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Groundwater Quality Characterization for Safe Drinking Water Supply in Sheikhpura District of Bihar, India: A Geospatial Approach

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Groundwater quality due to geogenic factors, aggravated by anthropogenic activities, is a significant threat to human wellbeing and agricultural practices. This study aimed at mapping the spatial distribution of low and high groundwater-contaminated regions in the Sheikhpura district of Bihar for safe drinking and irrigation water availability. To account for spatial distribution, groundwater quality parameters, such as fluoride, iron, total dissolved solids, turbidity, and pH, were analyzed using integrated interpolation, geographical information systems, and regression analysis. A total of 206 dug wells and bore wells were analyzed for *in-situ* observations in the Sheikhpura district of Bihar, India. The analysis indicated that the periphery south of Chewara and Ariari blocks, i.e., about 9.16% of district area, is affected by fluoride content (1.55–2.32 mg/l) which is highly unsuitable for consumption, as recommended by the WHO and BIS standards. However, the remaining area (90.84%) is within the permissible limit of fluoride content (0.37–1.54 mg/l). In most areas, iron content is beyond WHO permissible limits (>0.1 mg/l), except 3.1% area in the eastern region with 0.06–0.12 mg/l iron, although iron concentrations in groundwater are under the acceptable limit (<0.3 mg/l) as per BIS standard across the district. However, pH and total dissolved solids were within permissible limits. Each of the modeled geospatial maps was validated using a set of 17 *in-situ* observations. The best-fit model between observed and predicted variables such as fluoride, iron, total dissolved solids, and pH produced a coefficient of determination (R^2) of 0.96, 0.905, 0.91, and 0.906, respectively. The findings of this study provide insights and understanding on groundwater pollution regimes and minimize uncertain causes because of the high spatial distribution of geogenic fluoride and iron occurrence, and will also be helpful to policymakers for better planning, investments, and management to supply potable water in the area.

Keywords: groundwater pollution, geospatial modeling, fluoride, iron, Bihar

INTRODUCTION

Water, whether on the surface or underground, is the most essential and significant natural resource for sustaining life on Earth and for the sustainable growth of socioeconomic sectors such as irrigation and industrialization. Water, in each form, is an essential component of hydro-geo-ecological and various other metabolic, physiological, and ecological processes of living beings. The "resourcism" and unethical human activities in the Earth's biosphere–hydrosphere–geosphere have created a global water imbalance and crisis which threatens the life of the billion individuals and numerous natural ecosystems (Mekonnen and Hoekstra, 2016; Falkenmark et al., 2019). At the global scale, in developed nations, per head water consumption is reported to be 382 l in the USA and 110 l in France (Grafton et al., 2009), whereas, in developing countries like India, it is 150–200 l for drinking and domestic purposes (CGWA, 2016). Even though nearly four billion people are facing severe water scarcity across the world (Rijsberman, 2006; Mekonnen and Hoekstra, 2016; Adams et al., 2020; Tzanakakis et al., 2020), potable water scarcity is projected to affect nearly 10 billion people by 2050 (Chouchane et al., 2018; Boretti and Rosa, 2019). Further, at the regional level, water quality deterioration, abstraction, drought, floods, erratic rainfall, etc., affect a large population due to which water scarcity has become a global issue (Kumar et al., 2010; Jain, 2012; Jain et al., 2013; Boers et al., 2017; Ellison et al., 2017).

Groundwater aquifers are the primary source of water supply in rural and urban areas, mainly in the arid and semiarid regions worldwide (Dash et al., 2010; Uyan and Cay, 2013; Rao et al., 2020). Groundwater scarcity in dry seasons draws global attention and perceived risk due to anthropogenic activities, like overexploitation of groundwater for irrigation, industrial, and drinking purposes (Mekonnen et al., 2015; Adimalla et al., 2020b). Therefore, the abuse of groundwater spawns hazardous impacts, mainly water quality, and quantity, in general (Ray and Elango, 2019). Furthermore, groundwater resources are contaminated *via* anthropogenic activities and geogenic contaminants bearing rocks and soils (Saha et al., 2018). Consequently, the groundwater crisis is driven by land-use changes, cropping patterns, high water demand, high-yielding crop races, and water availability (Ellison et al., 2017). Inadequate management has further disturbed the global water cycle, likely accelerating groundwater pollution and climate change (Abbott et al., 2019).

Groundwater systems have their unique chemistry and characteristics at each location and depend on various climatic changes, precipitation, surface water, and recharge parameters. Water quality depends mainly on underlying rock's geochemical and lithological composition and subsurface factors (Magesh and Chandrasekar, 2013). Time-sensitive undulation in the source and the configuration of revived water and the hydrological and social variables may generate irregular changes in the parameters dealing with water quality (Sahoo et al., 2019; Ijumulana et al., 2021, 2022). Heavy metals, such as fluoride, arsenic, cadmium, iron, and mercury, and other toxic chemicals either geogenic or discharged from residential areas, industries, and agricultural land contaminate surface and subsurface systems and have been reported to have more than the permissible concentration in drinking water (WHO, 2004; Bhagure and Mirgane, 2011; Sahoo et al., 2019; Adimalla et al., 2020a; Ijumulana et al., 2021, 2022). Groundwater quality has been measured using physicochemical properties, such as the concentration of arsenic, fluoride, pH, bicarbonates, chlorine, and total dissolved solids (Kannel et al., 2007; Ijumulana et al., 2020, 2021; Ligate et al., 2021). In India, including the present study area, arsenic, fluoride, iron, manganese, chromium, radon, uranium, etc., are geogenic contaminants from mineral deposits in the aquifer and have a significant health concern (Banerjee et al., 2012; Thakur and Gupta, 2015; Saha and Sahu, 2016; Krishan et al., 2021; Sahoo et al., 2022). Bihar has severe problems of arsenic, fluoride, iron, nitrate, etc., contamination in groundwater. The majority of the Indo-Gangetic plain is formed by quaternary alluvium deposition (old and new). In the Southern Gangetic Plains of Bihar, groundwater from quaternary aquifers is the principal source for water supply in rural and urban areas through bore wells, dug wells, etc. (Saha et al., 2007). The origin of contaminants is attributed to late quaternary stratigraphy and sedimentation in Middle Ganga Plains (Shah, 2008). Fluoride contamination from underlying parent rocks and soil affects the water quality in the upper layer of alluvium and is a well-known menace (Saha and Sahu, 2016). In the larger scenario, unsustainable and unplanned groundwater exploitation is constructing a negative influence on aquifer systems. It is complex (Saha et al., 2019) and unfit for human consumption and irrigation purposes (Earle, 2019).

