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RESEARCH ARTICLE

A mathematical approach to groundwater quality and pollution of Adyar sub-basin, Tamil Nadu, India

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Abstract - The quality of drinking water sources in the Adyar river sub-basin of northern Tamil Nadu is assessed in this study. This research uses a combined water quality index (WQI) and pollution index (PI) to assess and characterise groundwater quality. Water samples will be collected from nine locations in the study area for the assessment. The water quality index was calculated based on Total Dissolved Substances (TDS), Nitrogen oxides (NOx), Calcium (Ca), Magnesium (Mg), Sodium (Na), Potassium (K), Chloride (Cl), Sulphate (SO4), Bicarbonate (HCO3), Fluoride (F), Power of Hydrogen (pH) and Electrical Conductivity (EC). These twelve parameters were analysed and characterised according to standard methods and the Indian standard, which were then used in calculating the water quality index. Groundwater quality and pollution status of the Adyar river basin were assessed using the Groundwater quality index and comprehensive pollution index for the years 1990, 2005, and 2020. A result reveals that the groundwater quality has decreased from 1990 to 2020. Around seven parameters exceeded the permissible limits in 1990, nine parameters exceeded the permissible limits in 2005, and around eight parameters exceeded the allowable limits in 2020. The pollution status of the groundwater has considerably reduced from 1990 to 2020. Eastern parts of the study area were highly polluted and had low groundwater quality.

Keywords: Water quality parameters, groundwater quality index, pollution index, Adyar sub-basin

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INTRODUCTION

Water is essential for human survival; hence termed water as life (Dirican, 2015; Bouslah et al., 2017). According to the hydrological cycle, water availability in the atmosphere, oceans, seas, lakes, and groundwater accounts for a significant portion of the earth's composition. However, due to water contamination, not all water accessible in all of the locations mentioned above may be safe for human consumption or human activities such as crop irrigation, fish aquaculture, or even all agricultural activities in general (Khan et al., 2003; Khan et al., 2013; Sargaonkar & Deshpande, 2003). Across the world today, water pollution is a significant cause of undesirable water quality may be due to the contamination of the water bodies by either emission of acidic gases into the atmosphere or the release of industrial waste products into water bodies (Duan et al., 2016; Walakira & Okot, 2011; Muwanga & Barifaijjo, 2006; Wanasolo et al., 2018). The anthropogenic factors are pesticides and chemical fertilisers in agriculture (Vadde et al., 2018; Selvam et al., 2014). Improving the growth of plants may also result in pollution and contamination of groundwater which has been widely used as the primary source of freshwater. All the anthropogenic activities mentioned result from the increased population over the years and unpredictable climatic changes (John et al., 2014; Scanlon et al., 2007). Therefore, water quality analysis or evaluation is required to determine whether

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the available water from the so-called trustworthy sources is safe for drinking (Tuzen & Soyla, 2006; Heydari & Bidgoli, 2012) and other applications. The water quality index was designed initially by Horton in 1965 (Horton, 1965) and Brown et al., 1970 and later advanced by (Landwehr & Deininger, 1976; Dinius, 1987; Dojlido et al., 1994). Therefore, it is considered a crucial tool for water quality assessments by many researchers worldwide (Jahin et al., 2020; Medeiros et al., 2017). It entails using various physio-chemical parameters characterised as Total Dissolved Substance (TDS), Nox, Calcium (Ca), Magnesium (Mg), Sodium (Na), Potassium (K), Chlorine (Cl), Sulphate (SO_4), Bicarbonate (HCO_3), Fluorine, (F), pH and Electrical Conductivity (EC) which are more critical for groundwater quality (Barbosa and Oliveira, 2021) and compared to a standard regulatory value. Water quality is then rated to obtain a single quality indicator termed the water quality index (Chatterjee & Raziuddin, 2002; Brown et al., 1972). The comprehensive pollution index has been utilised to predict polluted groundwater (Gulshan et al., 2017). The single value is essential to any manager who needs precise and concise information on water quality. The study aims to find groundwater quality and pollution status in the Adyar sub-basin for the years 1990, 2005, and 2020. The Adyar sub-basin has been considered for the study due to the expansion of the city around Chennai city which lies in the Adyar sub-basin where numerous industries are buildup with will prone to groundwater quality.

STUDY AREA

The study area of the Adyar sub-basin is one among the eight sub-basins of the Chennai basin falling in Chengalpattu, Kancheepuram, and Thiruvallur districts in the northern part of Tamil Nadu (Figure 01). Adyar sub-basin is bounded by the Cooum sub-basin in the north, Kovalam sub-basin in the south, Palar basin in the west, and Bay of Bengal in the east. The total geographical area of the sub-basin is 868.97Sq.Km and geographically lies between 12º47'15''-13º07'30'' North latitude and 79º48'15''-80º17'15'' East longitudes. The study area presented two hundred forty-seven villages (fully or partially).Out of 38 firkas in the Adyar sub-basin, an over-exploited category is seen in 15 firkas one firka comes under critical, six firkas in semi-critical, and the remaining 16 firkas fall in the safe category based on groundwater assessment (GW). Due to the over-exploited and critical categorisation of firkas, getting Institutional finance for groundwater development is very complicated for the poor farmers in these firkas, and hence socio-economic problems arise. These farmers are mostly marginal to small landholders. Therefore they are migrating to adjacent towns, cities, and states for their livelihood, leaving fertile cultivable lands, existing groundwater structures, cattle, etc., for water for irrigation and quenching their thirst. Hence the present study contributes by targeting potential groundwater zone for sustainable groundwater development for farmers and domestic utilities with the latest technologies. The central and western parts of the study area were occupied with Calcareous sandstone, Northwestern parts occupied with Amphibolite, Southern parts occupied with Granite, Northern parts occupied with clay, and Eastern parts occupied with Sand and silt. Mylonite, Syenite, and Graphite gneiss are also in the study area.

