An evaluation of groundwater quality in Bilaspur Municipality – A geographical analysis

Chandrani Tiwari[1], Gouri Sankar Bhunia*
[1]*Siddharth College, Bilaspur, Chhattisgarh, India*
**Independent Researcher, Paschim Medinipur, West Bengal, India*

Abstract: Rapid urbanization and expanding industrial and agricultural activities in Bilaspur have raised concerns regarding groundwater contamination and depletion. To understand these issues, groundwater samples were collected from various locations across the municipality and analyzed for physical, chemical, and biological parameters, including pH, turbidity, heavy metals, nitrate levels, and microbial contaminants. This study evaluates groundwater quality in Bilaspur Municipality through a comprehensive geographical analysis, aiming to assess the water's suitability for domestic, agricultural, and industrial uses. Geographic Information Systems (GIS) and areal interpolation techniques were employed to map and visualize spatial variations in water quality, allowing for the identification of areas with high contamination risk and potential sources of pollution. The findings indicate that certain areas exceed safe drinking water standards, posing health risks to the local population. This assessment highlights the need for proactive groundwater management strategies, sustainable practices, and policy interventions to safeguard groundwater quality in Bilaspur Municipality.

Keywords: Groundwater quality, Urbanization, GIS, Geostatistical Model, Sustainable practices

INTRODUCTION

Bilaspur, an urban hub in Chhattisgarh, faces significant challenges regarding groundwater quality due to rapid urbanization, industrial expansion, and agricultural activities. Groundwater serves as a primary source for drinking, domestic, and agricultural needs in the region. However, unsustainable extraction, coupled with increasing pollution, has led to concerns over the quality and safety of these resources (Khan & Jhariya, 2017). The primary issues affecting groundwater quality in Bilaspur include contamination from agricultural runoff containing pesticides and fertilizers, industrial effluents, and leaching from waste disposal sites (Verma et al., 2017; Singh et al., 2022). High levels of nitrates, heavy metals like lead and arsenic, and microbial contamination are increasingly reported in groundwater samples, posing health risks to the population (Khan and Jhariya, 2017). Additionally, inadequate infrastructure for sewage treatment and waste management contributes to groundwater pollution, especially in densely populated areas.

Remote sensing techniques are widely applied in groundwater studies to estimate parameters such as land use/land cover, soil moisture, precipitation, and evapotranspiration, which are integral to groundwater recharge and depletion analysis. Studies by Famiglietti and Rodell (2013) have demonstrated the effectiveness of satellite-based sensors like GRACE (Gravity Recovery and Climate Experiment) for estimating groundwater storage changes. Khan and Sadiq (2012) demonstrated how remote sensing data on land use could be combined with GIS data on aquifer parameters to model contamination risk, identifying potential zones vulnerable to nitrate and heavy metal contamination. Studies like those by Rahman et al. (2012) have employed GIS to map groundwater quality indices over time, providing insights into pollution trends and sources. In recent years, advances in machine learning have begun to complement RS and GIS-based groundwater assessments, with studies like Naghibi et al., (2018) using hybrid models for more accurate groundwater potential mapping. Mallick et al., (2020*)* demonstrated a framework for integrating IoT-derived groundwater quality data into GIS, providing actionable insights for timely management interventions.

Bilaspur Municipality, located in a region with growing population density, industrial activities, and agricultural practices, relies significantly on groundwater to meet its water needs (Duggal et al., 2017). Over the years, increased urbanization and agricultural runoff, coupled with inadequate waste management practices, have raised concerns regarding the quality and safety of groundwater (Kumar et al., 2018). Evaluating the groundwater quality in Bilaspur is essential for ensuring the water's suitability for drinking, irrigation, and industrial purposes. The primary objectives of this study are to give a summary of current groundwater quality for parameters like pH, calcium, magnesium, iron, manganese, sodium, potassium, TDS, total hardness, and turbidity levels (Tiwari et al., 2020). Using GIS and geostatistical techniques, geostatistics (areal interpolation) was utilized to ascertain the spatial distribution of groundwater quality parameters in the Bilaspur Municipality. By identifying areas with deteriorating water quality and possible contamination sources, this assessment can help guide policy and decision-making for sustainable groundwater management in Bilaspur Municipality.

