

Groundwater and surface water quality under urbanization pressure: A water quality index assessment in Siliguri Planning Area, India

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Abstract

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Safe drinking water and sustainable water resource management require routine evaluations of groundwater and surface water quality. Rapidly expanding urban areas depend heavily upon these crucial assessments. Consequently, the spatial distribution of water quality parameters within the Siliguri Planning Area of West Bengal, India, was evaluated in this work. The Water Quality Index (WQI) was also calculated for both groundwater and surface water resources. The Weighted Arithmetic Water Quality Index method categorized the overall condition of these hydrological resources. A spectrum ranging from good to very poor conditions (WQI ranging from 34.02 to 182.30) defines the current groundwater quality. Elevated nitrate (up to 118 mg/L), iron (0.55 mg/L), and potassium concentrations heavily contaminate the central and southeastern urban zones. Strong positive relationships among nitrate, sodium, and sulphate ($r > 0.90$) were identified through correlation analysis. Human-driven pollution from agricultural runoff and domestic sewage is clearly indicated by these substantial linkages. Notable spatial variation characterized the surface water quality, with SWQI scores fluctuating between 12 and 76.97. Elevated BOD, TDS, and chloride concentrations drove a progressive deterioration along the urban corridors of the Mahananda River. Conversely, relatively healthy conditions were maintained throughout the Balason River. Agricultural activities, improper waste disposal, and intense urbanization severely impact these vital reserves. Immediate intervention is absolutely necessary to halt this widespread degradation. Ultimately, policymakers and civic authorities can construct targeted water quality management strategies using these empirical results. The design of vital treatment infrastructure throughout the region can be supported by the scientific foundation presented in this study.

1. Introduction

In many regions of the world, groundwater is the primary supply of freshwater needed for agricultural and home uses. Groundwater is an ideal resource for drinking since it is widely distributed, readily available, and consistently of high quality. Roughly one-third of Earth population depend on groundwater for drinking [1]. The demand for groundwater resources as fresh water has significantly increased as a result of the fast population growth, urbanization, intensified industrialization, and insufficient availability of surface water. Groundwater quality and quantity have been negatively impacted by overexploitation brought on by urban expansion [2]. The Central Groundwater Board estimates that 396 km³ of India's 432 km³/year fresh groundwater resources are useable [3].



The quality of groundwater fluctuates significantly between areas due to the different ways that land is used. For that reason, water quality must be monitored, particularly in urban areas where groundwater is more vulnerable to pollution from residential, commercial, and agricultural operations [4]. In this context, numerous studies regarding the quality of groundwater for drinking and irrigation has been evaluated in many regions of India, since determining groundwater's suitability for residential, commercial, and agricultural uses requires an understanding of its chemical quality [5-7]. Moreover, groundwater chemistry can be utilized to comprehend hydro geochemistry, the mechanism regulating groundwater quality, since it is influenced by numerous interconnected processes and depends on the minerals that compose geological formations [8].

Surface water serves as the primary source of drinking water in Siliguri [9]. The northern part of the state, known as North Bengal, has a distinctive geographical setting. It includes the Himalayan foothills, plains, and various perennial rivers. The Siliguri planning area is an important urban centre in this region and is growing rapidly due to its location and economic importance. It also connects northeastern India with neighbouring countries such as Nepal, Bhutan, and Bangladesh. Several rivers pass through Siliguri such as Mahananda, Balason, and Panhna in addition to Teesta-Mahananda link canal, which serves as the main source of drinking water in Siliguri Municipal Corporation. In this sense, the study of surface water quality in Siliguri region is of high importance.

Due to rapid urban growth, the demand for water has increased in the study area. This increased demand puts continuous strain on water resources. Both surface water and groundwater are used in this region, since most people depend on surface water for drinking, while groundwater is also widely used, particularly in villages. However, water quality can differ drastically across study area due to different land use, soil conditions, and human activities. Waste disposal, agriculture, and urban growth are affecting water quality [10]. Therefore, this study aims to provide a comprehensive assessment of surface and groundwater quality in Siliguri Planning Area. Such a study is necessary to highlight the critical linkages between public health, urban planning, and long-term environmental sustainability. The research would serve not merely as a scientific inventory, but as an essential decision-making tool for policymakers, civic authorities, and community stakeholders.

