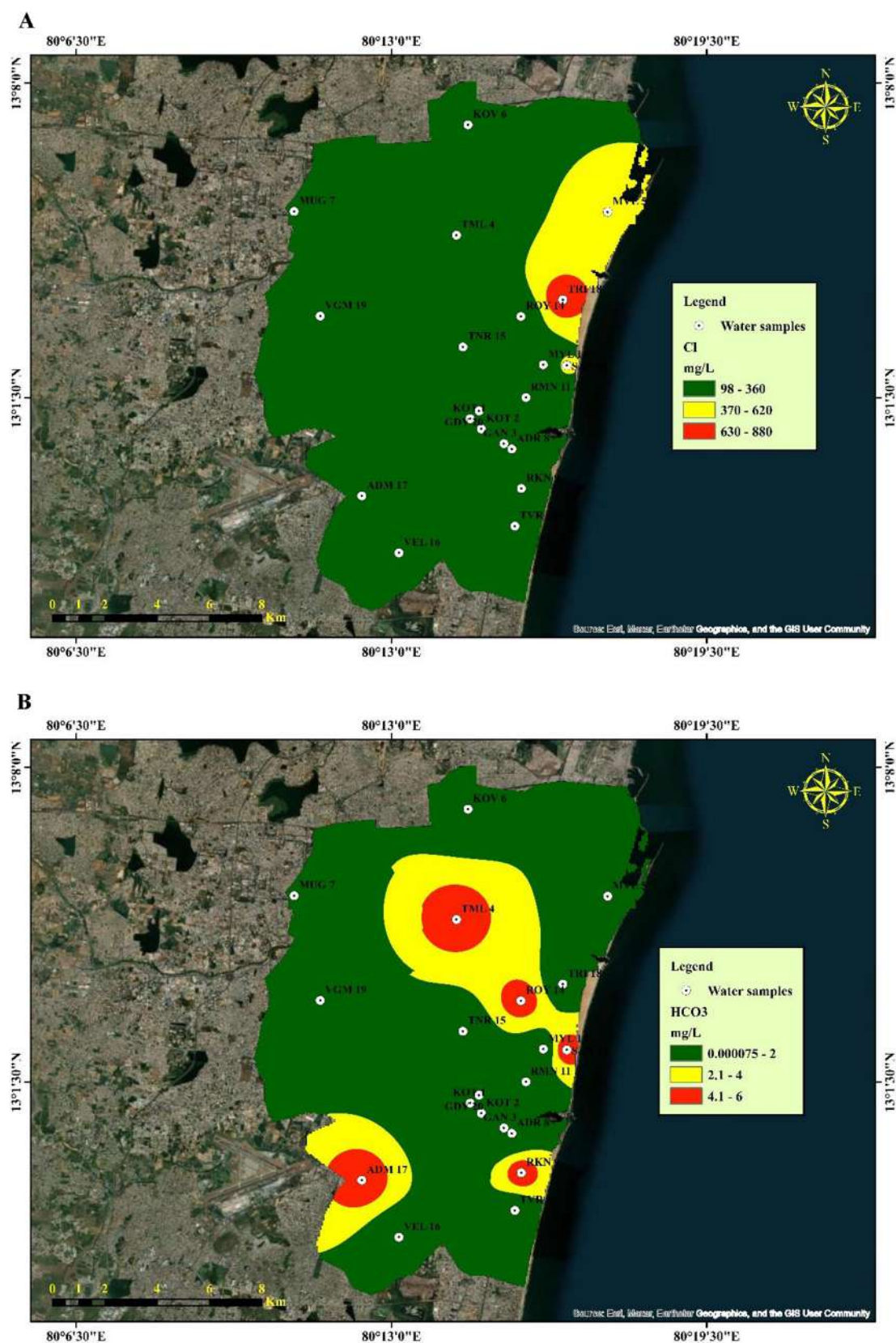


Fig. 5 **A** Spatial diagram of Cl^- in the study area. **B** Spatial diagram of HCO_3^- in the study area. **C** Spatial diagram of So_4^{2-} in the study area