Study Area

Bilaspur Municipality is located in the central part of Chhattisgarh, India (Figure 1). The municipality covers an area of approximately 80.74 square kilometers, encompassing urban and peri-urban regions with a mix of residential, commercial, and industrial zones. Bilaspur experiences a tropical climate characterized by three distinct seasons: summer, monsoon, and winter. The region receives most of its rainfall during the monsoon season (June to September), with an average annual precipitation ranging from 1,200 to 1,500 mm. Humidity levels are generally high during the monsoon season, contributing to a moist atmosphere. The soils in Bilaspur are primarily classified as alluvial and black cotton soils. The geological formations in and around Bilaspur predominantly consist of sedimentary rocks, primarily belonging to the Gondwana group. Groundwater is primarily found in alluvial and weathered rock formations, serving as a crucial resource for drinking water and irrigation. The municipality is characterized by a gently undulating topography, with elevations ranging from 300 to 500 meters above sea level. Bilaspur is drained by various small rivers and streams, including the Kharun River, which plays a vital role in the local hydrology. The land use pattern includes residential, commercial, agricultural, and industrial areas, with agricultural practices concentrated in the outskirts.

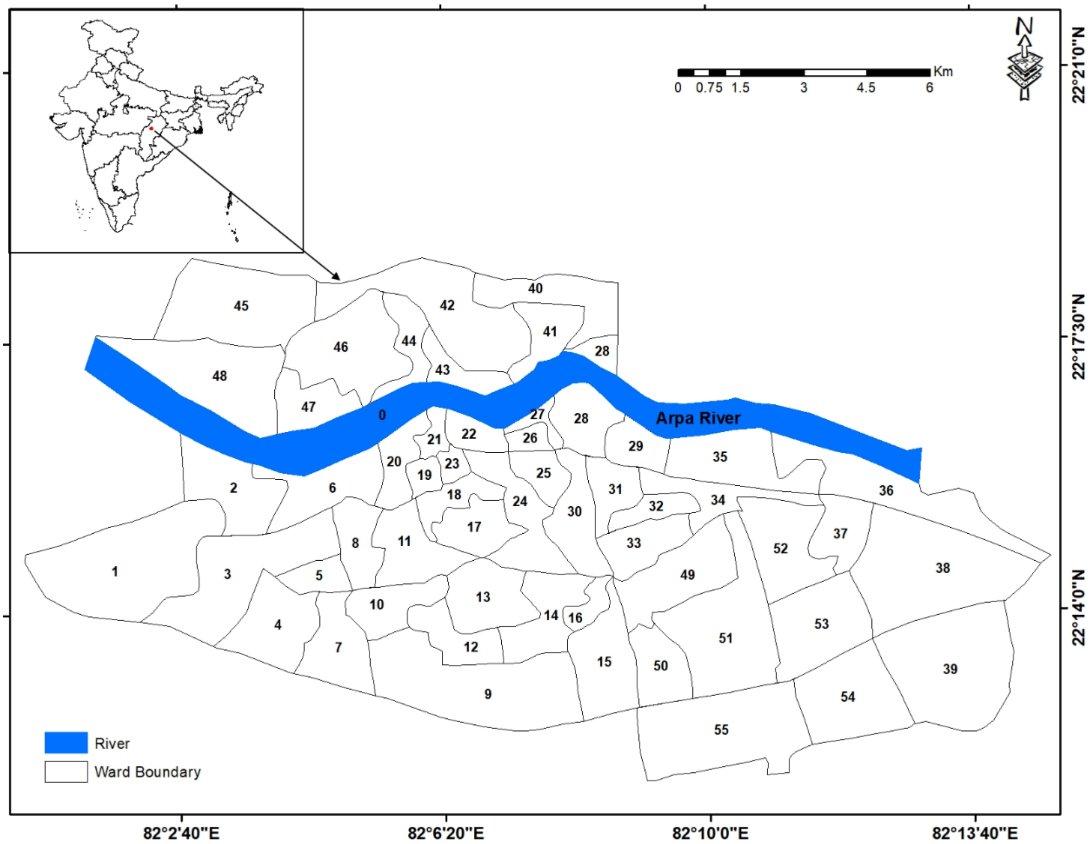


Figure 1: Location map of the study area

Recent studies indicate that groundwater quality in Bilaspur varies significantly. Parameters such as pH, turbidity, electrical conductivity, and the presence of contaminants like nitrates, heavy metals, and coliform bacteria are of concern. Regular monitoring, sustainable practices, and community awareness are essential for addressing groundwater quality challenges in Bilaspur.