2. Material and Methods

2.1. Study area

Siliguri Planning Area is situated on the bank of River Mahananda in the Darjeeling Himalayan foothills region. The study area is bound by Kurseong to the north, Bangladesh to the south, Jalpaiguri to the east, and Nepal to the west. It is also known as the "Gateway of north-eastern states" extending between $26^{\circ}36'36''$ N to $26^{\circ}47'28''$ N and $88^{\circ}17'30''$ E to $88^{\circ}30'45''$ E (Fig. 1). The area spans 260 Km² and has a total population of 963,498 [11]. The study area belongs to the monsoonal climatic region. The average annual rainfall of this region ranges from 2600 mm to 4000 mm. The warmest month is June (35°C), and the coldest month is January (7°C) with an average elevation of 130 m above the sea level. It is found that, except for Kolkata Municipal Corporation, the population density of Siliguri Municipal Corporation (SMC) is much higher than all other cities in West Bengal. More specifically, it has the highest population density among the newly upgraded corporation cities of

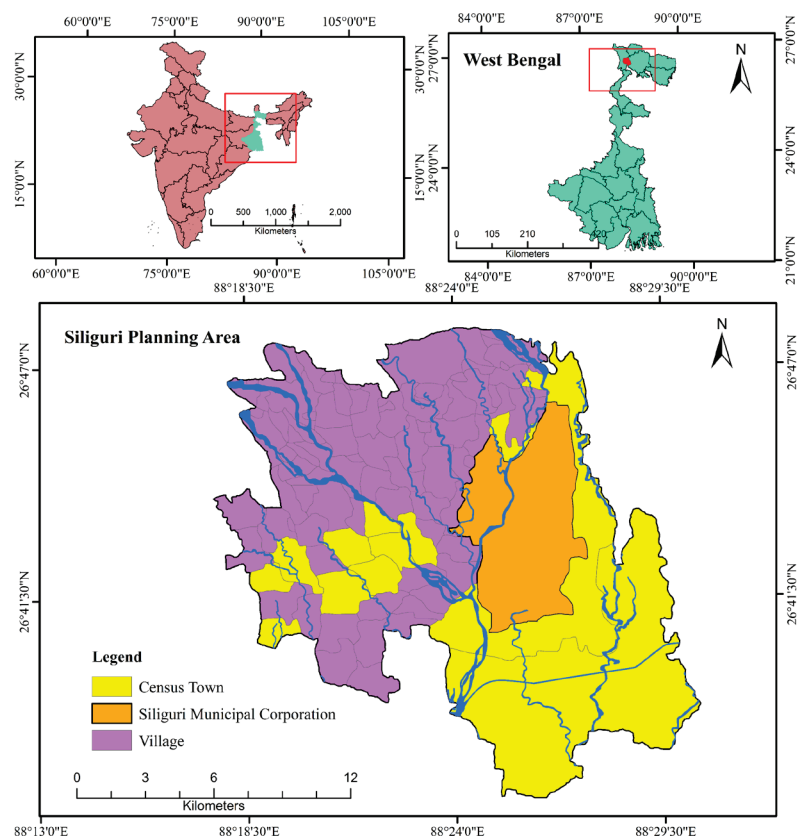


Figure 1. Location map of Siliguri Planning Area

West Bengal (12,250 person/km²) [12]. On the other hand, along with the development of SMC, the surrounding areas such as Matigara, Shivmandir, Bagdogra, and Dabgram-Fulbari regions are also growing rapidly. The demand for all resources, especially water, has significantly increased due to high population growth and urbanization.

2.2. Sampling

To analyse the groundwater quality in the studied region, nineteen bore wells with depths ranging from 80 to 150 meters were selected based on geographic distribution to generate a representative groundwater sample [13] (Fig. 2 A). Ten parameters were investigated: iron (Fe), sodium (Na), magnesium (Mg), potassium (K), chloride (Cl), nitrate (NO₃), sulphate (SO₄), pH, electrical conductivity (EC), and total hardness (TH).

To evaluate the status of surface water quality in the study area, three fluvial systems were selected, namely the Balason River, Mahananda River, and the Teesta–Mahananda Link Canal. These water bodies constitute the principal surface water resources of the region and play a significant role in domestic water supply and irrigation. Overall, 14 water samples were collected (Fig. 2 B) and subsequently analyzed for pH, Total Dissolved Solids (TDS), temperature, chloride (Cl), iron (Fe), nitrate (NO₃), dissolved oxygen (DO), total hardness (TH), and biochemical oxygen demand (BOD).

The sampling sites were distributed to capture spatial heterogeneity in water quality under varying environmental settings. Site selection was carried out based on multiple criteria, including (i) upstream–downstream variation, (ii) proximity to urban settlements and agricultural fields, (iii) accessibility, and (iv) potential sources of pollution such as domestic discharge points and runoff zones. This approach ensured that the dataset adequately represents both relatively less disturbed and highly influenced segments of the water bodies.

Surface water samples were collected during the field survey following standard protocols for water quality assessment. At each sampling station, water was collected from the midstream section at a uniform depth to avoid marginal contamination and ensure representative sampling conditions. Clean, pre-treated polyethylene bottles were used for sample collection. Prior to sampling, the containers were rinsed with the sample water to minimize contamination.