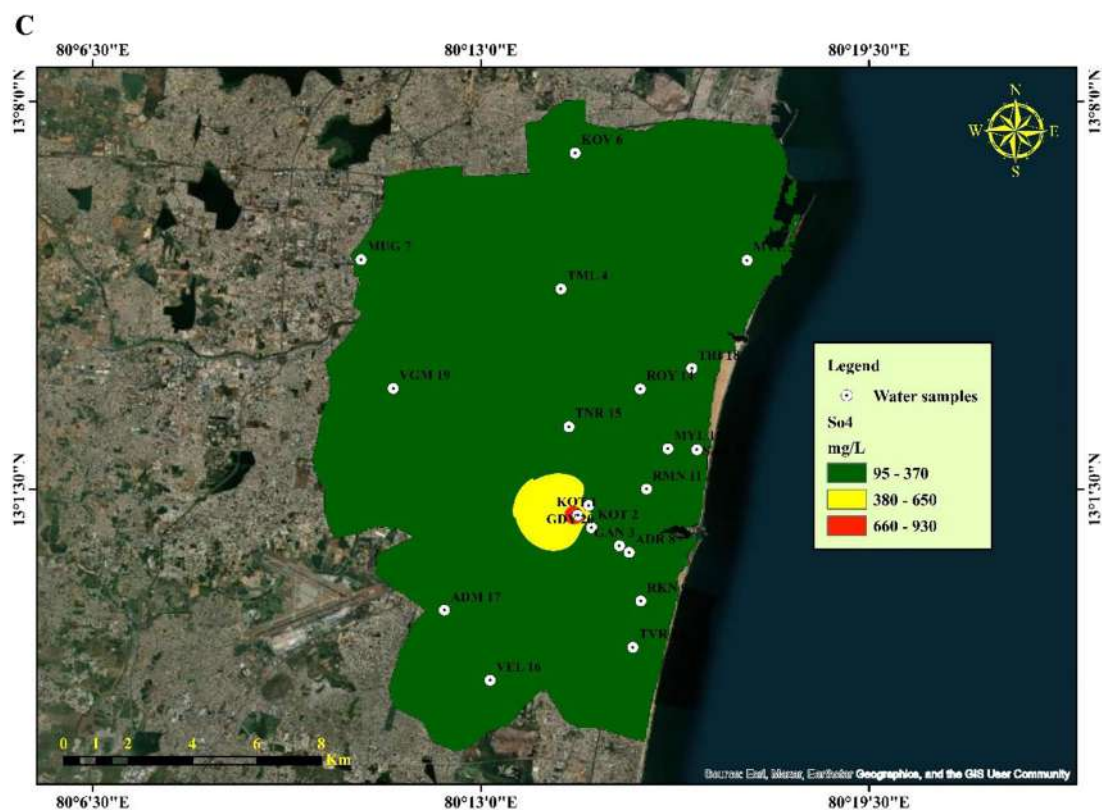


Fig. 5 (continued)

allowable limit concentration. The minimum value for carbonate in item 19 is 12.2, while the maximum value in item 7 is 18.3. The average is 6.1 mg/liter.

USSL diagram

The sodium adsorption ratio (SAR) measures the salt or alkali hazard in irrigation water. High salt concentrations (EC) in water lead to saline soil, while high sodium concentrations lead to alkaline soil. Salinization is one of the most common negative environmental impacts of irrigation. The relationship between salt adsorption ratio (SAR) and electrical conductivity (EC) has been illustrated using US salinity, where EC is a salinity hazard and SAR is an alkalinity hazard. If the sodium adsorption ratio (SAR) and electrical conductivity (EC) of the water are known, the water can be classified for irrigation by plotting these values on the US Salinity Laboratory (USSL1954) chart. Figure 6A shows the USSL diagram for the research area.

The USSL diagram divides the water samples from the study area into different categories. The majority of the samples (13) belong to the group with low sodium content and high conductivity (C3S1). These liquids can be used for the irrigation of salt-tolerant and semi-tolerant plants if the drainage is adequate. The USSL diagram divides the

water samples from the study area into different categories. The majority of the samples are classified as C3S3, which means a high EC and SAR value. Therefore, they are naturally saline and therefore unsuitable for irrigation (Table 4). Only two samples fall into the C3S1 category, which is suitable for the cultivation of salt-tolerant plants. The remaining 18 samples fell into the categories C3S2, C3S4, C3S3, and C4S4, which are not suitable for cultivation.

Wilcox diagram

The Wilcox diagram (Wilcox 1955) plots the sodium content (Na%) against the conductivity. It is necessary to classify irrigation water because salt reacts with the soil and reduces its permeability. Alkaline soils consist of sodium and carbonate as the main anion, while saline soils consist of chloride or sulfates. The sodium content is calculated as the ratio of sodium to the total cations (sodium, potassium, calcium, and magnesium). All concentrations are expressed as equivalents per million (epm). Figure 6B shows the Wilcox diagram for the study area. The Wilcox diagram for the study area shows that 17 samples are “very good” for irrigation; 2 samples from Santhome and Maduravoyal are “doubtful to unsuitable,” and only one sample is unsuitable for irrigation: sample 17 from Triplicane (Table 5).