MATERIALS

The ward boundary is collected from the municipal office. Drinking groundwater was extracted from these study regions, and the water quality standards were examined using standard procedure analysis. Samples were collected from the key locations across Bilaspur that represent different water uses and sources, such as residential areas, industrial zones, agricultural land, and near public water wells. The water samples that were collected were kept in an ice-cooled container in a darkened environment. The preparation of the solution and evaluation were both conducted using double-distilled water. The water index parameters, including pH, turbidity, total hardness (TH), calcium, magnesium, fluoride (F^{-1}), chloride (Cl^{-1}), iron, TDS, and residual Cl, are measured using standard techniques during the post-monsoon season and compared to IS:10500 standards set by the Bureau of Indian Standards (BIS) for drinking water in India.

METHODS

Database generation

A digital database of ward boundary is generated on QGIS platform. The ward boundary is registered on Universal Transverse Mercator Projection System with World geodetic System (WGS) 84 datum. The water quality parameters of each ward are incorporated into excel file along with ward number and this is integrated into ward shapefile.

Areal Interpolation

Areal interpolation refers to the process of transferring data from one set of spatial boundaries (source zones) to another (target zones) when direct data for target zones are unavailable. In the ArcGIS Geostatistical Analyst Extension, areal interpolation is a geostatistical interpolation method that applies kriging theory to data that has been aggregated or averaged across Municipal boundary. All point locations inside and between the input wards can have predictions and standard errors created for them. The predictions and standard errors can then be reaggregated to create a fresh set of wards. Discrete counts are made possible using areal interpolations. As a co-kriging variable, a second set of wards can also be employed; the polygons in these secondary wards may be entirely different or they may share the same geometry as the underlying variable's wards. Ward boundaries are reaggregated in two steps. Initially, the source wards are used to produce a smooth prediction surface for individual wards, which is then aggregated back to the target wards. This surface is frequently interpreted as a density or risk surface. This statistic does, however, have some significant limitations, including being insensitive to variogram errors and relying on the scale of the data. In order to standardize the ME, the MSE is typically set to zero; that is, a realistic model would have an MSE that is near zero.

For the purpose of choosing the optimal semivariogram model, four different types—Circular, Spherical, Exponential, and Gaussian—were investigated for each of the water quality parameters: Ca, Mg, pH, Mn, Fe, Turbidity, TDS, and Total Hardness (TH). Using cross validation tests, the predictive capabilities of the fitted models were examined. The performance of the generated models was determined by estimating the mean error (ME), mean square error (MSE), root mean error (RMSE), average standard error (ASR), and root mean square standardized error (RMSSE). If the forecasts are objective, the ME ought to be close to zero.

Descriptive Statistics and cross correlation analysis

To investigate the significant associations between distinct variables and to give a better understanding of the interaction between multiple parameters, post-statistical techniques like descriptive statistics. Pearson correlation have been used to measure the cross-correlation analysis.

RESULTS

Although there are other interpolation methods, areal interpolation is the most appropriate and has numerous benefits over other methods, as noted in the literature; for this purpose, areal interpolation was also utilized in the present investigation for the examination of spatial variation.

The acidity of a water solution is indicated by the pH scale. The Bureau of Indian Standards says so. If the pH of the water is higher than 7.0, it is categorized as basic or alkaline; if it is lower than 7.0, it is categorized as acidic. Conversely, healthy water with a pH of 7.0 is referred to be neutral (Narayan, 2021). All locations had pH values between 6.7 and 7.6, which is within the permissible range of 6.5 to 8.5 as depicted in Figure 2. This indicates that the circumstances are neutral to slightly alkaline and appropriate for a variety of uses.

The cloudiness or haziness of a fluid due to an excessive number of tiny fragments that are often invisible to the human eye is known as turbidity. These particles may consist of bacteria, silt, clay, sediment, or other small materials suspended in the liquid. It is a crucial metric for assessing the water's clarity and a crucial component of water quality assessment. Higher turbidity levels (over 100 NTU) signify a higher concentration of suspended particles and make the water murky, which can have an impact on the water's quality and attractiveness. Nephelometric Turbidity Units (NTU) are a typical way to express turbidity measurements. Here, we observed its value in every sample using a nephelometer. This device calculates the magnitude of light passing through the sample by measuring the amount of light scattered by turbid particles at right angles to the incident light beam. Colloidal suspended particles exhibit the Tyndall effect, which causes light scattering. Turbidity values in our instance ranged from 0.14 NTU to 4 NTU, indicating that every sample was within the allowable range. In the study area, the highest concentration of Turbidity (>2.5 NTU) is observed in ward no. 4, 5 and 10. The medium concentration (1.3 – 2.4 NTU) of turbidity is found in ward no. 5, 8, 9, 24, 33, 42, 49, and 50. The lower concentration (<0.57 NTU) of turbidity is observed in ward no. 1, 2, 3, 13, 14, 17, 18, 28, 29, 30, 31, 36, 45, 48, 52, 53 and 54.