All water samples were collected in the year of 2025 and analyzed according to the American Public Health Association (APHA) [14]. The collected data were then used to map the Groundwater Quality Index (GWQI) and Surface Water Quality Index (SWQI). This methodological approach helps to understand the present condition of water resources and identify the major factors affecting water quality in the Siliguri Planning Area.

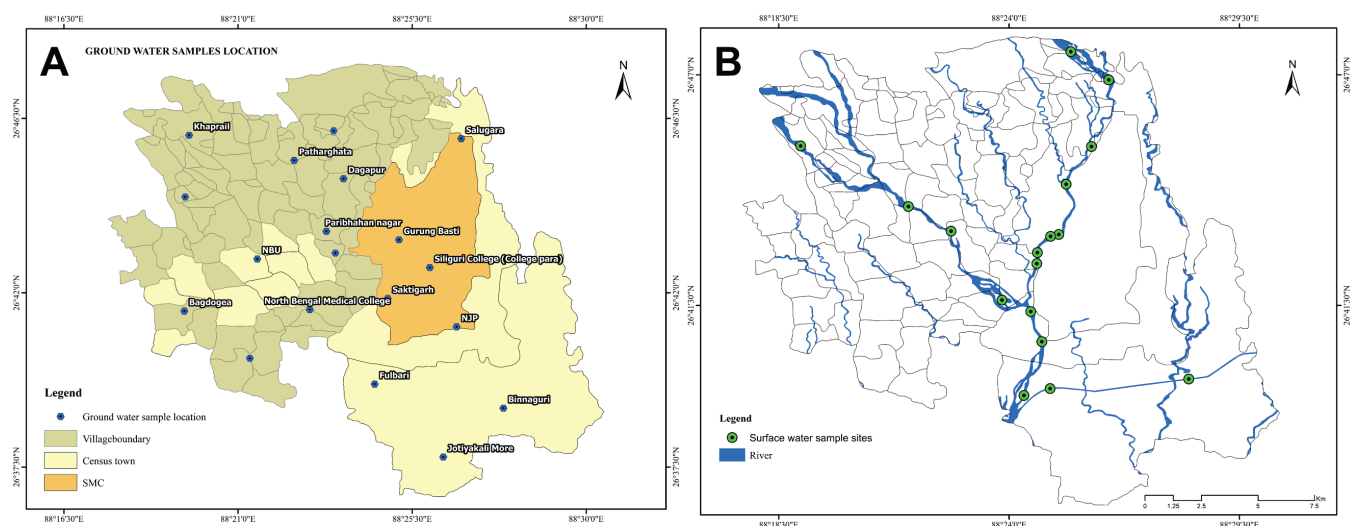


Figure 2. Groundwater (A) and surface water (B) sample sites

2.3. Water Quality Index (WQI)

The Weighted Arithmetic Water Quality Index (WAWQI) approach has been used in this study for assessing the Groundwater Quality Index (GWQI) and Surface Water Quality Index (SWQI). Ten parameters of water quality have been used. For GWQI, seven chemical variables: iron (Fe), sodium (Na), magnesium (Mg), potassium (K), chloride (Cl), nitrate (NO₃), and sulphate (SO₄) and three physical variables: pH, electrical conductivity (EC), and total hardness (TH) were taken into account. For SWQI, on the other hand, four chemical variables: chloride (Cl), iron (Fe), nitrate (NO₃), and total hardness (TH), three physical variables: pH, temperature, and Total Dissolved Solids (TDS), and two biological variables: dissolved oxygen (DO) and biochemical oxygen demand (BOD) were considered. The WAWQI is one of the widely used techniques for assessing water quality at present time. It provides an in-depth understanding of the quality of surface as well as groundwater using the most frequently measured water quality variables [15]. The following equation was used to calculate the WQI [16]:

First, Unit Weight (W_i) is calculated:

$$W_i = \frac{K}{S_i}$$

$$K = \frac{1}{\sum_{i=1}^n \frac{1}{S_i}}$$

S_i = Standard permissible value of the i^{th} parameter

$\sum W_i = 1$ (Sum of all unit weights equals 1)

Quality Rating (Q_i) is then calculated to express the deviation of the observed concentration from the ideal value:

$$Q_i = \frac{V_{\text{actual}} - V_{\text{ideal}}}{S_i - V_{\text{ideal}}} \times 100$$

where:

V_{actual} = Observed concentration of the parameter

V_{ideal} = ideal value [0 for most parameters, except for pH ($V_{\text{ideal}} = 7$), and for DO ($V_{\text{ideal}} = 14.6$ mg/L)].