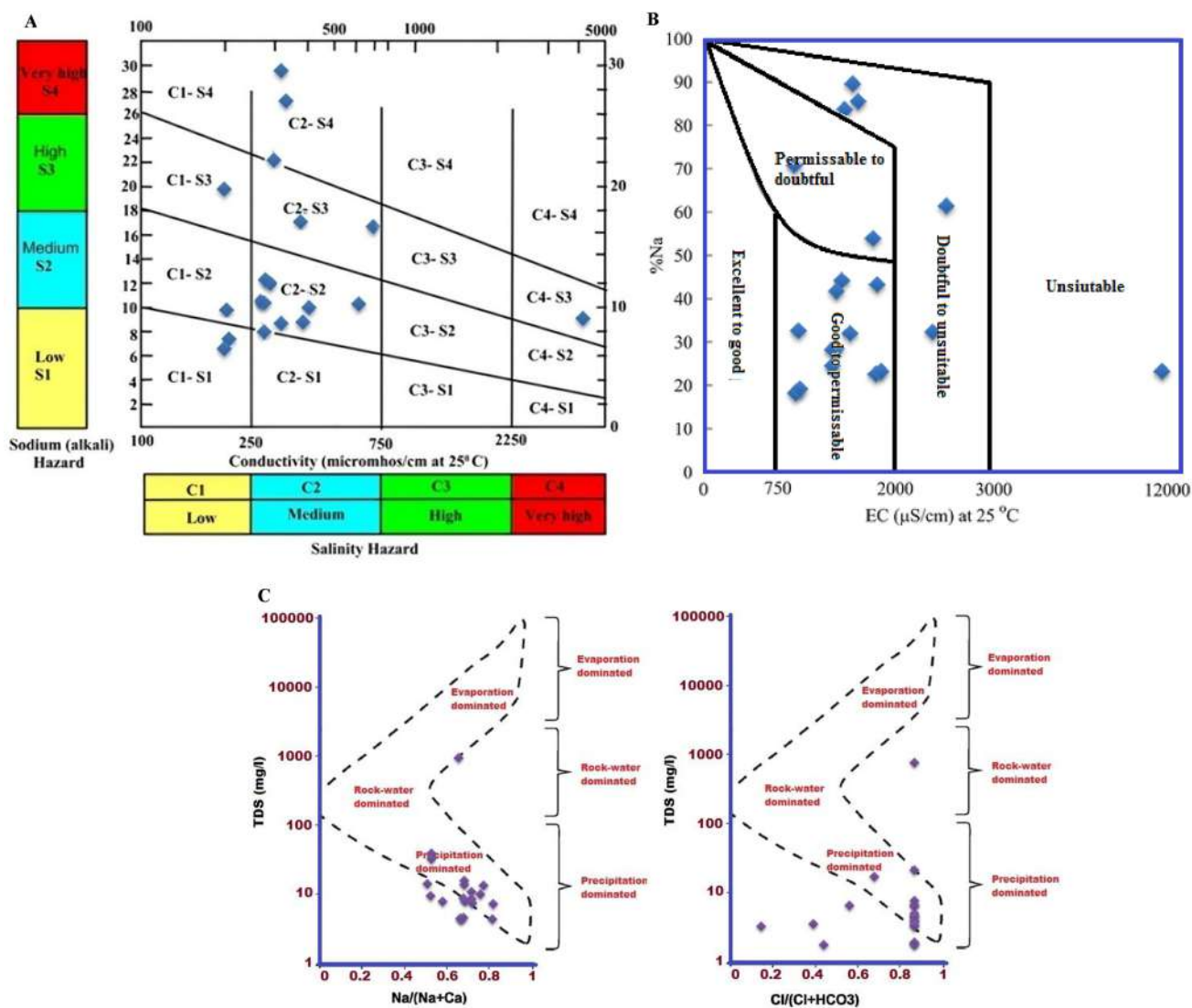


Fig. 6 A Wilcox diagram of the study area. B USSL diagram of the study area. C Gibbs diagram of the study area

Table 4 Classification of irrigation water based on USSL diagram

Class	No: of samples	Description
C3S1	2	Fair water
C3S2	6	Poor water
C3S3	8	Saline water
C3S4	4	High saline water
C4S4	1	Very high saline water