As demonstrated in *Figure 1*, the sample water's total hardness ranges from 30 to 4000 mg/L, indicating that the water is unsuitable for human consumption. Some categories classify water with a hardness of up to 75 mg/L as soft, 76-150 mg/L as moderately soft, 151-300 mg/L as hard, and more than 300 mg/L as very hard (Arumugam & Elangovan, 2009). Wards 39 and 50 are also appropriate for drinking purposes with somewhat greater TH content, as it is recommended that the total hardness value ranges for drinking water should not exceed 500 mg/L of calcium carbonate (Narayan, 2021). In the study area, the maximum TH concentration (>1001 mg/L) is observed in ward no. 50 and 39, followed by small pockets of ward no. 49, 51 and 55. The lowest concentration (<200 mg/L) of TH is observed in ward no. 2, 7, 24, 41, 52, 53, and 54.

Figure 1 illustrates the highest recommended limit for calcium and magnesium concentrations. It can be shown that the amount of calcium in the water is higher than the permitted requirement (45 mg/L), which raises some concerns about the sample's water hardness. In the study area, the maximum concentration of Ca (>101 mg/L) is observed in Ward No. 4, 9, 12, 13, 36, 39 and 55. The lower concentration of Ca is found in ward no. 2, 7, 41, 52, 53, and 54. To identify the cause of elevated calcium levels, more research could be necessary. However, the majority of the samples have magnesium levels that fall within the acceptable range. This suggests that groundwater is suitable for domestic use as well.

As per Bureau of Indian Standards (BIS), the acceptable limit for magnesium in drinking water is 30 mg/L, with a permissible limit of 100 mg/L in the absence of an alternate water source. In the study area, the highest concentration of Mg is observed in Ward no. 51, followed by ward 39 and small pockets of ward 34. The lowest concentration of Mg is observed in ward no. 2, 3, 7, 17, 20, 21, 22, 23, 40, 41, 42, 43, 44, 45, 47, 52, 53 and 54.

As predicted by Dhaswadikar Usha Sitaram (2022), the chloride content of water samples should be low during post-rainy seasons. This is evidenced by the fact that all of the chloride and fluoride values found in this investigation were extremely low and below the allowable limit, indicating that the ground waters that were chosen are safe for human consumption. The WHO has set a maximum allowable level of 500 mg/L for chloride and 5 mg/L for fluoride. The results of the current investigation fall within the permitted range, with the fluoride level ranging from 0 to 0.6 mg/L (Figure 1) and the chloride content ranging from 25 to 203 mg/L. The maximum concentration of chloride is observed in ward no. 39 and ward no. 49. The lowest concentration of chloride is found in ward no. 1, 2, 3, 7, 17, 19, 20, 21, 22, 23, 41, 47, 48, 51, 52, 53 and 54.