Finally, The Weighted Arithmetic Water Quality Index (WAWQI) is computed as the weighted sum of quality ratings:

$$\text{WAWQI} = \frac{\sum_{i=1}^n (Q_i \times W_i)}{\sum_{i=1}^n W_i}$$

WQI values were then used to classify water samples (Table 1) and a Groundwater Index Zone (GWIZ) map was constructed accordingly.

Table 1. Water Quality Index (WQI) and status of water quality

Water Quality Index value	Water quality status
0 – 25	Excellent water quality
26 – 50	Good water quality
51 – 75	Moderate water quality
76 – 100	Poor water quality
Above 100	Very poor water quality

2.4. Mapping

The spatial distribution of groundwater and surface water quality parameters was analyzed and visualized within a Geographic Information System (GIS) environment. The geographic coordinates of the sampling locations were integrated with the corresponding measured physicochemical parameters and calculated Water Quality Index (WQI) values to construct the spatial database. To estimate water-quality conditions at unsampled locations and generate continuous spatial surfaces, the Inverse Distance Weighting (IDW) interpolation technique was applied. IDW is a deterministic spatial interpolation method based on the principle of spatial proximity, whereby observations located closer to an unsampled location exert a greater influence on the estimated value than more distant observations. This approach was considered suitable for representing the localized spatial variability of water-quality parameters across the study area based on the available sampling network. Individual thematic maps were generated for the principal

groundwater and surface water quality parameters. Subsequently, the calculated WQI values were interpolated using the same approach to produce the Groundwater Quality Index (GWQI) and Surface Water Quality Index (SWQI) maps. The resulting WQI surfaces were classified according to the water-quality categories presented in Table 1, enabling the identification and comparison of spatial patterns of water-quality deterioration across the study area.

3. Results and Discussion

3.1. Spatial distribution groundwater parameters

One of the most important aspects in water chemistry is pH. A maximum range of 6.5 to 8.5 has been specified by the BIS (Bureau of Indian Standards, 10500-2012) [17]. The pH value in study area ranged between 6.23 to 8.28 with an average of 7.34 (Fig. 3 A). Most samples demonstrated pH values close to neutral; however, the northern part near Matigara and Patharghata area showed slightly higher levels.

Electrical Conductivity (EC) is another essential water quality indicator, which is preferably below 300 $\mu\text{S}/\text{cm}$, with a guideline limit of 400 $\mu\text{S}/\text{cm}$ and a maximum allowable value of 1500 $\mu\text{S}/\text{cm}$ according to World Health Organization (WHO) guidelines [18]. Considering the aforementioned limits, the present study shows that most of the samples are within the WHO guideline limits for EC. However, higher EC values are found near the central region (Fig. 3 B).

Total hardness is the sum of dissolved calcium and magnesium ions in water. According to WHO guidelines [18], water in the northern and southern regions of the study area ranged from soft (<75 mg/L) to moderately hard (75–150 mg/L) in terms of total hardness (TH). In contrast, samples from the central region fell into the hard (150–300 mg/L) to very hard (>300 mg/L) categories (Fig. 3 C). The lithological structure of an area mostly determines the hardness of groundwater. Calcium (Ca^{2+}) and magnesium (Mg^{2+}) ions are released into aquifers when minerals including hornblende, mica, feldspar, calcite, and dolomite dissolve [19].

According to WHO and BIS [17][18], Na levels in drinking water should not exceed 200, while 30 mg/l is the maximum allowed limits for K and Mg. Both Na and K demonstrated similar distributions throughout the study area, with higher concentrations in the central regions, where maximum values of 104 mg/L and 48 mg/L were recorded, respectively (Fig. 3 D and F). The weathering of silicates (e.g., Albite plagioclase, halite, K-feldspar, and biotite) is the main source of sodium and potassium increases in groundwater samples [20]. Additionally, the increased use of potassium-based fertilizers, such as potassium chloride and potassium nitrate, can significantly increase potassium levels in groundwater through leaching [21]. Magnesium concentrations were found to be below the desired limit in all samples except for that at Dagapur, where a maximum value of 32 mg/L was recorded (Fig. 3 E). Iron (Fe) concentrations in the groundwater samples of the Siliguri Planning Area varied widely from 0.1 mg/L to 0.55 mg/L in the central and south-eastern regions, exceeding the recommended Fe limit set by WHO (0.3 mg/L) (Fig. 3 G).

The most common contaminants in underground environments are nitrogen compounds, which mainly originate from non-point and multi-point agricultural sources [22]. According to epidemiological data several chronic diseases, including cancer and thyroid disease, are closely linked to nitrate intake through drinking water [23]. Therefore, Nitrate contamination poses a major risk to human health and the public drinking water supply. Out of all investigated groundwater samples, only three samples have crossed the permissible limit set by BIS and WHO [17][18] of 50 mg/L (Fig. 3 H) reaching up to 118 mg/L.