India's dependency on groundwater for crop irrigation and drinking water is very high (Shankar et al., 2011). The primary consumers of groundwater are utilizing about 70–90% of annual extrication for irrigation in global agriculture (Llamas and Martínez-Santos, 2005; Kulkarni et al., 2015). It is assessed that the contribution of groundwater for irrigation is 62%, and the requirement of rural and urban water consumption is 85 and 50%, respectively, in India (Saha and Ray, 2018; Saha et al., 2019). However, the dependency on groundwater utilization in rural Bihar is about 80%. In 2001, the per capita availability of groundwater was 1950 and 1816 cubic m for Bihar and India, respectively, and reported to decrease because of increased population, industrialization, irrigation, etc. Due to the ever-increasing population in India, the annual per capita water availability is projected to shift down from 5,177 cubic m in 1951 to 1,140 cubic m in 2051 (MoWR, 2015). The total water gap across the Sheikhpura district was estimated to be 148.2 million cubic meters (MCM). For water budget, in 2020, it was estimated that groundwater and surface waters were 180.7 and 49.0 MCM, respectively (TRUAGRICO, 2017). Water quantity and quality are inextricably related to water resource management and must be controlled using integrated ways to prevent water pollution.

Fluoride (F) contamination is a severe problem in groundwater across India and the world (Changmai et al., 2018). It has a direct impact on the health of human beings, animals, and plants due to exceeded limits, and it varies in the air (0.1–0.6 μg/l), plant (0.01–42 mg/kg), soils (150–400 mg/kg), rocks (100–2,000 mg/kg), and water (1.0–38.5 mg/l) (Singh et al., 2018). Fluoride concentration is acceptable with $<$1.5 mg/l for drinking and irrigation purposes (WHO, 1997).

Millions of people are affected by diseases such as skeletal and dental fluorosis in many parts of India, caused by high fluoride contamination. Both lower concentrations of fluoride (0.6 mg/l) and upper concentrations of fluoride (1.2 mg/l) are harmful to health for prolonged consumption (Singh et al., 2016). The fluoride concentration of 1.5–3.0 mg/l can cause dental fluorosis, and the concentration of 3.0–4.0 mg/l causes to stiffens brittle bones, and more than 4.0 mg/l of fluoride concentration can cause crippling fluorosis (Saxena and Sewak, 2015). Besides, fluoride can also affect bruising of the liver, thyroid, and other organs, including deformation in bone and teeth spotting/flaking (Jiménez-Reyes and Solache-Ríos, 2010). Total dissolved solids (TDS) are a useful parameter for deciding safe drinking water quality with a lower range of 500 mg/l to a higher permissible limit of 2,000 mg/l (Jain et al., 2010); however, the World Health Organization (WHO) permits TDS for an extreme concentration of 1,700 mg/l (WHO, 2008). The permissible limit of TDS with <300 mg/l is excellent, 300–600 mg/l good, 600–900 mg/l poor, and >1,700 mg/l unacceptable (WHO, 2008). However, the TDS concentration varies significantly due to diverse geological locations (WHO, 2004; Magesh and Chandrasekar, 2013). The prevalence of high iron (Fe) in drinking water causes severe impacts on human health, such as diabetes, heart diseases, cirrhosis of the liver, liver cancer, and infertility (Kumar et al., 2017). The permissible limit of iron content in drinking water is <0.1 mg/l (Borah et al., 2010; WHO, 2011). pH, a crucial constraint in drinking water, varies greatly, and the permissible range is 6.5–9.5 (Saxena and Ahmed, 2001; WHO, 2011).

In Bihar, among 38 districts, 13 districts are located beside the Gangetic river are partly impaired by pollution due to the high concentration of arsenic (As >0.05 mg/l), affecting 1,590 habitations (Singh et al., 2014), whereas 11 districts are profoundly affected by fluoride pollution (F >1.5 mg/l), having a detrimental impact over 4,157 habitations. The iron concentration (Fe >1 mg/l) was found in 9 districts over 18,673 residences. Previous studies reported fluoride concentrations with respective concentrations of 0.00–1.34 mg/l in Bhagalpur (Verma et al., 2017), 0.10–2.50 mg/l in Rohtas (Ray et al., 2000), and 0.19–14.4 mg/l in Gaya (Yasmin et al., 2011; Ranjan and Yasmin, 2012). The fluoride concentration in groundwater in the Sheikhpura district of Bihar is more than 1.5 mg/l, affecting 193 habitations (PHED, 2009), and iron is <1 mg/l; however, the WHO recommended 0.1 mg/l Fe as the permissible limit for drinking purposes.

Geostatistics has been globally applied as a decision-making tool for groundwater level (Knotters and Bierkens, 2001), contamination analysis (Gaus et al., 2003), groundwater quality analysis (Yeh et al., 2006; Lee and Song, 2007; Sakram et al., 2019), and storage and reservoir capacity (Rakhmatullaev et al., 2011). In the groundwater pollution modeling, the geostatistical interpolation techniques applied are kriging, inverse distance weighting (IDW), principal component analysis (PCA), etc. (Chatterjee et al., 2010; Machiwal et al., 2011; Belkhiri and Narany, 2015; Bodrud-Doza et al., 2016; Verma et al., 2017; Kawo and Karuppannan, 2018). Investigating different groundwater quality parameters at every location would be time-consuming and economically inviable. The geospatial interpolation techniques are used significantly in unsampled areas. In this context, two different approaches, deterministic and geospatial methods, are adopted for groundwater pollution studies (Sarangi et al., 2005; Dash et al., 2010), and geospatial interpolation techniques are reported and extensively applied in hydrology, hydrogeology, geography, geology, soil science, atmospheric science, etc. (Diodato and Ceccarelli, 2005; Sarangi et al., 2006; Tweed et al., 2007; Dash et al., 2010; Pandian and Jeyachandran, 2014; Bodrud-Doza et al., 2016; Kawo and Karuppannan, 2018; Aher and Deshmukh, 2019).

This study aims for adequate information on spatial distribution of groundwater quality for long-term assessment and implementation of groundwater management strategies for irrigation and potable water supply. Therefore, this study proposed spatial mapping and distribution of groundwater quality parameters, such as fluoride, iron, pH, and TDS, using integrated interpolation techniques, geographical information systems, and regression analysis into low and high groundwater contaminated regions in the Sheikhpura district of Bihar for safe drinking and irrigation water supply. Geospatial pattern analysis of different quality parameters is essential for management and monitoring agencies such as Central and State Pollution Control Boards, farmers, agricultural research institutes, the Government of Bihar, and India to implement schemes and policy in different regions.

