Habitable Planet, 2026, 2(1), 216–233

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Article

Multicriteria Groundwater Quality Assessment Using AHP–GIS Integration of Physiochemical and Geohydrological Parameters in the Bundelkhand Region, India

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ABSTRACT

This study introduces a novel approach by integrating the Multi-Criteria Decision-Making (MCDM) technique of the Analytical Hierarchy Process (AHP) with Geographic Information System (GIS) to develop a Geospatial Groundwater Quality Index (GWQI) for the semi-arid Lalitpur district. To carry out the GWQI assessment, seven hydrogeological parameters, such as geology, geomorphology, lineament density, drainage density, slope, rainfall and Land use Land cover (LULC) thematic layers, were used in generating GWPZ. These layers were integrated with physiochemical parameters that include pH, TDS, Ca^{2+}, Mg^{2+}, Cl^-, HCO_3^-, CO_3^{2-}, SO_4^{2-}, F^-, and NO_3^- to generate GWQI. The weights are assigned based on their relative influence on groundwater quality. A Weighted Arithmetically Water Quality Index (WAWQI) map is prepared using physicochemical parameters alone and compared with the GWQI. The WAWQI categorises the study area into Very Poor (1.22%), Poor (11.54%), Moderate (32.41%), Good (43.40%), and Very Good (11.41%) classes. In contrast, the GWQI classified water quality into five categories and the percentage area was found to be Very Good (7 samples, 5.01%), Good (58 samples, 38.39%), Moderate (57 samples, 38.55%), Poor (25 samples, 17.12%), and Unsuitable (3 samples, 0.91%). A sympathetic relationship between the physiochemical parameters and hydrogeological parameters was observed. GWQI integrated method provide more valuable and informative results than WAWQI in the Lalitpur district.

ARTICLE INFO

History:

Received: 04 December 2025
Revised: 16 January 2026
Accepted: 14 February 2026
Published: 26 February 2026

Keywords:

multicriteria;
bundelkhand;
AHP–GIS techniques;
groundwater;
WQI

Citation:

Bisen, U.; Singh, S.P. Multicriteria Groundwater Quality Assessment Using AHP–GIS Integration of Physiochemical and Geohydrological Parameters in the Bundelkhand Region, India. *Habitable Planet* **2026**, *2*(1), 216–233. https://doi.org/10.63335/j.hp.2026.0036

Research Highlights

- The integrated approach of the GIS platform and AHP technique reveals spatial variations in GWQI linking poor groundwater quality to low recharge hard rock terrains.
- Effective, precise and informative method for groundwater quality assessment by integrating hydrogeological and physiochemical parameters.
- The close interplay between hydrogeological factors and groundwater quality highlights the crucial role of recharge in mitigating poor groundwater conditions.

1. Introduction

The Water Quality Index (WQI) is a numerical expression used to evaluate the suitability of groundwater for specific purposes such as drinking, irrigation, or industrial use. It has become an essential tool for addressing environmental concerns in industrial and agricultural regions [1]. The WQI categorizes water quality into different classes, like Excellent, Good, Poor, and Very Poor, based on its suitability for use [2]. The conventional method for determining WQI, developed, is based on various physicochemical parameters measured in the laboratory and their corresponding standard values, known as the Weighted Arithmetic Index Method (WAIM) [3]. This approach provides a comprehensive view of the multiple physicochemical factors that collectively influence water quality. It simplifies complex datasets but has a limited scope for supporting sustainable water management and serves as an effective decision-making and public awareness tool for planners, policymakers, and local authorities in prioritising treatment or remediation efforts [4]. It is known that geological and geochemical processes play a crucial role in controlling both the quality and quantity of groundwater, particularly in hard rock terrains [4, 5]. Hard rock formations dominate the semi-arid region of Bundelkhand, which faces significant challenges related to groundwater quantity and quality [6]. In the Lalitpur district, massive granitic lithology and prevailing pediment and pediplain geomorphology and fractures reduce infiltration and groundwater recharge, while enhancing water–rock interaction.

Hydrogeological parameters play their role in nullifying groundwater pollution [7]. To maintain the sustainability and protect water resources from contamination, hydrogeological parameters must be involved in groundwater resource management studies [8]. Lineament density is one of the significant hydrogeological parameters that plays an important role in groundwater recharge [9]. Drainage density and slope lead to surface recharge of the groundwater [10]. Geo-hydrological parameter such as lithology, geological set up determines the quality of the groundwater resources [11]. Better groundwater potential leads to formations of recharging zones, which leads to dilution of the contaminants. Dilution can play a significant role in reducing contamination levels [12]. Attenuation of the aquifer contaminants is achieved by dilution [13].