Sulphate (SO_4) and Chloride (Cl) concentrations in the groundwater of the study area ranged between 2 and 147 mg/L for SO_4 and between 7 to 120 mg/L for Cl (Fig. 3 I and J), indicating that all collected groundwater samples were within WHO preferable SO_4 and Cl limits (250 mg/L) [17][18].

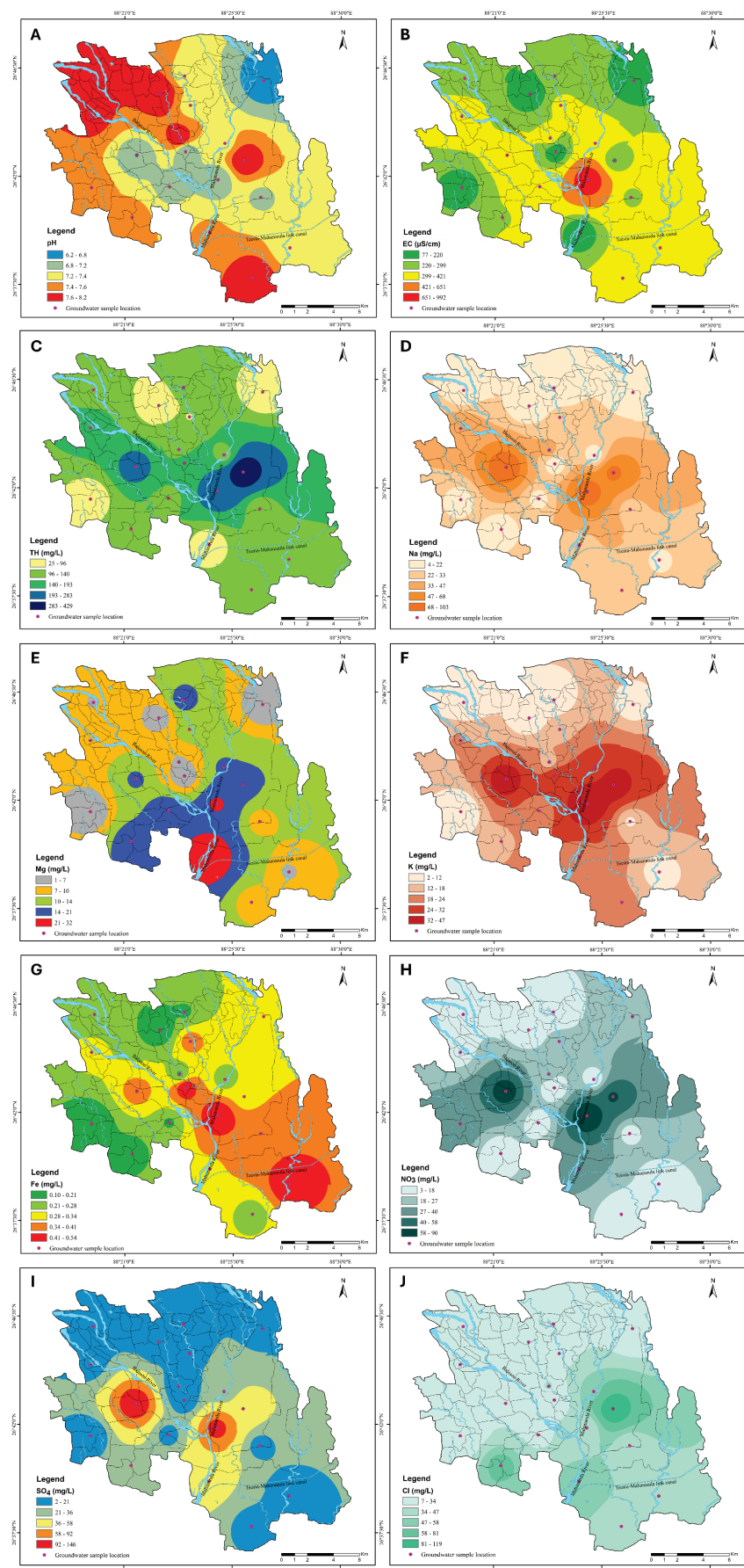


Figure 3. Spatial distribution of groundwater quality parameters in the study area. pH (A), Electrical Conductivity (EC) (B), Total Hardness (TH) (C), Sodium (Na) (D), Magnesium (Mg) (E), Potassium (K) (F), Iron (Fe) (G), Nitrate (NO₃) (H), Sulphate (SO₄) (I), and Chloride (Cl) (J)

3.2. Groundwater quality index (GWQI)

Drastic differences in GWQI was noted throughout the study area (Fig. 4). The WQI values ranged between 34.02 and 182.30 (Fig. 4 A), which means the water quality varies from good to very poor (Fig. 4 B). The western and northwestern parts of the area mostly fall under good to moderate water quality (34–75), which means the water in these areas is comparatively safer for use. The central and southeastern parts, on the other hand, shows moderate to very poor water quality (51–182), indicating that groundwater resources in these areas (especially the southern sector of Siliguri Municipal Corporation). This degradation is largely attributable to untreated domestic sewage, industrial effluents, and surface runoff. These findings underscore the urgent need for targeted intervention and indicate that water from these areas requires treatment prior to consumption.