DATA AND METHODOLOGY

The secondary data of groundwater parameters has been gathered from the Tamil Nadu Ground Water Board, Taramani. The twelve parameters of Total Dissolved Substances (TDS), Nitrogen oxides (NOx), Calcium (Ca), Magnesium (Mg), Sodium (Na), Potassium (K), Chloride (Cl), Sulphate (SO4), Bicarbonate (HCO3), Fluoride (F), Power of Hydrogen (pH) and Electrical Conductivity (EC).

Ground Water quality index (GWQI)

Different methods are used to calculate WQI to compare physicochemical and biological parameters. Brown et al(1972)'s Weighted Arithmetic WQI (WAWQI) was used in this study. Using the observed water quality parameters TDS, NOx, Ca Mg, Na, K, Cl, SO4, HCO3, F, PH, and EC, the weighted arithmetic WQI approach classified the water quality according to the level of cleanliness. This approach was chosen since numerous researchers have utilised it (Balan et al., 2012; Ramakrishnaiah et al., 2009; Shweta & Satyendra, 2015). With the help of the following equation, the WQI was calculated:

$$WQI = \frac{\sum_{n=1}^{a} Q_n W_n}{\sum W_n}$$

The rating scale (Q_n) for each parameter is calculated by

$$Q_{n=}\left[\left(\frac{B_e - B_i}{C_v - B_i}\right)\right] * 100$$

Where B_e is the probable concentration of the nth variable in the water; B_i is the outstanding value of the given parameter in uncontaminated water, which is equivalent to zero (for pH, the value of Bi is seven); C_v is the recommended standard value of the nth parameter (Indian standard in this case), W_n is the unit weight of every water quality parameter summed up to one and calculated as

$$W_n = K \sum \frac{1}{C_v}$$

Where K is the proportionality constant, which can also be calculated using the equation below.