MATERIALS AND METHODS

Study Area

The study area was Sheikhpura, a district in South Bihar, India, which lies between 24°45′ and 25°45′ North and 85°45′ and 86°45′ East longitude. The district has six blocks and 360 villages, extending over 609.51 km^2 in size (**Figure 1**). Groundwater-bearing geological formations in the area have unconsolidated sediments of alluvium plain having hard rock with fissured quartzite formation, as shown in **Supplementary Figure 1** (Rajmohan and Prathapar, 2013; IEED, 2019). IEED (2019) reported that the geology of the Sheikhpura district is composed of quartzites, phyllite, and schist rocks. Further, several studies documented that the geological formations of quartzites, phyllite, and schist rocks are primary sources of fluoride and iron in groundwater (Rao and Devadas, 2003; Suthar et al., 2008; Okofo et al., 2021). The area is enriched with old alluvial soil. Most of the area is covered by sand, silt, and clay, with aquifer thickness in the range of 20–190 m because of uneven bed-rock topography across the district (CGWB, 2013; TRUAGRICO, 2017). The hydrogeology features comprise unconsolidated formation, i.e., quaternary alluvium and consolidated formation due to hard rocks (**Supplementary Figure 1**) (CGWB, 2013). The major part is covered with old alluvium, which receives sediments from the Phalgu-Kiul sub-basin of River Ganga. Soils are coarse loamy with dominant subgroups of typic ustifluvents, fine aeric ochraqualfs, fine vertical ochraqualfs, and fine vertical ustochrepts. The major part in the south has fine vertic ochraqualfs and fine vertic ustochrepts in the middle region. In the northern side, soils are coarse loamy typic ustifluvents. The fine aeric ochraqualfs randomly occupy in the west, southeast,

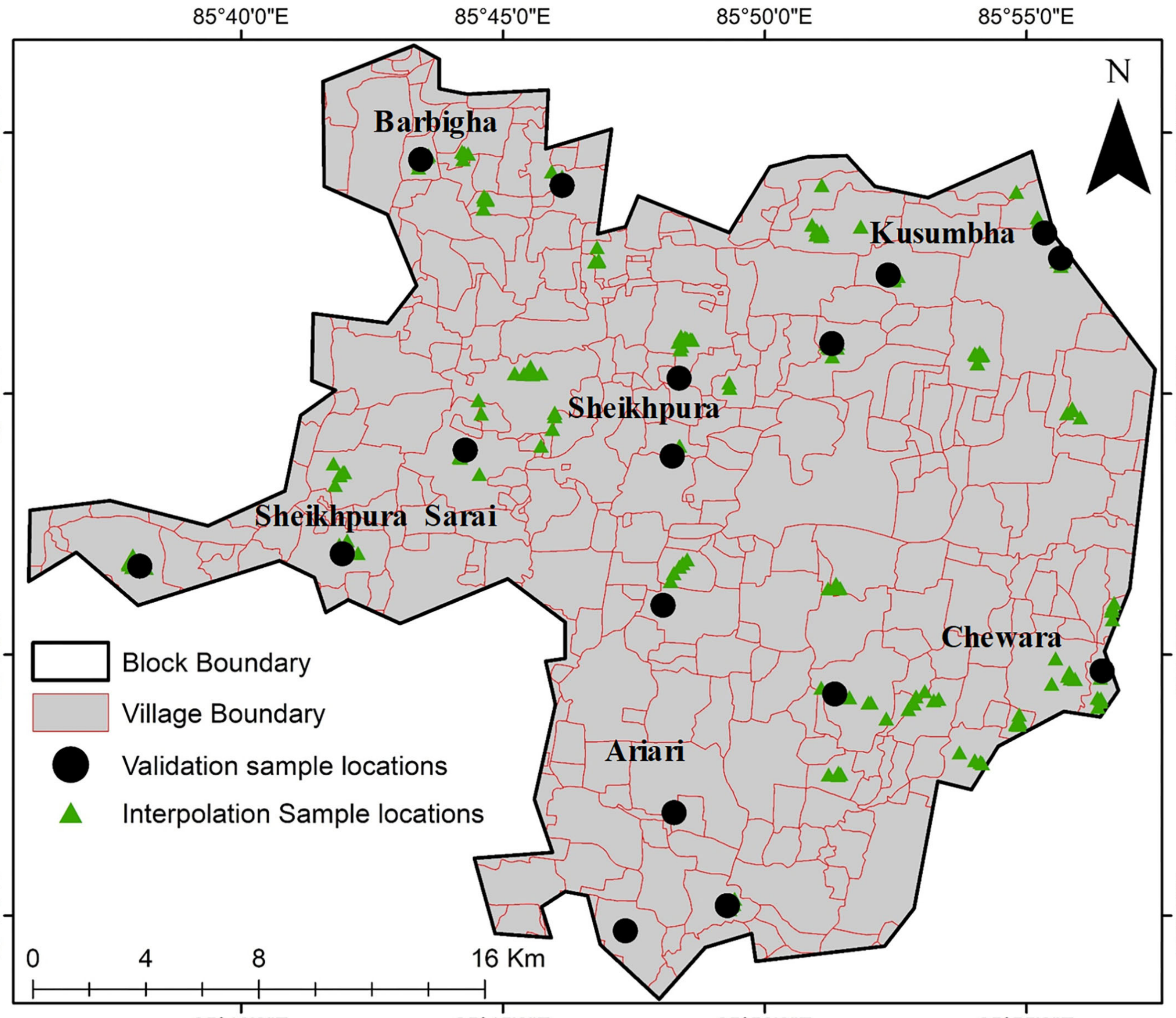

FIGURE 1 | Village map of Sheikhpura district indicates groundwater sample locations (*N* = 206) (source: http://www.sheikhpura.bih.nic.in/).

and northeast. The maps of soil types and dominant soil subgroups are shown in **Figures 2A,B**, respectively, and are used for water management strategy. The majority of the area is covered with greenish clay with caliche oxidized and pedocal soil, followed by silt and clay of variegated colors in the northeastern region and sand, silt, and clay unoxidized in the southeastern side. The greenish clay in the northern part occupies a significant area. The minimum area has silt and clay of variegated colors.