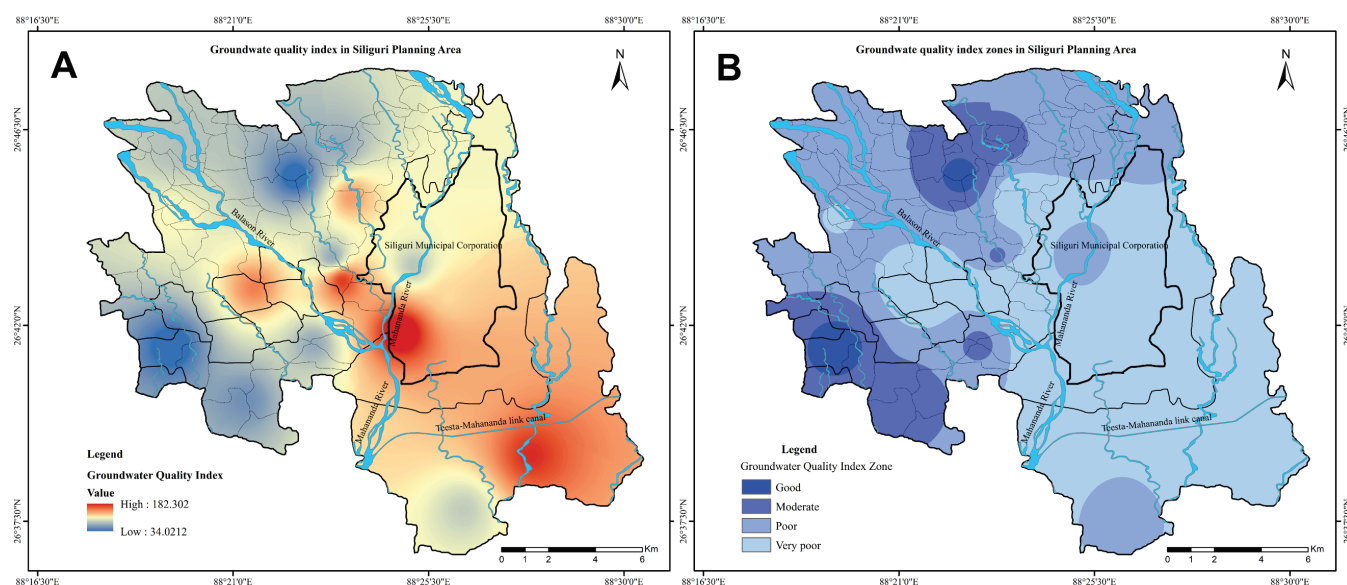


Figure 4. Groundwater Quality Index (GWQI) (A) and Groundwater Index Zone (GWIZ) (B) maps in Siliguri Planning Area

3.3. Groundwater parameter correlations

Correlation analysis revealed few distinct interrelationships among groundwater parameters in the Siliguri Planning Area (Fig. 5). Strong positive correlation values were observed between NO_3 and Na ($r = 0.94$), NO_3 and SO_4 ($r = 0.93$), and Na and K ($r = 0.89$), indicating shared sources or transport mechanisms. The strong Nitrate-Sodium-Sulphate cluster ($r > 0.90$) is characteristic of anthropogenic contamination. Domestic wastewater and agricultural runoff are prevalent in rapidly urbanizing areas [24][25]. Studies from comparable settings demonstrated similar ion associations with sewage infiltration and extreme application of fertilizer [26]. EC showed strong correlations with Na ($r = 0.78$) and SO_4 ($r = 0.77$), while pH exhibited a notable negative correlation with Fe ($r = -0.54$), suggesting pH-dependent iron mobility [27].

	pH	EC	TH	Na	Mg	K	SO ₄	Cl	NO ₃	Fe
pH	1									
EC	-0.21	1								
TH	0.11	0.52	1							
Na	-0.03	0.78	0.82	1						
Mg	-0.06	0.34	0.32	0.5	1					
K	-0.14	0.69	0.81	0.89	0.58	1				
SO ₄	-0.29	0.77	0.62	0.89	0.53	0.86	1			
Cl	0.31	0.1	0.69	0.4	0.5	0.57	0.28	1		
NO ₃	-0.15	0.71	0.66	0.94	0.37	0.81	0.93	0.26	1	
Fe	-0.54	0.37	0.38	0.45	0.13	0.51	0.44	0.1	0.38	1