$$K = \frac{1}{\sum\left(\frac{1}{C_b}\right)}$$

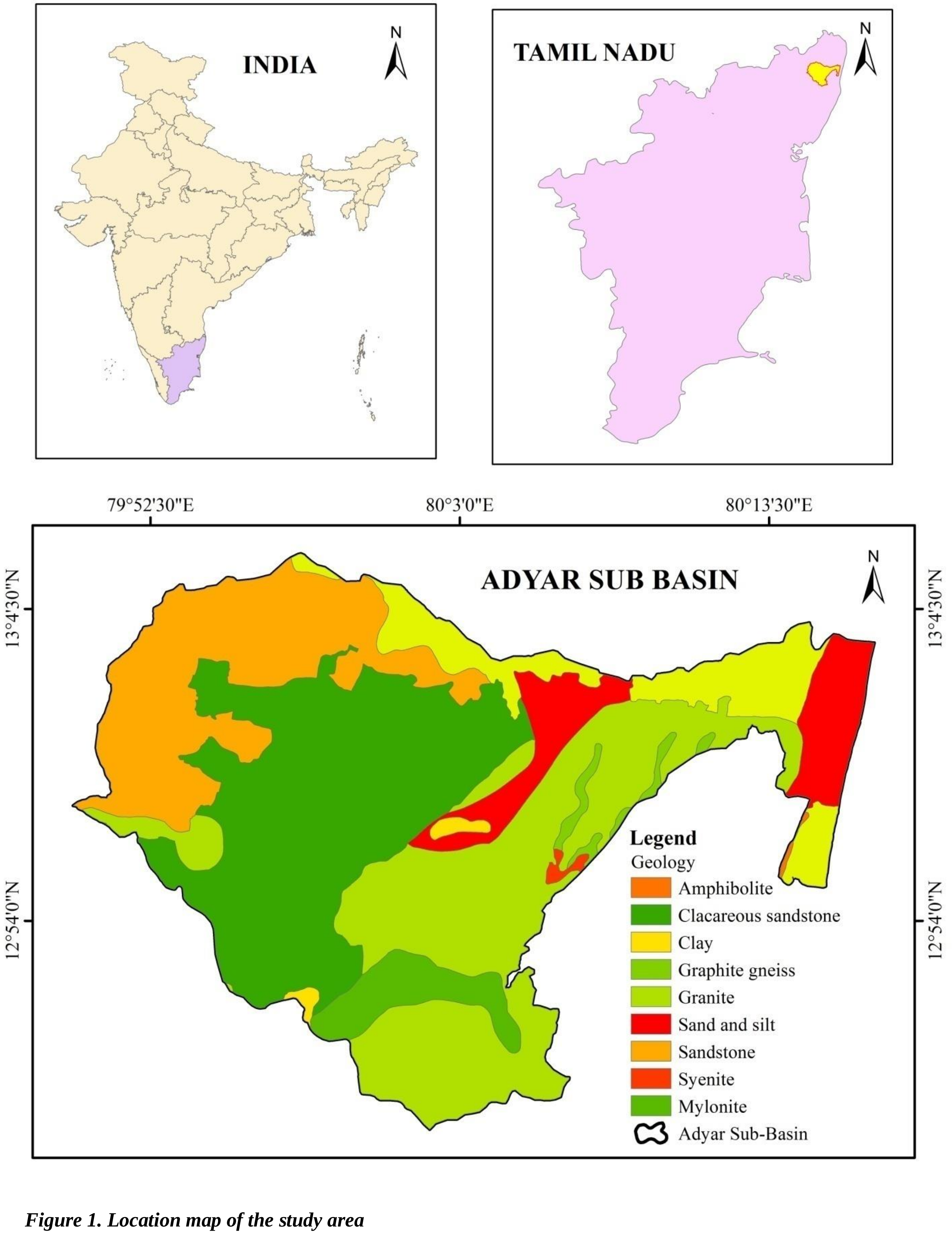

Figure 1. Location map of the study area

The WQI was well thought-out for human drinking water consumption in this research. The proposed rating scale was in the range of 0 to 100. water is Excellent if the index value is between 0 and 25; the value of Good water lies between 26 and 50; the value of Poor water lies between 51 and 75; The value from 76 to 100 is considered very poor water; and if the value is more than 100, then the water will be considered as unsuitable for drinking.

The CPI uses monitoring statistics to determine the degree of pollution in a certain watershed (Liu and Zhu, 1999). The formula for calculating the CPI is as follows:

$$CPI = \frac{1}{x}\sum_{i=1}^{n} Vi$$

where CPI = Comprehensive Polluted Index; *x*= number of monitoring parameters; v_i = the pollution index number *i*.

v_i is calculated based on the equation given below:

$$Vi = \frac{Oi}{Pi}$$

Oi = measured concentration of parameter number in water; Pi = permitted limitation of parameter number according to environmental standard.

CPI is classified into five categories:

1. Category 1 of CPI represents the value from 0 to 0.20 is considered 'clean';
2. Category 2 of CPI represents the value from 0.21 to 0.40 and is regarded as 'sub clean';
3. Category 3 of CPI represents the value from 0.41 to 1.00 and is considered as 'slightly polluted';
4. Category 4 of CPI represents the value from 1.01–2.00 and is considered as 'medium polluted';
5. Category 5 of CPI represents a value above 2.01 and is considered 'heavily polluted.

This work used 12 water parameters to calculate CPI: TDS, NOx, Ca Mg, Na, K, Cl, SO4, HCO3, F, PH, and EC. For the years 1990 and 2020, these parameters were evaluated in the research region.

RESULTS AND DISCUSSIONS

Indian standards for improved drinking water sources above the maximum allowable limits suggested the values of most parameters. The average value of 7 out of the 12 parameters was above the permissible limit in 1990. TDS, Nox, Ca, Mg, Na, Cl, HCO3, and EC were above the permissible limit in 1990. Eight out of the 12 parameters were above the allowable limit in 2020. TDC, Ca, Mg, Na, K, Cl, HCO3, and EC were above the permissible limit in 1990.

Table 1.Statistical analysis of the observed groundwater quality parameters

Parameters	1990			2005			2020		
	Avg.	Min	Max	Avg.	Min	Max	Avg.	Min	Max
TDS	**1465.44**	373.00	8156.00	**1233.5**	402.00	2065.00	**628.00**	442.00	1075.00
NOx	8.89	3.00	33.00	11.5	1.00	22.00	11.22	0.00	42.00
Ca	**104.44**	32.00	300.00	**511.5**	23.00	1000.00	**219.78**	42.00	1400.00
Mg	**81.14**	10.94	486.00	**415.875**	9.00	822.75	**150.19**	9.00	1032.75
Na	**359.78**	19.00	2454.00	**1747.5**	45.00	7450.00	**1216.56**	64.00	10120.00
K	12.01	0.10	35.00	**34.95**	1.90	68.00	**31.33**	3.00	98.00
Cl	**596.78**	64.00	3900.00	**6324**	87.00	12561.00	**2454.56**	117.00	20561.00
SO4	163.00	14.00	946.00	**340**	10.00	670.00	86.56	9.00	470.00
HCO3	**253.85**	117.11	603.90	**270.7**	112.00	429.40	**234.49**	122.00	329.40
F	0.66	0.18	1.93	0.475	0.08	0.87	0.07	0.00	0.57
pH	8.18	7.60	8.50	8.2	7.80	8.60	8.32	8.00	8.70
EC	**2792.22**	670.00	16210.00	**21280**	560.00	42000.00	**7711.11**	760.00	60000.00

Total Dissolved Substances (TDS) indicate the presence of inorganic as well as organic substances in the water. The study has found that the average value of TDS has decreased from 1990 to 2020 though higher than the permissible limit, which causes heart-related diseases (Lata et al., 2015). Similarly, (Appavu et al., 2016) reported high TDS in Cauvery river water in Erode district of Tamil Nadu. The pH scale represents the acidity or alkalinity of water sources, which can result in sour or alkaline flavours. The result shows pH values range was within the prescribed standard in 1990. In 2005 the pH values ranged slightly increased from 1990. In 2020, pH range was slightly above the permissible range as in Rajasthan where the pH range was high in Chapra village, Banothri Khurd and Bangothir Kalan (Taruna & Alankrita, 2013).