Research Methods and Data Collection

With a sampling intensity of 10%, 36 villages encompassing all the blocks were randomly selected based on strata of location, population, block, and village size (big, medium, and small). Out of 2,000 bore wells in the area, 206 bore wells were sampled and analyzed. The data on F, Fe, TDS, turbidity, and pH collected by the Ministry of Drinking Water and Sanitation, Government of India, in 2017 under the National Rural Drinking Water Programme were used in this study. The geotagging of these wells was done using the Garmin eTrex Legend navigation system. We prepared a geospatial database of soil types and subgroups (ICAR, 1998) in the geospatial information system (GIS) domain and land use/land cover using satellite data. Geo-coordinates of 206 well locations were imported in the GIS domain, and attributes on F, Fe, TDS, and pH were assigned to prepare geospatial maps using Arc GIS 10.9 software (**Figure 1**).

Geospatial Modeling

The geospatial approaches such as Kriging and IDW interpolate the spatial variability of point attributes and predict for an unobserved location using nearby known attributes (Rakhmatullaev et al., 2011; Sahoo et al., 2019; Ijumulana et al., 2020, 2021, 2022; Ligate et al., 2021). The Kriging

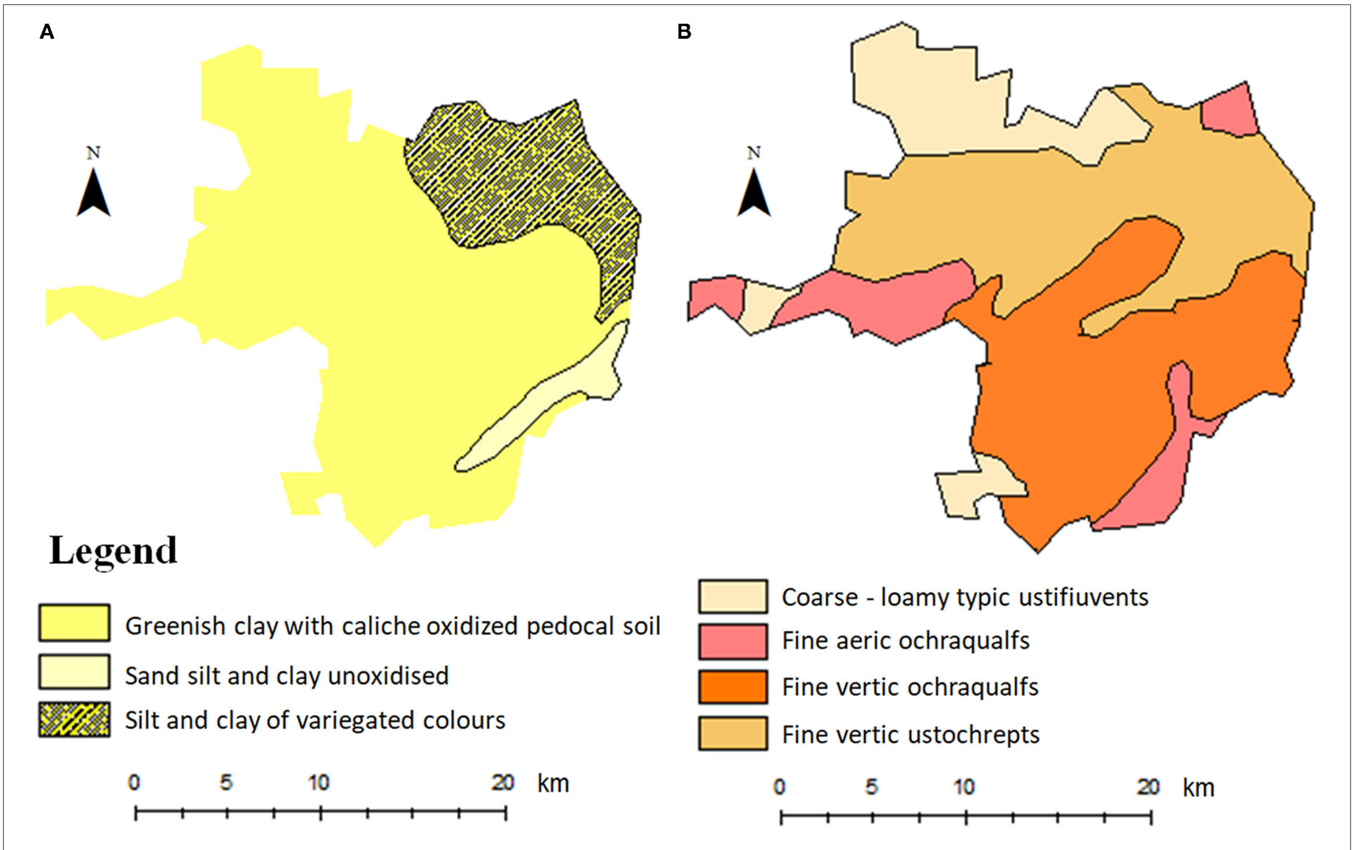

FIGURE 2 | Soil maps **(A)** soil type, **(B)** dominant soil subgroups (source: NATMO, Kolkata, India).

interpolation technique is the optimal and widely applicable procedure for estimating unknown values (attributes) using normally distributed known data (Jager, 1990; Dong et al., 2011; Wu et al., 2011; Ijumulana et al., 2022). A linear interpolation method predicts the value of unobserved location attributes based on probabilistic models (Shyu et al., 2011; Ijumulana et al., 2021, 2022) with minimum error (Mendes and Ribeiro, 2010). In the present study, kriging was applied and validated the reliability of different groundwater quality parameters by incorporating geospatial statistical techniques. The water quality parameters, such as F, Fe, TDS, and pH, were characterized as good, moderate, and poor based on the ranges and permissible limits for groundwater quality characterization (**Table 1**). Under the National Rural Drinking Water Programme, Ministry of Drinking Water and Sanitation, Government of India, in 2017, turbidity was reported almost negligible (<2 NTU) across the Sheikhpura district of Bihar. Therefore, the turbidity data were not considered for integrated interpolation, GIS, and regression analysis. Therefore, except turbidity, each parameter was assigned weights considering their negative impacts. The highest weight of four was assigned to fluoride, then iron (3), TDS (2), and the lowest (1) to pH. Fluoride is more than its permissible limit (>1.5 mg/l); therefore, it was assigned high weight, and pH was set with the least weight due to its concentration being under the allowable limit (6.5–9.5). A simple overlay analysis considering the ranges and these weights were performed for suitability analysis. The groundwater suitability for irrigation and drinking water supply was characterized, assigned from very good (rank rating = 3), i.e., under the permissible limit, to very poor (rank rating = 1) for more than the allowable limit to each quality parameter (Islam et al., 2018). With criteria for drinking and irrigation purposes, the water quality has been characterized based on each contaminant presented in **Table 1**. The validation and adequacy of the model were tested by determining the coefficient of determination (R^2) based on 17 randomly selected point data to establish the relationship between the actual and predicted ranges of pollution parameters.