Figure 5. Pearson's correlation matrix of different groundwater parameters

3.4. Surface water parameters

The spatial distribution maps (Fig. 6) reveal a stark contrast in water quality parameters between the Mahananda and Balason rivers within the Siliguri Planning Area. The Mahananda River consistently exhibits elevated concentrations of Total Dissolved Solids (up to 99 mg/L), Chloride (18.55–25.98 mg/L), Total Hardness (up to 110 mg/L), and water temperature (25.60–27.90 °C), particularly along its middle and lower urbanized stretches. These observations are typical indicators of untreated influx of municipal wastewater, surface runoff, or domestic effluents from highly populated areas [28][29]. Conversely, the Balason River shows predominantly lower values for these same parameters, indicating a distinct spatial division in water quality.

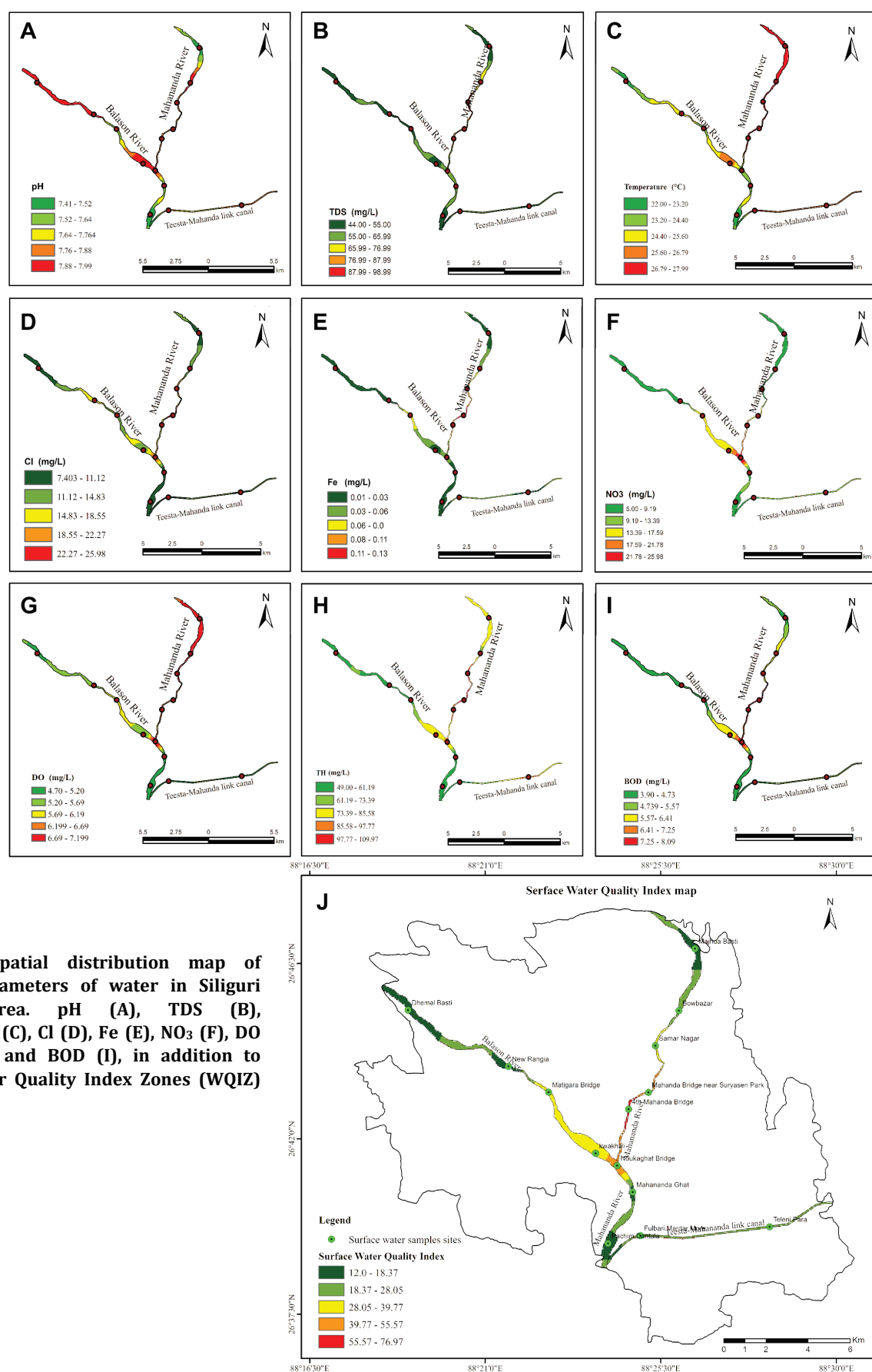
Varying spatial patterns for organic and nutrient pollution indicators can also be noticed. Biochemical Oxygen Demand (BOD) shows localized high concentrations specifically near the confluence of the two rivers and along sections of the Mahananda River, pointing to isolated areas of significant organic load (Fig. 6 I). This observation also refers to domestic sewage and wastewater discharges into river systems [30]. Dissolved Oxygen (DO) is highest in the upper section of the Mahananda River but drops to moderate or low levels elsewhere (Fig. 6 G). Meanwhile, parameters such as Iron (Fe) and Nitrate (NO₃) remain generally low across the entire study area, with only a few isolated hotspots of slightly elevated NO₃ near the river junction.