The EC value is an index that measures the concentration of soluble salts in a drinking water source that affects its flavour. The Electrical Conductivity of the groundwater in the study area is above the permissible limit during 1990, 2005 and 2020. The average EC has increased from 1990 to 2005 and decreased in 2020. Blue baby syndrome, malignancy, and splenic haemorrhage are all caused by high levels of NOx in drinking water (Aydin, 2007). In all the water samples, the values of Nox were within the range of Indian standards in all years. The range of ca ion during 1990, 2005 and 2020 was above the permissible limit. The average of Ca increased from 1990 to 2005 and decreased in 2020. The range of Mg ions during 1990,2005 and 2020 was above the permissible limit. The range of Na ions was above the permissible limit in all years. In all the water samples, potassium values were within the range of Indian standards in 1990, whereas it was above the permissible limit in 2005 and 2020. In all the water samples, chlorine values were above the permissible limit for all three years. The range of SO_4 ions during 1990 was below the permissible limit; it was above the permissible limit in 2005; in 2020, it was above the permissible limit, which causes health issues such as diarrhoea due to the consumption of high sulphate water. Similarly, Cauvery river water in Erode region of Tamil Nadu has reported high sulphate content in drinking water which cause respiration-related problems in humans (Appavu et al., 2016). The range of HCO3 ions was above the permissible limit in all three years. Fluoride ion was within permissible limits during 1990, 2005 and 2020 shown in Table 01.

With the help of the twelve parameters given in Table 01, the average water quality index was 55.01 in 1990, 69.41 in 2005, and 71.87 in 2020. The water quality index in 1990 is higher than that in 2005, which is higher than in 2020. However, the impact water quality index in 1990; was majorly due to the high TDS, C, MG, Na, Cl, HCO3, and EC. Based on the water quality categories discussed by (Chatterjee & Raziuddin, 2002; Brown et al., 1972) given in Table 04, 5 locations were excellent, two stations were good water, 1 location was poor water, and 1 location was unsuitable for drinking.

WATER QUALITY INDEX

Table 2 provides the relative weight used for calculating the Groundwater quality index. In 2005, the water quality had decreased compared to 1990, mostly due to the high TDS, C, Mg, Na, K, Cl, HCO_3, and EC. Based on the water quality categories discussed in Table 04, three locations were in the excellent class; two stations were good water, three were poor water, and 1 location was unsuitable for drinking purposes.

Table 2. Relative weight to the water quality parameters

Parameters	Indian Standard	Win
TDS	500	0.001548
NOx	45	0.017205
Ca	75	0.010323
Mg	30	0.025808
Na	200	0.003871
K	12	0.06452
Cl	250	0.003097
SO4	200	0.003871
HCO3	200	0.003871
F	1	0.774243
pH	8.5	0.091087
EC_	1400	0.000553

Table 3. Water quality index and water quality status

S.No	GWQI Values	Characteristics
1	0-25	Excellent
2	26-50	Good Water
3	51-75	Poor Water
4	76-100	Very Poor Water
5	>100	Unsuitable for Drinking

Table 4. Parameter characterisation and recommended standards

Sample	Latitude	Longitude	Groundwater Quality Index					
			1990	Classification	2005	classification	2020	Classification
1	13.034	80.153	72.62	Poor Water	68.21	Poor water	32.89	Good Water
2	12.883	80.026	9.82	Excellent	56.33	Poor water	69.18	Poor Water
3	12.992	80.097	12.34	Excellent	24..32	Excellent	69.55	Poor Water
4	13.033	80.006	9.68	Excellent	12.22	Excellent	39.57	Good Water
5	12.973	80.154	44.84	Good Water	55.21	Poor water	76.97	Very Poor Water
6	12.962	80.114	43.46	Good Water	44.32	Good water	34.71	Good Water
7	13.039	80.258	20.96	Excellent	26.23	Good water	49.62	Good Water
8	13.021	80.226	17.73	Excellent	48.22	Excellent	51.65	Poor Water
9	12.992	80.249	263.67	Unsuitable	245.23	Unsuitable	222.72	Unsuitable

In 2020 the water quality index had decreased further as compared to 1990 and 2005 due to the high TDS, C, Mg, Na, K, Cl, HCO_3, and EC. Similarly, (Ramachandran, 2020) found that the water quality decreased from 2000 to 2015 in Pudukkottai District of Tamil Nadu due to the extreme use of artificial fertiliser. Based on the water quality categories as discussed in Table 04, no location was in the excellent class; three stations were good water, 3 locations were poor water, 1 location was poor water, and 1 location was unsuitable for drinking purposes. Overall, the excellent water in 5 locations in 1990 decreased to 3 locations in 2005 and no excellent water quality in 2020. In contrast, one location with poor water in 1990 has increased to 5 locations with poor and above poor water conditions in 2020. Similarly, Sohail et al., 2022 have found that the water quality has decreased, which causes significant health issues in Pakistan.

A study on water quality performed in the highlands of Ethiopia has indicated that the water quality has become unsuitable for the purpose of drinking, which creates severe health impacts (Addisie, 2022). (Adimalla, N., & Qian, 2019) has reported that the water quality index has shown a poor quality of drinking water in Nanganur, South India.

Sample 1 is located in water bodies where the quality of water is increased due to incoming rainwater. Sample 2 is located in a built-up area where the quality of water was excellent in 1990 and became worst in 2005 due to the discharge of sewage water in 2020. The construction of the sewage discharge canal has stopped the percolation of sewage which has improved the groundwater quality. Sample 3 is located in an agricultural area where the quality of water has decreased from 1990 to 2020 due to the usage of artificial chemical fertiliser. Similarly, sample 4 is located in an agricultural area where the quality of water has decreased but is not severe as sample 3 due to the presence of a wetland nearer to this sample 4. Sample 5 had very poor water quality in the year 2020 due to coastal influence, and this location is situated in a built-up area. Sample 6 is located in a village area surrounded by wetlands and water bodies which maintained good water quality during 1990, 2005 and 2020. Samples 7, 8 and 9 are located in built-up areas where the water quality has decreased considerably.