RESULTS AND DISCUSSION

Geospatial Mapping of Groundwater Pollutants

In this study, groundwater quality parameter limits followed the standards outlined by WHO (1997) and BIS (2012) for drinking and irrigation purposes. Fluoride and iron concentrations exceed the permissible limit, whereas TDS and pH values are under permissible limits. Fluoride level was observed within the permissible limit except in the southeastern region (**Figure 3A**). The northern part is occupied by "Tal" (a low-lying area having

TABLE 1 | Parameterization of groundwater quality assessment.

Parameters	Weightage	Range	Suitability	Rating	Permissible limit	
					WHO (1997)	**BIS (2012)**
Fluoride (F)	4	F < 1	Very good	3	< 1.5 mg/l	< 1.5 mg/l
		1 ≤ F ≤ 1.5	Moderate	2		
		F > 1.5	Very poor	1		
Iron (Fe)	3	Fe < 0.07	Very good	3	< 0.1 mg/l	< 0.3 mg/l
		0.07 ≤ Fe ≤ 0.1	Moderate	2		
		Fe > 0.1	Very poor	1		
TDS	2	TDS > 500	Very good	3	300–1,700 mg/l	2,000 mg/l
		500 ≤ TDS ≤700	Moderate	2		
pH	1	7.11 ≤ pH ≤ 7.51	Very good	3	6.5–9.5	6.5–8.5

WHO, World Health Organization; BIS, Bureau of Indian Standard.

soil of silt and clay of variegated colors), contaminated with fluoride ranging between 0.37 and 0.76 mg/l. The southeastern part has slightly higher concentrations of fluoride that range from 1.024 to 1.45 mg/l, which are also within the acceptable limit. The fluoride concentration is acceptable with <1.5 mg/l for drinking and irrigation purposes, according to the WHO and BIS (Bureau of Indian Standards) standards (WHO, 1997; BIS, 2012). Geospatial analyses indicated that the fluoride contamination with permissible limit is higher in most of the area; the moderately affected (1.16–1.54 mg/l) area in the Ariari block covers 6.54% of the total area. The majority of the area is within the fluoride concentration of 1.5 mg/l, which possesses coarse-loamy soils in the northeastern region and fine-loamy soil in the southern region of the Sheikhpura district. Besides this, the lowest range of fluoride from 0.37 to 0.76 mg/l was associated with greenish clay, characterized by caliche oxidized with pedocal soils, and covered almost 76.10% area of the entire district. 91.15% area comes under Sheikhpura, Ghat Kusumbha, Barbigha, and Sheikhpura Sarai, and major portions of Ariari blocks have groundwater with fluoride concentrations in the range of 0.37–1.54 mg/l, i.e., under the WHO-permissible limit of fluoride concentrations, and are suitable for drinking purposes. The maximum fluoride concentration was 1.54–2.32 mg/l in the southeastern region, where groundwater is unsuitable for domestic and drinking purposes. The analysis indicated that the southern peripheral area of Chewara is profoundly affected with fluoride concentrations of 1.55–2.32 mg/l, which covers 5.07% of the total district area. Pedocal soils have high concentrations of fluoride (1.94 mg/l< F <2.32 mg/l) in groundwater (**Figure 3A**) and are unsuitable for drinking purposes. This is the highest level of fluoride spread in ∼24.71 km^2 (4.09%) of the total area.

Iron is a vital element and occurs naturally in water. The geogenic source of iron in groundwater is due to the underlying quartzite rocks of Sheikhpura. A similar geogenic source of iron in groundwater is reported in the literature (Rao, 2008; Amanambu, 2015). In general, the desirable limit of iron is <0.1 mg/l (WHO, 2011) and <0.3 mg/l (BIS, 2012), according to the WHO and BIS standards for drinking purposes. The high concentration of iron in groundwater has a direct impact on health. The categorization of groundwater quality parameters for drinking and irrigation purposes based upon iron is presented in **Table 1**. In this regard, the spatial distribution of iron concentration is shown in **Figure 3B**, indicating that 96.9% of the total area has a concentration of more than 0.1 mg/l. The analysis also revealed that the northern region has 0.23–0.29 mg/l of iron concentration, covering Barbigha, Sheikhpura, and Ghat Kusumbha blocks and a small portion in the Chewara block. Moreover, the west and south regions of the district exhibit a high iron level of 0.20–0.22 mg/l in Sheikhpura Sarai, Ariari, and Chewara blocks. Iron concentrations ranged from 0.13 to 0.18 mg/l in most northeastern blocks, like Sheikhpura, Chewara, and Ghat Kusumbha (**Figure 3B**). The permissible limit (0.00–0.12 mg/l) for drinking purposes was found in pockets of Sheikhpura and Chewara blocks in the northeastern region. Based on the BIS standard, iron concentrations are under the required acceptable limit (<0.3 mg/l).

The pH determines the acidity and alkalinity of groundwater as a significant water quality parameter. The permissible limit of pH ranged from 6.5 to 9.5 as per WHO recommendations (WHO, 2011) and 6.5 to 8.5 according to BIS standards (BIS, 2012) for drinking purposes. **Figure 3C** depicts the geospatial pattern of pH and is in the desirable limit. It varied from 7.04 to 7.51, under permissible limits recommended by the WHO and BIS standards in drinking water. In the northern area of the district, it ranged from 7.23 to 7.51.