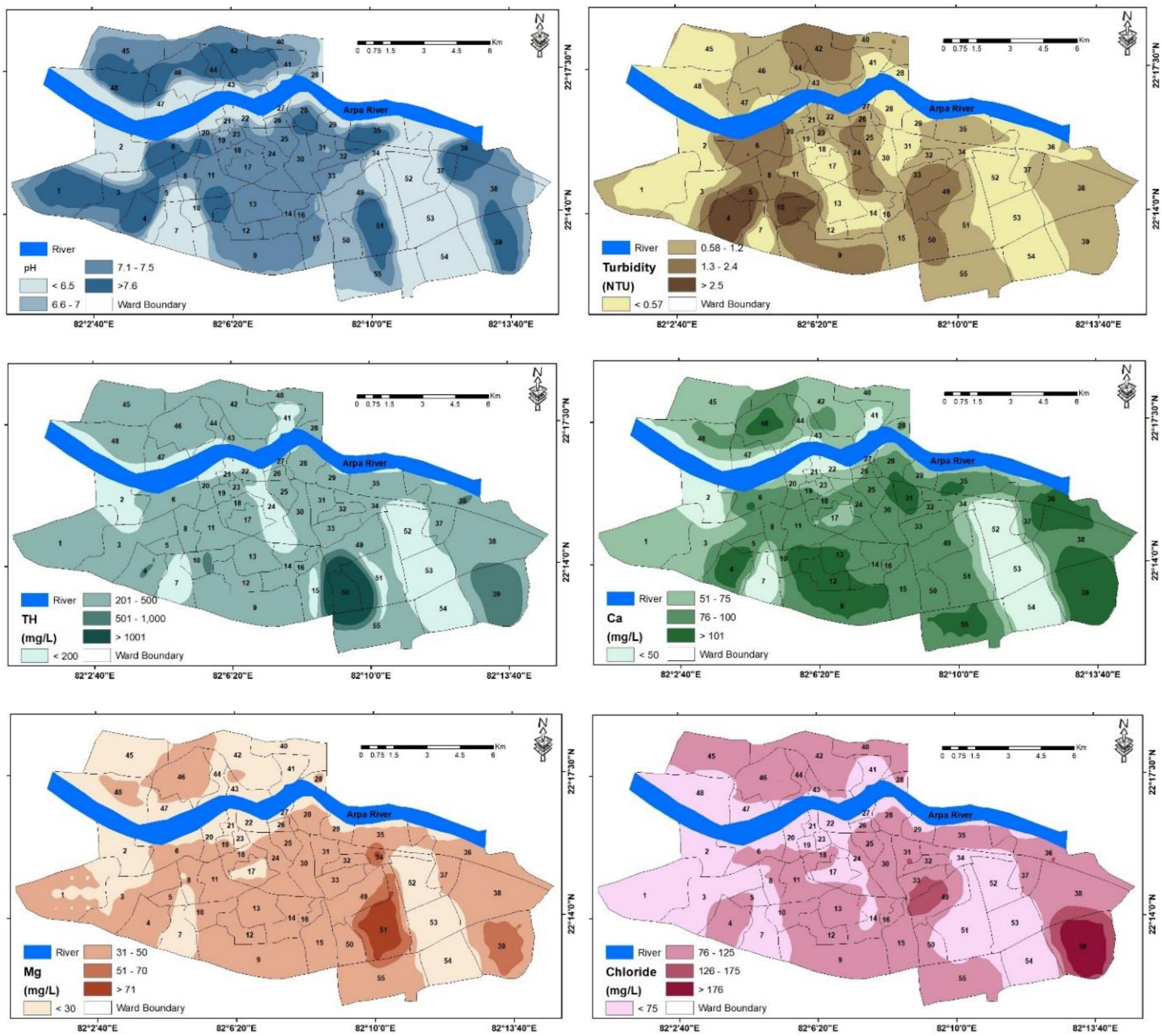
The Iron level in the study area ranges between 0.11 and 0.6 mg/L. The acceptable limit for iron in drinking water is 0.3 mg/L. There is no additional permissible limit set if this concentration is exceeded, as higher iron levels generally lead to taste, odor, and staining issues. The estimated mean value of Iron is observed as 0.18 with a standard deviation of ±0.017. The maximum concentration of iron is found in Ward no. 50, 51 and 55. The medium concentration of iron is observed in ward no. 3, 13, 14, 28, 29, 30, 31, 32, 33, 34, 35, 36, 38 and 39.

According to BIS, the acceptable limit for fluoride in drinking water is 1.0 mg/L, with a permissible limit up to 1.5 mg/L in the absence of an alternate water source. Higher concentrations can lead to health issues, especially dental and skeletal fluorosis. In the study area, the fluoride value ranges between 0.2 mg/L and 0.6 mg/L with calculated mean ±SD is 0.38±0.093. The maximum concentration of fluoride is observed in ward no. 1, 3, 4, 11, 39, 49, 51, and 55. The minimum concentration of fluoride is observed in ward no. 2, 7, 28, 29, 30, 52, 53 and 54.

Table 1: Descriptive statistics of groundwater quality in Bilaspur district

Descriptive Statistics	pH	Turbidity	TH	Ca	Mg	Chloride	Iron	Fluoride	TDS	Residual Cl
Mean	6.36	0.93	367.23	74.26	31.95	76.39	0.16	0.31	387.74	0.18
Std. Dev.	2.21	0.86	507.55	31.17	16.43	38.08	0.13	0.17	160.46	0.22
Skewness	-2.55	1.93	6.56	-1.15	0.65	-0.03	0.78	-0.69	-1.11	2.04
Kurtosis	7.56	7.38	47.73	4.04	6.48	4.42	4.48	2.53	4.56	8.24
1st Quartile	7.01	0.39	257.5	63.75	25.75	60	0.08	0.3	338.5	0
3rd Quartile	7.16	1.15	398.5	96	38.5	100	0.22	0.4	486.25	0.03