The spatial distribution of groundwater quality is represented in Figure 3 for the years 1990 and 2020, and Figure 6 represents the spatial distribution of groundwater quality for 2005. Excellent water in the year 1990 was seen in the middle region of the study area; in 2005, excellent water and good water had reduced as compared to 1990, whereas excellent water was absent during the year 2020. Significant parts of the region were in good water during 1990 and have changed to poor water by 2020. The unsuitable drinking water condition prevailed in the eastern parts of the study area between 1990, 2005, and 2020.

The spatial representation of excellent water conditions during 1990 was reduced in 2005, and this condition became absent in 2020. Good water conditions during 1990 were reduced in 2005 and further reduced in 2020. Unsuitable drinking water condition has increased from 1990 to 2020 shown in Table 05 and Figure 2.

COMPREHENSIVE POLLUTION INDEX

The CPI data show the value of the entire study area with no significant difference in the years 1990, 2005, and 2020. In 1990, the CPI of the study area with an average value of 2.99. According to the CPI's classification, the study area was slightly and heavily polluted. Among the nine sample stations, six stations were slightly polluted, two stations were moderately polluted, and one station was heavily polluted. In 2005, the CPI of the study area with an average value of 2.23. According to the CPI's classification, the study area was slightly and heavily polluted. Among the nine sample stations, seven stations were slightly polluted, one station was moderately polluted, and one station was heavily polluted

Table 5. Groundwater quality classification based on WQI value

S. No.	GWQI Values	Characteristics	Area in Sq. Km		
			1990	2005	2020
1	0-25	Excellent	239.55	72.95	0.00
2	25-50	Good Water	470.60	417.04	132.16
3	50-75	Poor Water	70.71	287.48	627.80
4	75-100	Very Poor Water	30.88	33.78	43.85
5	>100	Unsuitable For Drinking	56.26	56.76	64.19

In the year 2020, the CPI of the study area with an average value of 1.46. According to the CPI's classification, the study area was slightly and heavily polluted. The result indicates that seven stations were slightly polluted, one was moderately polluted, and another one was heavily polluted. Similarly, (Chaudhary et al., 2017) have studied pollution using a comprehensive pollution index, revealing that Ganga water became heavily polluted and unsuitable for drinking during pre and post-monsoon season. The pollution level has considerably decreased (improved) from 1990 to 2020 shown in Table 06. The spatially comprehensive pollution index shown in Figure 04 indicates that no region was clean or sub-clean in all their years. The slightly polluted region was located in small central parts during 1990 and increased in 2005, whereas during 2020 slightly polluted region raised in the study area's north and central parts. Entire western and central parts of the study area during 1990 were medium polluted similarly in 2005, reduced and spread to only southwestern parts of the study area during 2020. The heavily polluted region was located in the eastern parts of the region during all years, but it has been reduced from 1990 to 2005 shown in Figures 5 and 5.

The slightly polluted region in the year 1990 increased in 2005 and further increased in the year 2020. Medium-polluted areas in 1990 rose slightly in 2005 and then decreased in 2020. The heavily polluted region decreased in 2005 compared to 1990 and then further reduced in 2020, as shown in Table 7 and Figure 4.

CONCLUSION

Groundwater quality and pollution status of the Adyar river basin were assessed using the Groundwater quality index and comprehensive pollution index between 1990, 2005 and 2020. Results reveal that the groundwater quality has decreased from 1990 to 2020. Around seven parameters (TDS, Ca, Mg, Na, Cl, HCO_3, and EC) exceeded the permissible limits during 1990, nine parameters (TDS, Ca, Mg, Na, K,SO_4, Cl, HCO_3, and EC) exceeded in 2005 and around eight parameters (TDS, Ca, Mg, Na, Cl, K, HCO_3, and EC)exceeded the permissible limits in 2020. Excellent water quality has decreased from 239 sq. km in 1990 to 0 in 2020, and unsuitable for drinking water has increased from 56 sq. km to 64 sq. km. The pollution status of the groundwater has considerably reduced from 1990 to 2020. The heavily polluted region has been slowly shifting to a slightly polluted region. Eastern parts of the study area were highly polluted and had low groundwater quality in all three years. The government should ensure the industries in the basin release their wastewater after treatment.