3.5. The spatial distribution of the Surface Water Quality Index

The spatial distribution of the Surface Water Quality Index (SWQI) in the Siliguri Planning Area reveals a clear variation in water quality along the investigated river stretches and canal systems (Fig. 6 J). The SWQI values ranged between 12 to 76.97, which stand for good to very poor quality, respectively. The upper stretches of the Balason River and parts of the Mahananda River show low SWQI values (12.0–28.05). These areas indicate good water quality, which may be attributed to lower anthropogenic influence and relatively natural environmental conditions in upstream zones.

In contrast, the central portion of the Mahananda River, particularly near the Siliguri Municipal Corporation area, exhibits moderate to poor water quality (28.05–55.57), suggesting increasing levels of pollution. The deterioration in water quality in this region is likely associated with urban discharge, domestic wastewater, and unregulated anthropogenic activities. A small but significant section of the Mahananda River shows very high SWQI values (55.57–76.97), reflecting severe contamination in this zone. This condition is mainly observed in the lower section of the river, which is directly linked to intensive urban runoff, solid waste disposal, and untreated sewage inflow in the surrounding densely populated areas. The Teesta–Mahananda link canal generally shows moderate water quality, with values mostly within the acceptable to slightly polluted range. This suggests a relatively controlled but still impacted water condition, possibly influenced by both natural flow and human activities.

Overall, the results demonstrate that water quality degrades from upstream to downstream, with the most critical conditions observed in urbanized zones. The findings clearly highlight the impact of urbanization and human activities on river water quality, emphasizing the need for effective wastewater management and pollution control strategies in the Siliguri Planning Area.



5. Conclusions

Severe geographical differences and alarming contamination levels across both groundwater and surface water resources are exposed by this extensive evaluation of the Siliguri Planning Area. Conditions ranging from good to very poor throughout the examined territory are demonstrated by the Groundwater Quality Index (GWQI) analysis. Comparatively safer environments characterize the western and northwestern regions, where GWQI values between 34 and 75 are recorded. Conversely, moderate to very poor water is found within the central and southeastern zones. This degradation is especially severe across the urbanized sectors of the Siliguri Municipal Corporation with GWQI reaching up to 182. Groundwater quality is primarily deteriorated by nitrate, iron, and potassium. Permissible limits were breached by nitrate concentrations in three distinct samples, peaking at 118 mg/L. The anthropogenic origins for this pollution are firmly established through correlation analysis, with strong positive links connect nitrate, sodium, and sulphate. Untreated domestic sewage, agricultural runoff, and industrial effluents primarily introduce these specific chemicals.

A sharp contrast between the Balason and Mahananda rivers is revealed by the surface water quality assessment. Relatively good conditions are maintained by the Balason River, which features SWQI values below 28 in its upper section. In contrast, progressive deterioration from upstream to downstream stretches is exhibited by the Mahananda River. Poor to very poor conditions (SWQI values between 55.57 and 76.97) are ultimately recorded within its urban corridors. Substantial organic and chemical pollution from municipal wastewater and urban runoff is indicated by elevated BOD, TDS, and chloride metrics. Reduced DO levels further confirm this severe contamination. Meanwhile, mixed environmental influences are reflected by the moderate quality of the Teesta–Mahananda link canal.

An urgent necessity for integrated water resource management is highlighted by these empirical discoveries. The construction of wastewater treatment facilities, routine monitoring programs, and strict pollution control regulations is heavily demanded. Public health must be protected through targeted interventions. Long-term environmental sustainability also depends directly upon these focused actions. Naturally, the severely impacted central and southeastern urban zones require the most immediate attention. Effective water quality management strategies can be readily developed by policymakers and civic authorities using this literature. Ultimately, a critical decision-making framework for the territory is supplied by this research.

Conflict of interest statement

The authors declared no conflict of interest.

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Data availability statement

The authors stated that experimental results related to the collected groundwater and surface water samples will be made available upon reasonable request from the corresponding author.

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