TDS characterizes the total concentration of dissolved substances in groundwater, an important parameter to measure drinking water/groundwater quality. TDS indicate fully dissolved minerals, such as calcium, chlorides, carbonates, bicarbonates, magnesium, silica, and sodium, in groundwater (Anbazhagan and Nair, 2004). The permissible limit <300 mg/l is excellent, and the unacceptable limit is >1,700 mg/l (WHO, 2008) and 2,000 mg/l according to BIS (2012) standards. In this regard, TDS varied between 271 and 713 mg/l. A slightly higher level of TDS (713 mg/l) was noted in small pockets of Sheikhpura and Ghat Kusumbha blocks (**Figure 3D**). Thus, it is not much of a concern for drinking and irrigation purposes (**Table 1**). Therefore, this study recommends the development of a practical

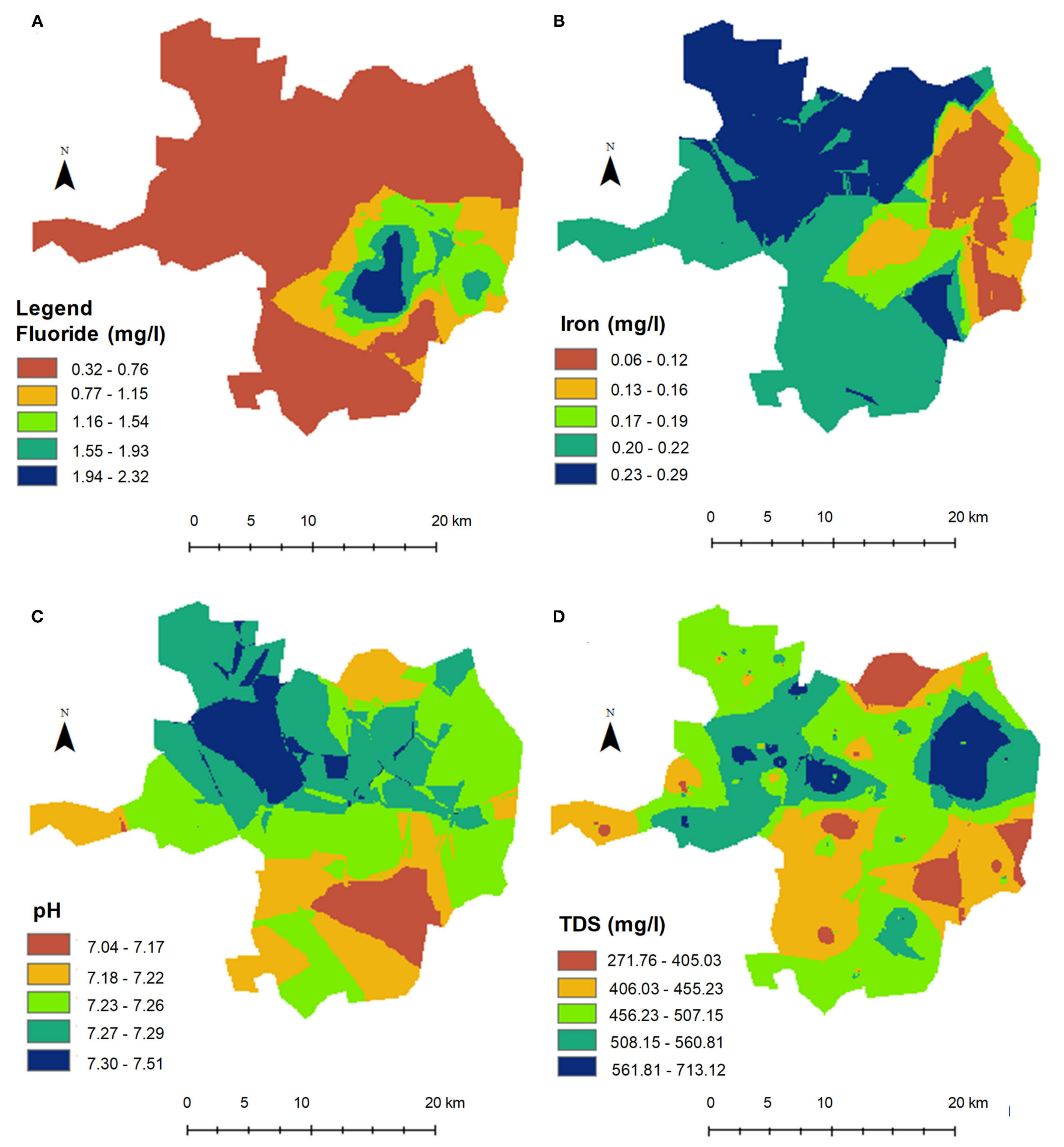

FIGURE 3 | Geospatial maps of groundwater quality: **(A)** fluoride, **(B)** iron, **(C)** pH, and **(D)** TDS based on kriging interpolation of field observations.

groundwater management support tool for fluoride-free water for drinking and irrigation purposes. Besides, implementing an efficient and reliable technique should be adopted to achieve groundwater quality under WHO and BIS standard permissible limits.

Model Accuracy

Seventeen observational data points were used to validate the results of Kriging interpolation. The actual observations were evaluated concerning the predicted values. The goodness of fit for an actual concentration of contaminants indicated that the