The acceptable limit for TDS in drinking water is 500 mg/L, with a permissible limit up to 2,000 mg/L if no alternate source is available. Higher TDS levels can affect taste, hardness, and may indicate the presence of various contaminants. Total dissolved solids (TDS) levels in groundwater varied between 257 and 785 mg/L, with a mean of 433.35 mg/L and a standard deviation of 93.13 mg/L. The highest concentration of TDS is found in ward no. 4, 9, 12, 13, 1528, 33, 31, 39, 46 and 50. The minimum concentration of TDS is observed in ward no. 1, 2, 52, 53, and 54.



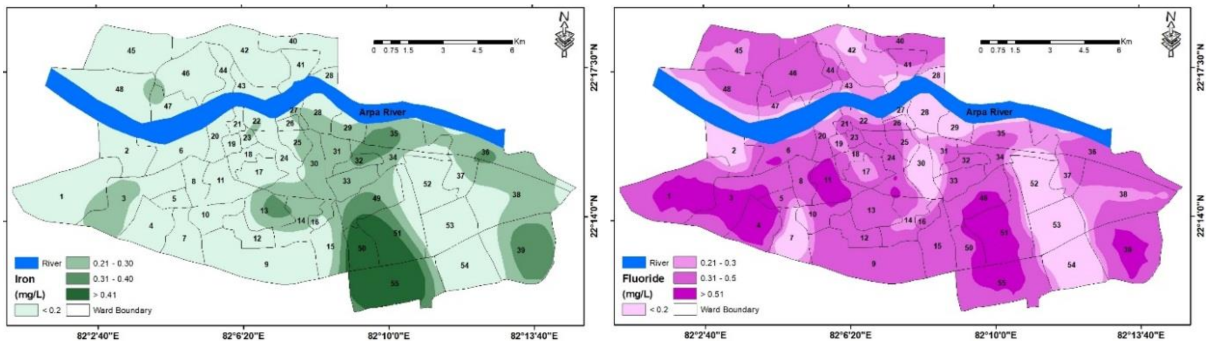


Figure 2: Geographical variation of groundwater quality parameters in Bilaspur Municipality

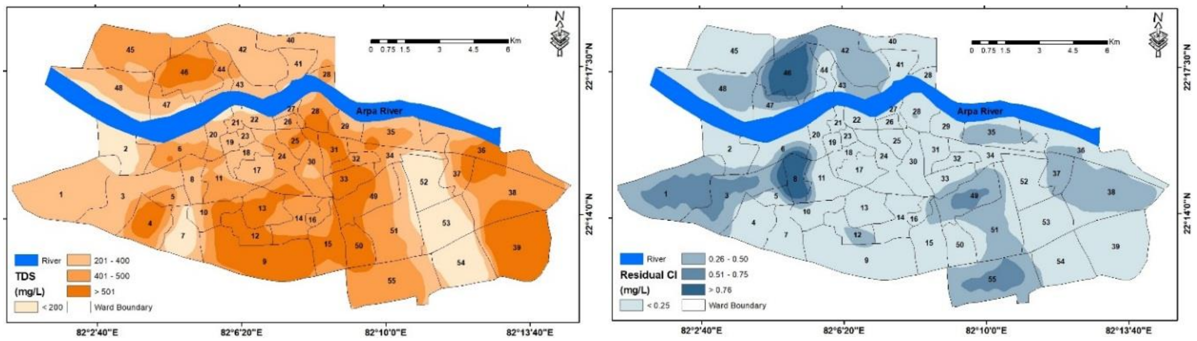


Figure 3: Geographical variation of groundwater quality parameters in Bilaspur Municipality

A brief description of the main trends and variances in the water quality metrics is given by the mean and standard deviation figures. It is noteworthy that several indicators, such Total Hardness and TDS, show comparatively high standard deviations, suggesting that the values of these parameters vary significantly between the wards in Bilaspur Municipality (***Table 1***). The TH levels for individual samples might differ greatly from the average, as demonstrated by the fact that the mean TH value is 367.23 mg/L and the standard deviation is 507.55. TH results may be significantly higher or lower than the mean in some instances. Likewise, a greater TDS standard deviation (160.46 mg/L) indicates that the hardness levels in the studied areas in Bilaspur Municipality vary significantly.