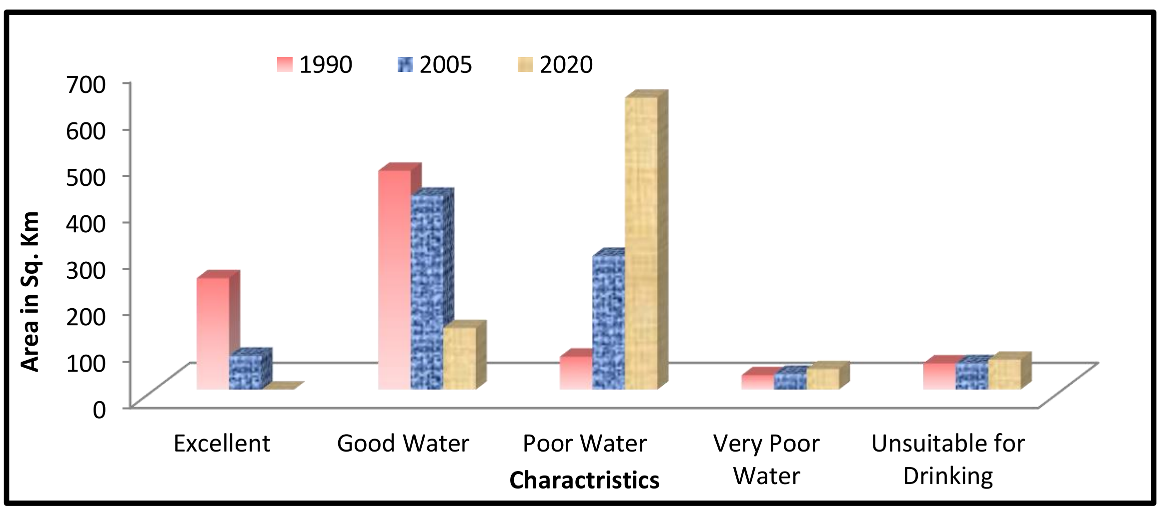

Figure 2. Areas of GWQI Characteristics

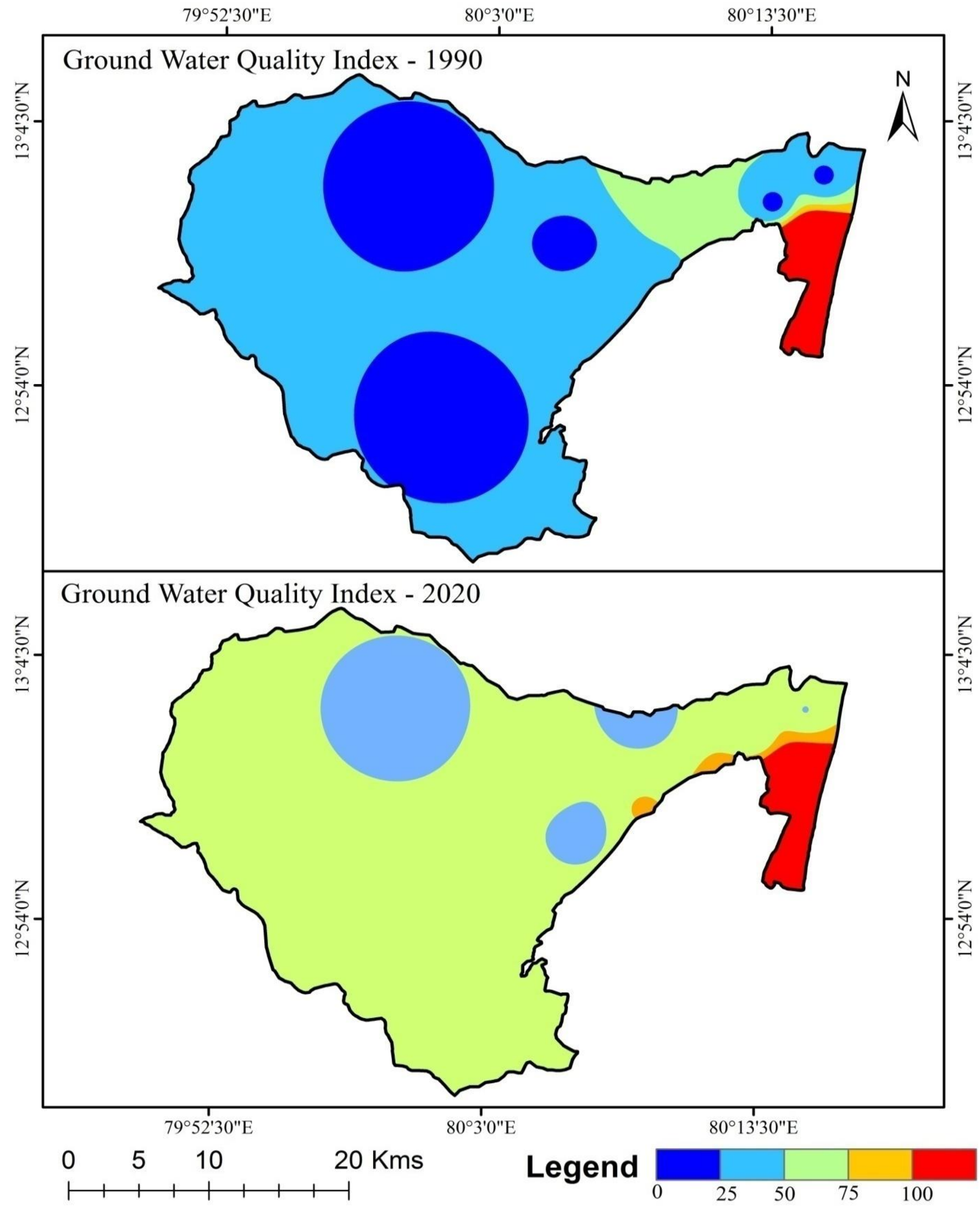

Figure 3. Spatial distribution of GWQI

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Table 6. Water Pollution Indices