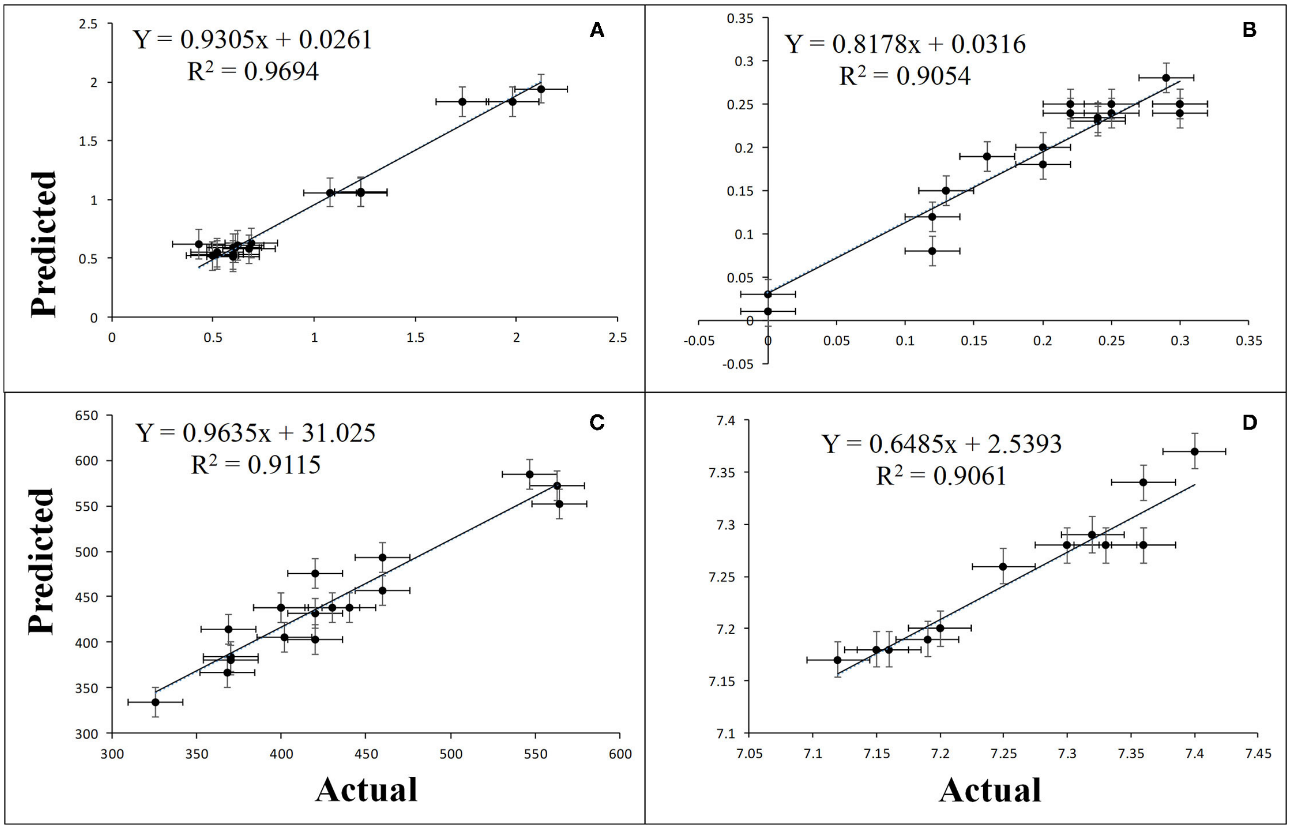

FIGURE 4 | Model accuracy assessment between observed and predicted groundwater quality parameters: **(A)** fluoride, **(B)** iron, **(C)** pH, and **(D)** TDS.

TABLE 2 | Relationship between observed vis-à-vis predicted groundwater quality.

Parameter	Actual range	Predicted range	R^2
Fluoride	0.36–2.12 mg/l	0.37–2.32 mg/l	0.960
Iron	0.00–0.3 mg/l	0.06–0.33 mg/l	0.905
TDS	251–700 mg/l	269–712 mg/l	0.910
pH	7.02–7.33	7.11–7.38	0.906

coefficient of determination (R^2) between observed/actual and predicted for F, Fe, TDS, and pH were 0.96, 0.905, 0.91, and 0.906, respectively (**Figures 4A–D**), which shows heterogeneity in the quality parameters (**Table 2**).

Geospatial Modeling for Suitability of Groundwater

Characterization for groundwater quality mapping based on class interval and weights to different layers of F, Fe, TDS, and pH per their significance is shown in a map (**Figure 5**). Prioritization of groundwater quality was done for planning and conservation of groundwater resources for drinking and irrigation purposes. Only 5.08% area is falling under the "very good" category. Many villages are in Sheikhpura block, whereas four villages, viz., Angpur, Bahuwara, Chakandara, and Chewara villages, are of the Chewara block, and two villages, Kusumbha and Rajauli villages, are of the Ghat Kusumbha block. Significant areas are covered under suitable groundwater conditions in each block, i.e., 55.84% of the total district area has groundwater fit for drinking purposes. Therein, the medium/moderate quality of groundwater is falling under all blocks, which covered 33.95% area of the district, except the Ariari block. The poor, unsuitable groundwater quality covered only 5.13% of the total area. The poor water quality only extended in Arari, Chewara, and Sheikhpura blocks. Nabinagar, Husenabad, Diha, Belchhi, Karki, and Pandhar villages are the most affected in the Arari block. In contrast, Sheikhpura and Eksari villages are affected in the Sheikhpura block, and Mane, Barari, and Chewara are the most affected from the Chewara block. Villages have been categorized under different water quality parameters with corresponding percent area, including the uninhabited village of Sheikhpura district polluted under quality parameters (**Supplementary Table 1**).

Relationship Between Soil Types and Groundwater Quality Parameters

Groundwater is vulnerable to contamination under different soil types (Li et al., 2020). Geogenic fluoride contamination is globally observed in shallow aquifers (Edmunds and Smedley, 2013). In the Indo-Gangetic plains, potential fluoride contamination