Numerous factors showed strong associations with one another, according to the correlation analysis. ***Table 2*** illustrates how the statistical analysis meaningfully reveals the correlation co-efficient between the different water quality metrics. Since alkalinity can affect the pH of water and contribute to its buffering capacity, the pH has a high negative correlation with both TH (-0.36) and Iron (-0.48), suggesting that improved water quality and reduced mineral content. Whereas, turbidity has moderate positive correlation between ca (*r=0.23*) and fluoride (*r=0.38*) and moderate negative correlation with iron (*r= -0.37*). This might indicate the presence of mineral particles or suspended solids that contain or adsorb calcium and fluoride. Sources could include geological formations (like limestone) or industrial and agricultural runoff. Inverse relation with iron indicates processes where iron is selectively precipitated out and removed, such as through aeration or chlorination, reducing iron while leaving other particulates. A strong positive relation between total hardness and Iron (*r*= 0.50), and medium positive relation between TDS (*r= 0.28*) and Ca (*r= 0.23*). This strong positive correlation indicates that as iron levels increase, the total hardness also tends to increase. Since hardness is largely due to the presence of dissolved minerals like calcium, magnesium, and sometimes iron, this relationship suggests that iron may be a notable contributor to the water's overall hardness. This strong positive correlation indicates that as iron levels increase, the total hardness also tends to increase. Since hardness is largely due to the presence of dissolved minerals like calcium, magnesium, and sometimes iron, this relationship suggests that iron may be a notable contributor to the water's overall hardness. Although the relationship between TDS and Ca is moderate, it indicates that calcium is present but may be less prominent compared to iron in influencing the hardness and overall dissolved solids.

A strong positive correlation is observed between Ca and Mg (*r= 0.47*), Chloride (*r= 0.68*) and TDS (*r= 0.87*). A moderate to strong positive correlation between calcium and magnesium indicates that these two ions often occur together in the water, which is typical of water passing through mineral-rich geological formations, such as limestone and dolomite. A strong positive correlation between calcium and chloride suggests that chloride ions are likely present along with calcium, potentially indicating sources such as groundwater influenced by mineral deposits, or possibly anthropogenic sources, such as agricultural runoff, wastewater discharge, or industrial processes. A very strong positive correlation between calcium and TDS indicates that calcium is a significant component of the dissolved solids in the water. Since TDS includes all dissolved ions, a high correlation with calcium suggests that a substantial portion of the TDS is attributable to calcium ions, along with associated ions like magnesium and chloride.

Table 2: Cross correlation of ground water samples in Bilaspur Municipality

Parameters	pH	Turbidity	TH	Ca	Mg	Chloride	Iron	Fluoride	TDS	Residual Cl
pH	1.00									
Turbidity	0.17	1.00								
TH	-0.36	0.07	1.00							
Ca	0.06	0.23	0.23	1.00						
Mg	0.04	0.06	0.06	0.47	1.00					
Chloride	0.04	0.08	0.06	0.68	0.05	1.00				
Iron	-0.48	-0.37	0.50	0.10	0.25	0.13	1.00			
Fluoride	0.19	0.38	0.16	0.18	0.27	0.13	0.00	1.00		
TDS	-0.04	0.17	0.28	0.87	0.44	0.78	0.23	0.18	1.00	
Residual Cl	-0.13	-0.11	-0.11	0.06	0.05	0.03	0.03	0.04	-0.06	1.00

A moderate positive correlation is observed between Mg and Iron (*r = 0.25*), Fluoride (*r = 0.27*) and TDS (*r = 0.44*). A moderate positive correlation with fluoride suggests that both are naturally occurring in the water source, possibly due to contact with fluoride-bearing minerals (e.g., fluorite) or sedimentary deposits that contain both magnesium and fluoride. The positive correlation with TDS suggests that magnesium contributes moderately to the overall TDS content, though it is likely one of several dissolved solids. There is a strong positive correlation is observed between chloride and TDS (*r = 0.78*) which indicates that chloride is a primary contributor to the overall dissolved solids content, possibly from natural geologic or coastal influences, or from human activities affecting the water source.

The presence of outliers may be indicated by high skewness levels. A measured sample point that is extremely high or low in comparison to the values in the dataset is called an outlier. Finding outliers is crucial because they could represent values that were measured or recorded inaccurately, and in this scenario, they would have a detrimental impact on later phases of the geostatistical investigation. No data transformation was performed prior to the geostatistical evaluation in the current investigation.