Sample	Latitude	Longitude	Comprehensive Pollution Index					
			1990	Classification	2005	Classification	2020	Classification
1	13.034	80.153	0.87	Slightly Polluted	0.74	Slightly Polluted	0.60	Slightly Polluted
2	12.883	80.026	0.71	Slightly Polluted	0.99	Slightly Polluted	1.27	Medium Polluted
3	12.992	80.097	0.59	Slightly Polluted	0.67	Slightly Polluted	0.75	Slightly Polluted
4	13.033	80.006	0.50	Slightly Polluted	0.57	Slightly Polluted	0.63	Slightly Polluted
5	12.973	80.154	1.45	Medium Polluted	0.97	Slightly Polluted	0.48	Slightly Polluted
6	12.962	80.114	1.18	Medium Polluted	1.08	Medium Polluted	0.97	Slightly Polluted
7	13.039	80.258	0.65	Slightly Polluted	0.63	Slightly Polluted	0.61	Slightly Polluted
8	13.021	80.226	0.57	Slightly Polluted	0.55	Slightly Polluted	0.53	Slightly Polluted
9	12.992	80.249	20.43	Heavily Polluted	13.89	Heavily Polluted	7.34	Heavily Polluted

Table 7. Area of Comprehensive pollution index

CPI Value	Classification	Area in Sq. Km		
		1990	2005	2020
0.0-0.2	Clean	0	0	0
0.2-0.4	Sub Clean	0	0	0
0.4-1.0	Slightly Polluted	159.92	179.66	367.70
1.0-2.0	Medium Polluted	590.09	599.28	422.36
>2.0	Heavily Polluted	117.99	89.05	77.94

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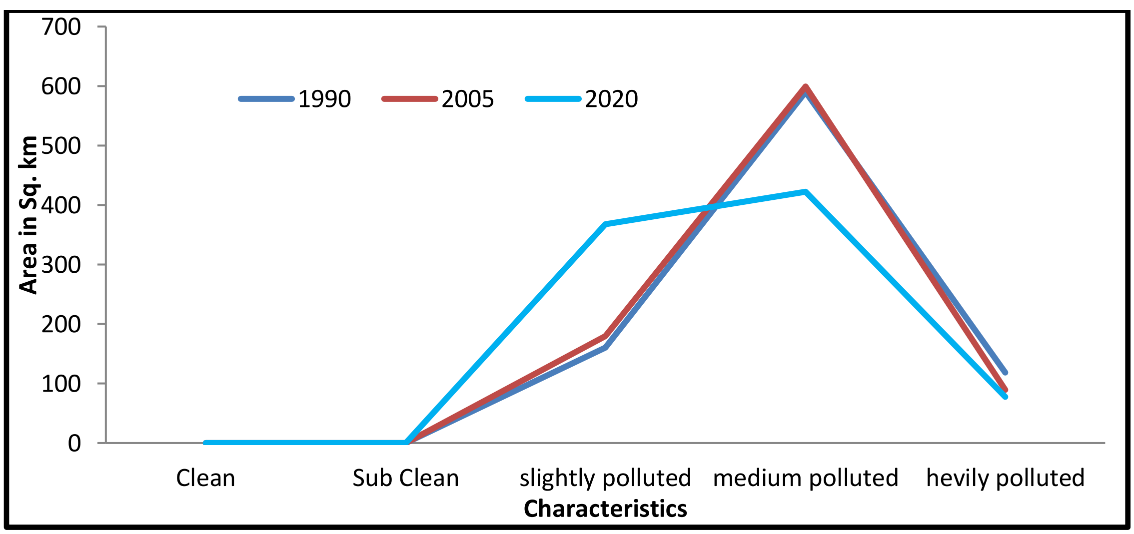