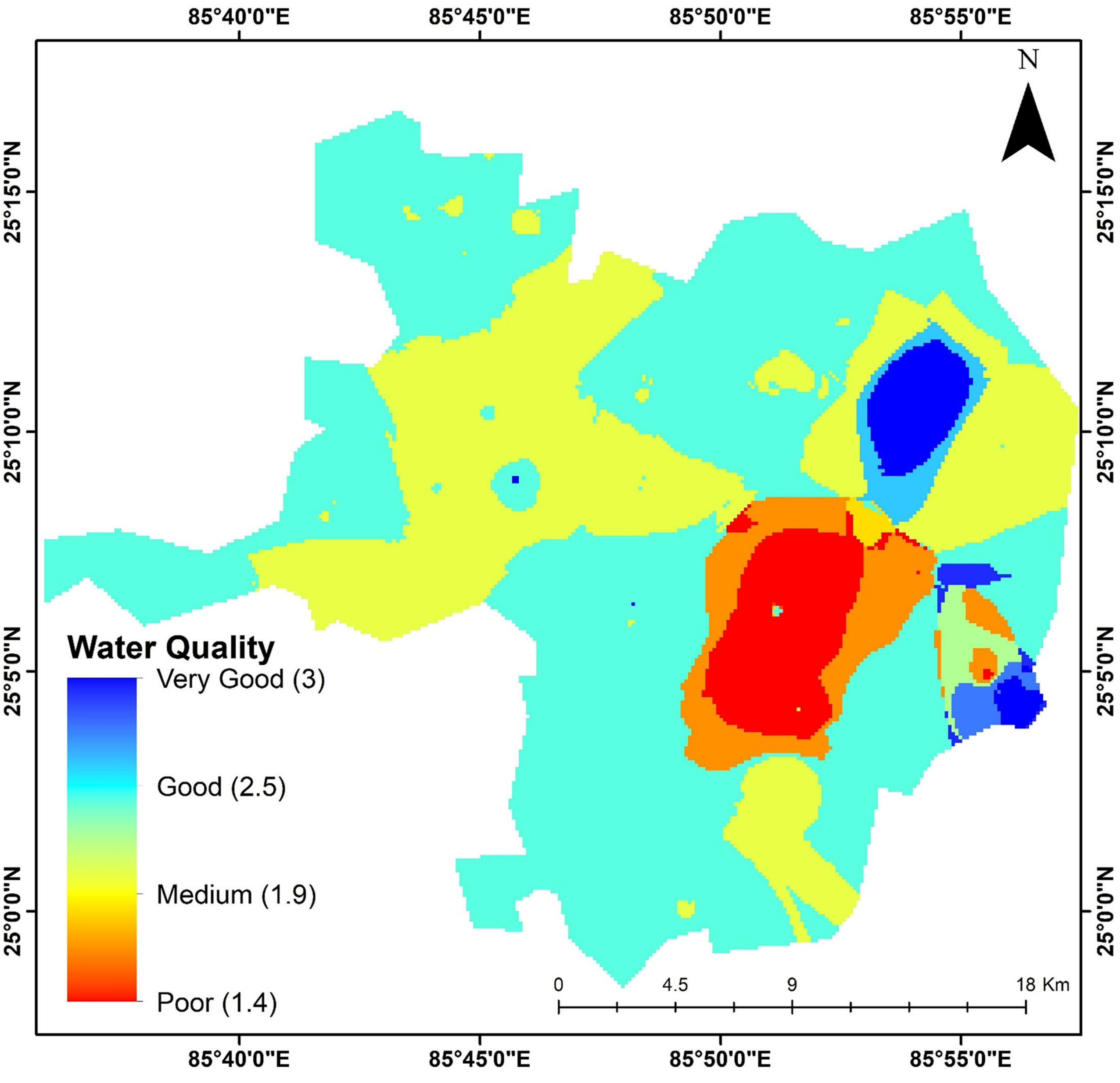

FIGURE 5 | Potential groundwater quality map for planning and management of groundwater harvesting and supply.

was observed in alluvial aquifers of northwest India, but <1.5 mg/l of fluoride concentration in groundwater (Lapworth et al., 2017). Therefore, the principal source of contamination might be from underlying rocks and the flow rate in the aquifers (Saha et al., 2007; Saha and Sahu, 2016). Overall, it was observed that the groundwater quality parameters exceed the desirable limits for domestic, drinking, and agriculture purposes at several locations in the Sheikhpura district. In Sheikhpura, the high fluoride concentration in the range of 1.55–2.32 mg/l was found in the southeastern region. In addition, the iron concentration is found in the range of 0.13–0.30 mg/l, which is above the permissible limit recommended by the WHO. The geological characteristics which constituted quartzites, phyllite, and schist rocks are responsible for the enrichment of fluoride and iron in groundwater in the Sheikhpura area of Bihar. Both fluoride and iron are likely to indicate geogenic contamination of aquifers in the area (Saha et al., 2007; Saha and Sahu, 2016). The pH and TDS are well within the permissible limits, i.e., 7.04–7.51 and 271–713 mg/l, respectively, as per WHO recommendations. The causal relationship between soil types and groundwater contaminants across the district is tabulated (**Table 3**).

Groundwater contaminant concentrations were randomly distributed among different soil types in the area. There is no noticeable, quantifiable, and significant relationship between soil

TABLE 3 | Summarized relationship between soil types and groundwater quality.

Soil type	Soil subgroups	Groundwater quality parameters			
		Fluoride	pH	TDS	Iron
Greenish clay caliche oxidized, pedocal soil	Fine vertic ochraqualfs	0.37–2.32	7.04–7.26	269–507	0.13–0.22
Sand silt and clay unoxidised	Coarse loamy typic ustifiuvents	0.77–1.15	7.27–7.38	406–560	0.19–0.30
Silt and clay of variegated colors	Fine aeric ochraqualfs	0.37–0.76	7.18–7.29	406–560	0.19–0.22
-	Fine vertic ustochrepts	0.37–1.54	7.18–7.38	456–712	0.00–0.30

types and groundwater contaminants. A similar study by Sheehan et al. (2003) highlighted no statistical correlation between groundwater chemistry and toxicity and soil. However, the lack of correlation between soil and groundwater contaminants must not ignore the potential risk assessment to quantify contaminated soils for determining underlying aquifers characteristics, land uses, and groundwater footprint.

CONCLUSIONS

Integrated interpolation techniques, geostatistical systems, and regression analysis have proved efficient decision-making tools for groundwater quality analysis, monitoring, and management. In this study, the spatial groundwater quality parameters, such as F, Fe, TDS, and pH, were analyzed across six blocks of the Sheikhpura district of Bihar. Groundwater in Sheikhpura, Arari, and Chewara blocks were contaminated with high fluoride concentrations up to 2.42 mg/l. In addition, iron has also spread with more than the WHO permissible limit (>0.1 mg/l) across all six blocks. Reasons behind the enrichment of fluoride and iron in the groundwater of the Sheikhpura district of Bihar are the underlying geological features composed of quartzites, phyllite, and schist rocks. Besides this, TDS and pH were found under the allowable limit across the district. The spatial analysis of different parameters is conducted based on the Kriging method by estimating unobserved locations relating to the known values. This study also attempted to establish the relationship between soil types and groundwater contaminants; however, no statistical correlation was found for each groundwater quality parameter considered for spatial mapping in the Sheikhpura district. The final groundwater quality map highlighted the area having groundwater quality from "poor" to "very good" across the district. In the interpolated map, the overall groundwater quality of the Arari, Chewara, and Sheikhpura blocks is not appropriate; thus, aquifer quality is relatively low and not acceptable for drinking and irrigation purposes. Thus, spatial mapping of groundwater quality will help policymakers to better operate and manage the groundwater resources through detecting pollutants, demand–supply gap, etc. Overall, proper utility and management of groundwater through canals, channels, and underground movement from safe to affected blocks/zones are recommended for drinking and agricultural purposes to avoid carcinogenic diseases among the population in the future.

DATA AVAILABILITY STATEMENT

Publicly available datasets were analyzed in this study. This data can be found at: All the primary groundwater quality data were obtained from the website of Ministry of Drinking Water and Sanitation, Government of India, surveyed in 2017 under the National Rural Drinking Water Programme and has been duly acknowledged. Map of soil types and soil subgroups published by the National Bureau of Soil Survey and Land Use Planning (ICAR 1998), Nagpur, India. were used.

AUTHOR CONTRIBUTIONS

RiK: conceptualization, sampling strategy, fieldwork, GIS database creation and analysis, and writing of the first draft of the manuscript. SS: conceptualization, sampling strategy, methodology, GIS analysis supervision, review of results, and editing of the manuscript. RaK: support in GIS analysis, writing, reviewing, and editing of the manuscript. PS: initial conceptualization, review, and editing of the manuscript. All authors contributed to the article and approved the submitted version.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/frwa.2022.848018/full#supplementary-material

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