Table 5 Classification of irrigation water based on Wilcox diagram

Class	No. of samples	Sample numbers
Good to permissible	17	S-1,S-2,S-3,S-4,S-6,S-7,S-8,S-9,S-10,S-11,S-13,S-14,S-15,S-16,S-17,S-19,S-20
Doubtful to unsuitable	2	S-12,S-5
Unsuitable	1	S-18

GIBB'S plot

Groundwater chemistry is influenced by variety of processes and mechanisms. The Gibb diagram (Gibbs 1970) can be used to understand the mechanism of chemical reactions that contribute to changes in groundwater composition and the

source of dissolved ions. The Gibbs diagram recognizes three types of fields: precipitation, evaporation/crystallization, and rock-water interaction. The graph shows $(Na+K+)/(Na+K+Ca+2+)$ vs. TDS and $Cl/(Cl+HCO_3-)$ vs. TDS, describes the interaction between rock and water in



groundwater chemistry. As evaporation increases, salinity also increases due to the increase in Na^+ and Cl^- , while TDS increases in groundwater. According to Gibb's scheme (Fig. 6C), most of the samples in the study region fell into the "evaporation" and "anthropogenic activity" domains, while others fell into the "rock-water interaction" domain. Evaporation leads to an increase in salinity by increasing Na and Cl in proportion to the increase in TDS.

Conclusions

Physical and chemical tests were analyzed to determine the quality of groundwater in and around Chennai. The pH values revealed that 20 samples show less than 6.5, as required by the BIS (2012). Water with the pH below 6.5 is more acidic and likely to contain impurities, making it unsuitable for consumption. Therefore, all samples in this study were classified as unfit for human consumption. A high electrical conductivity (EC) value indicates high salinity in the area, with sample 18 from Triplicane having the highest salinity, while sample 4 from Thirumullaivoyal had the lowest. The chemical parameters K , Ca^{2+} , HCO_3^- , and CO_3^{2-} in the study region were within the acceptable limits defined by BIS (2012). The USSL diagram divided the water samples into groups, with most falling into the C3S3 category, which means high EC and SAR values that make the saline water unsuitable for irrigation. The highest SAR value was found in sample 2 from Kotturpuram and the lowest in sample 16 from Velacherry. The Wilcox diagram rated 17 samples as "very good" for domestic use, while two from Santhome and Maduravoyal were rated as "doubtful to unsuitable." Only one sample, number 17 from Triplicane, was rated as completely unsuitable for domestic purposes. The Gibbs diagram shows that most of the samples fall into the "evaporation" and "anthropogenic activity" categories, with a which fall into the "rock-water interaction" category. Evaporation increases salinity by increasing Na and Cl content relative to total dissolved solids (TDS). The spatial Na-Cl maps show that the eastern part of the study area has high levels of sodium and chloride ions, indicating salinity intrusion. High TDS values indicate dissolution of minerals, which can be exacerbated by wastewater and unprotected drainage systems. Elevated physicochemical parameters at certain locations may be caused by improper disposal of solid waste, depth of wells, or geologic elements in contact with groundwater. Finally, the investigation revealed that the groundwater at ten specific locations (S-1, S-5, S-12, S-14, S-15, S-16, S-17, S-18, and S-19) are not potable.

Future research should concentrate on continuous and seasonal monitoring of groundwater quality in order to capture temporal fluctuations and long-term patterns. Advanced hydrogeochemical modeling and isotopic

analysis have the potential to provide more information about salinity intrusion mechanisms and contaminants. To improve water quality, remedial solutions such as artificial recharge structures, controlled solid waste management, and stronger industrial effluent regulations should be explored and implemented. Furthermore, public awareness initiatives promoting water conservation and proper disposal techniques could greatly reduce anthropogenic impacts on groundwater systems. Expanding the scope of the study to include microbiological and heavy metal studies will result in a more comprehensive assessment of groundwater suitability for various applications.

Acknowledgements The first author expresses his sincere thanks to Mr. A.P.C.V. Chockalingam Secretary, our Principal, Dr.C. Veera Bhagu, V.O.Chidambaram College, Tuticorin. The Authors highly thankful to Professor and Head Department of Geology, University of Madras, Chennai for necessary analytical help during the time of this study.

Author contributions The author contributions are as follows: Ramachandran A., Stephen Pitchaimani V., and Richard Abishek S. were involved in the conceptualization and design of the study. Nayana M. P. and Nisha A. contributed to the data collection and analysis. Suresh Gandhi M. provided critical revisions and final approval of the manuscript.

Funding There is no funding source for this study.

Data availability The datasets generated during and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Declarations

Competing interests The authors declare no competing interests.

Ethics approval and consent to participate Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable.

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