Figure 4. Area of comprehensive pollution index

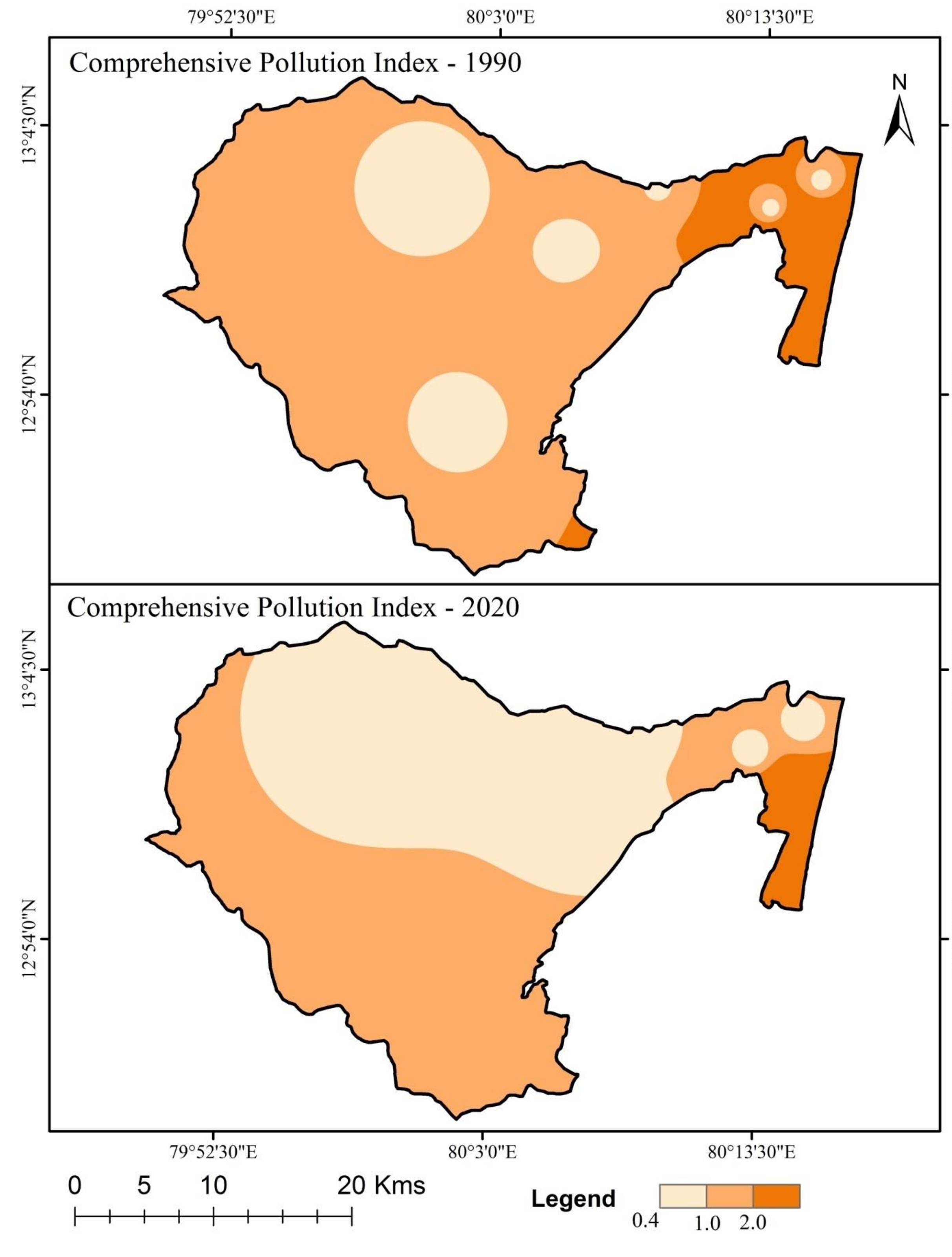

Figure 5. Spatial distribution of CPI

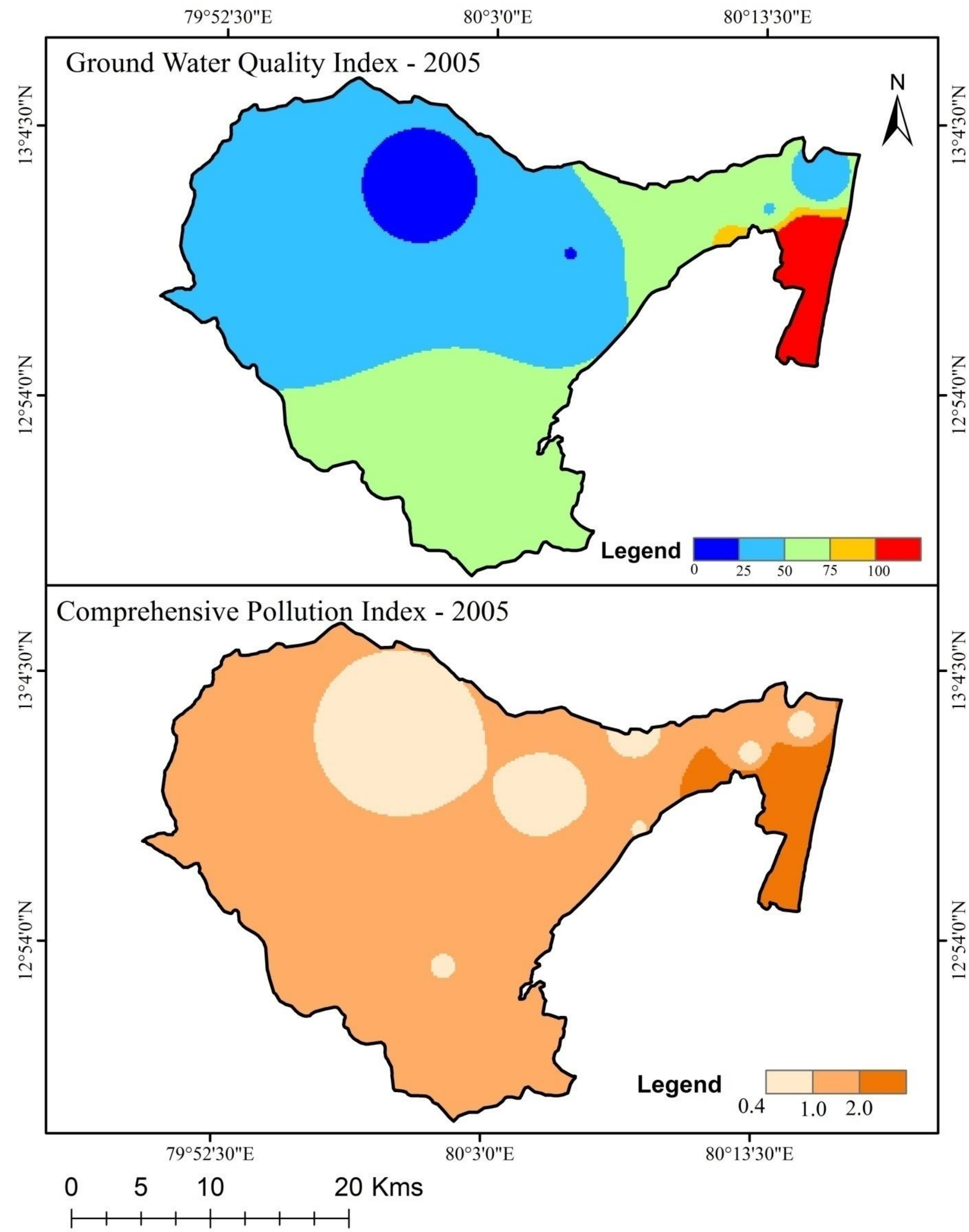

Figure 6. Spatial distribution of Groundwater quality index (2005) and comprehensive pollution index (2005)

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