DISCUSSION

Bilaspur city faces a range of water quality issues, reflecting challenges common in urban areas with growing populations and industrial activity. Bilaspur city faces a variety of water quality issues characterized by specific parameters such as pH, turbidity, total hardness (TH), calcium (Ca), magnesium (Mg), chloride, iron, fluoride, total dissolved solids (TDS), and residual chlorine (Cl). The quality of water is influenced by both natural and anthropogenic factors, leading to a significant impact on public health, the environment, and overall water availability (Chandravanshi & Chandrakar, 2014). The evaluation of groundwater quality in Bilaspur Municipality highlights critical insights into the sustainability of this vital resource in the context of rapid urbanization and industrialization. The study employed a comprehensive approach by assessing various physical, chemical, and biological parameters of groundwater, revealing significant variations across different locations within the municipality (Chandra & Upadhyay, 2024). The analysis indicated that several groundwater samples exceeded safe drinking water standards, particularly concerning parameters like nitrate levels, total dissolved solids (TDS), and the presence of heavy metals such as arsenic and lead.

High TDS levels, common in Bilaspur's groundwater, arise from sewage discharge, industrial effluents, and agricultural runoff. High nitrate concentrations, often linked to agricultural runoff and sewage discharge, raised concerns about potential health impacts, including methemoglobinemia (blue baby syndrome) in infants (Mishra et al., 2018). High total hardness, due to elevated levels of calcium and magnesium, is common in Bilaspur's groundwater. Hard water is safe to drink but affects household plumbing and reduces the effectiveness of soaps and detergents. Fluoride occurs naturally in groundwater but is elevated in Bilaspur due to mineral leaching from rocks. While low levels of fluoride prevent dental decay, excessive intake leads to dental and skeletal fluorosis, causing long-term health complications.

The use of Geographic Information Systems (GIS) allowed for effective visualization of spatial variations in groundwater quality. Areas near industrial sites demonstrated higher levels of contaminants, underscoring the need for stringent monitoring and regulation of industrial waste disposal practices. These findings emphasize the interconnectedness of land use practices and groundwater quality, suggesting that sustainable agricultural and industrial practices are essential for protecting water resources. The presence of microbial contaminants posed additional health risks, with the detection of coliform bacteria in several samples indicating potential fecal contamination. This highlights the urgent need for improved sanitation facilities and public health interventions to safeguard community health.

Elevated levels of turbidity and TDS are often linked to urban and agricultural runoff, while industrial discharge contributes to high concentrations of chloride and metals, disrupting water pH and contributing to toxicity. Excessive hardness (from Ca and Mg) and fluoride content in groundwater are attributed to natural mineral leaching, which is exacerbated by over-extraction of groundwater (Saini et al., 2015). High levels of iron result in metallic taste and staining, while residual chlorine from water treatment, if improperly managed, leads to taste issues and potential health risks. Present study revealing significant challenges in maintaining water quality amid rapid urban growth. The research underscores the importance of regular monitoring and data-driven decision-making to address groundwater quality issues (Tiwari et al., 2019). By addressing these challenges through a multi-faceted approach involving stakeholders from government, industry, and the community, Bilaspur Municipality can work towards ensuring the sustainability and safety of its groundwater resources for future generations. The study serves as a foundational resource for policymakers and researchers seeking to improve water quality management in similar urban contexts. Addressing these challenges requires an integrated approach involving infrastructure improvements, industrial regulation, sustainable agricultural practices, and community awareness to promote safe water use and resource conservation in Bilaspur.

CONCLUSION

The majority of the indicators in the physicochemical evaluation of the groundwater in the chosen locations of Bilaspur City meet set norms, indicating generally good water quality. These discoveries are essential to guaranteeing the supply of clean, safe water for industrial, agricultural, and residential uses. The statistical analysis offers important insights into the possible sources and influences on water quality by exposing intricate correlations between water quality metrics. To create focused plans for managing and conserving water quality, more research is advised, including localized studies and source identification. Given the complex relationships between different characteristics, the correlations shown highlight the significance of a thorough approach to water quality assessment. The study offers important new information about Bilaspur City's groundwater's physicochemical properties. In order to guarantee the supply of safe and clean groundwater for the people of Bilaspur City, the results can be used as a basis for sustainable water resource management and to identify locations that could need corrective action. Addressing these issues requires a comprehensive and multi-dimensional strategy. Prioritizing advanced water treatment facilities, stringent regulations on industrial waste, sustainable agricultural methods, and widespread community awareness will help mitigate the negative impacts on water quality. Additionally, regular water quality monitoring, improved waste management, and conservation practices can support healthier and more reliable water sources.

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