Some studies showed that there has been a sympathitical relationship between groundwater quality and groundwater potential. Low groundwater potential leads to low groundwater quality [14]. Lowest and highest TDS and Nitrate levels were observed to overlap with good to very good and low to very low groundwater potential [9]. An inverse relationship was observed between TDS and recharge potential [15].

The conventional WQI assessment methods are good but often struggle to classify groundwater as safe or unsafe because they typically overlook influencing geological parameters such as land use/land cover (LULC), slope, soil, lithological formations, drainage density, and lineament density [4, 16, 17]. To overcome this limitation, the present study integrates a Groundwater Potential Zone (GWPZ) layer encompassing these factors. The GWPZ is computed using seven thematic layers: slope, geology, geomorphology, lineament density, drainage density, rainfall, and LULC. These layers are integrated using the Analytical Hierarchy Process (AHP), a multi-criteria decision-making (MCDM) technique, and combined through a weighted overlay in ArcGIS. This multi-criteria and spatial integration approach provides a robust framework for assessing GWQI by combining physicochemical and geohydrological parameters within a GIS environment. This integration methodology has been successfully applied recently in various places [18–21].

In the present study, MCDM and AHP techniques are applied for the first time to assess the groundwater quality index in Lalitpur district. The integrated approach combines GWPZ layers, comprising geology, geomorphology, lineament density, drainage density, LULC, slope, and rainfall patterns with ten physicochemical parameters (pH, TDS, Ca^{2+}, Mg^{2+}, HCO_3^{-}, CO_3^{2-}, SO_4^{2-}, F^{-}, NO_3^{-} and Cl^{-}). The thematic layers were assigned weights based on their relative importance using Saaty's scale, and a final weighted overlay analysis was performed in the AHP–GIS environment to spatially assess the groundwater quality in the Bundelkhand region.

2. Study Area

The district Lalitpur is situated in the southern region of Uttar Pradesh, India and bounded between latitudes 24°10′ N and 25°20′ N and longitudes 78°10′ E and 79° E

(Figure 1). District Lalitpur consists geographical area of roughly 5039 km^2, with more than 1 million people residing in this region. The topographic relief ranges from 524 to 288 m. The slope of the study area decreases northwards, as the Vindhyan ranges from the southern periphery of the study area. Three rivers, namely the Betwa, Shahzad, and Sajanam, are flowing northward, comprise the drainage system in the study area (Figure 1). The study area comprises mainly granite-gneissic terrains (80% area). The sedimentary rocks are mainly confined in the southern part. Groundwater resources are limited in hard rock areas and are mainly used for drinking water purposes. The district has three main types of soils, namely black soils (lowland soil), red soils (upland soil), and alluvial soils. In instances, black soils prevent surface water from penetrating underground. More than 90% of the region's rural income comes from agriculture, livestock care, and seasonal migration. The district largely grows crops for the Rabi and Kharif seasons, including wheat, gram, pulses, and oilseeds. However, the inconsistent and unpredictable monsoons have a significant impact on the region's agrarian economy.

3. Materials and Methods

In the present study, 150 groundwater samples from different hand pumps were collected in two different polyethene bottles in the second week of May 2019, and analysis was completed within the month after the collection. The three parameters, pH, TDS and conductivity values were recorded at the sampling sites positively. For the remaining physiochemical analysis, the groundwater samples were brought to the groundwater laboratory in the Bundelkhand University, Jhansi. Calcium, sodium and potassium were analysed using a Flame Photometer (BWB, UK). Magnesium was analysed using an Atomic Absorption Spectrometer (Analitik Jena 400). Chloride, Carbonate, and Bicarbonate were analysed by titration methods. An IDW interpolation map was prepared for all the above-mentioned parameters on the ArcGIS (10.7.1). Whereas water potential mapping was carried out using seven thematic layers (Geology, Geomorphology, Drainage Density, Lineament density, LULC, and Slope), which underwent an Analytical Hierarchical Process and a Weightage overlay done on ArcGIS (10.7.1). The ranges of the parameters were divided into five categories, and these ranges were reclassified into five categories, i.e., Very good, Good, Moderate, Poor and Unsuitable.

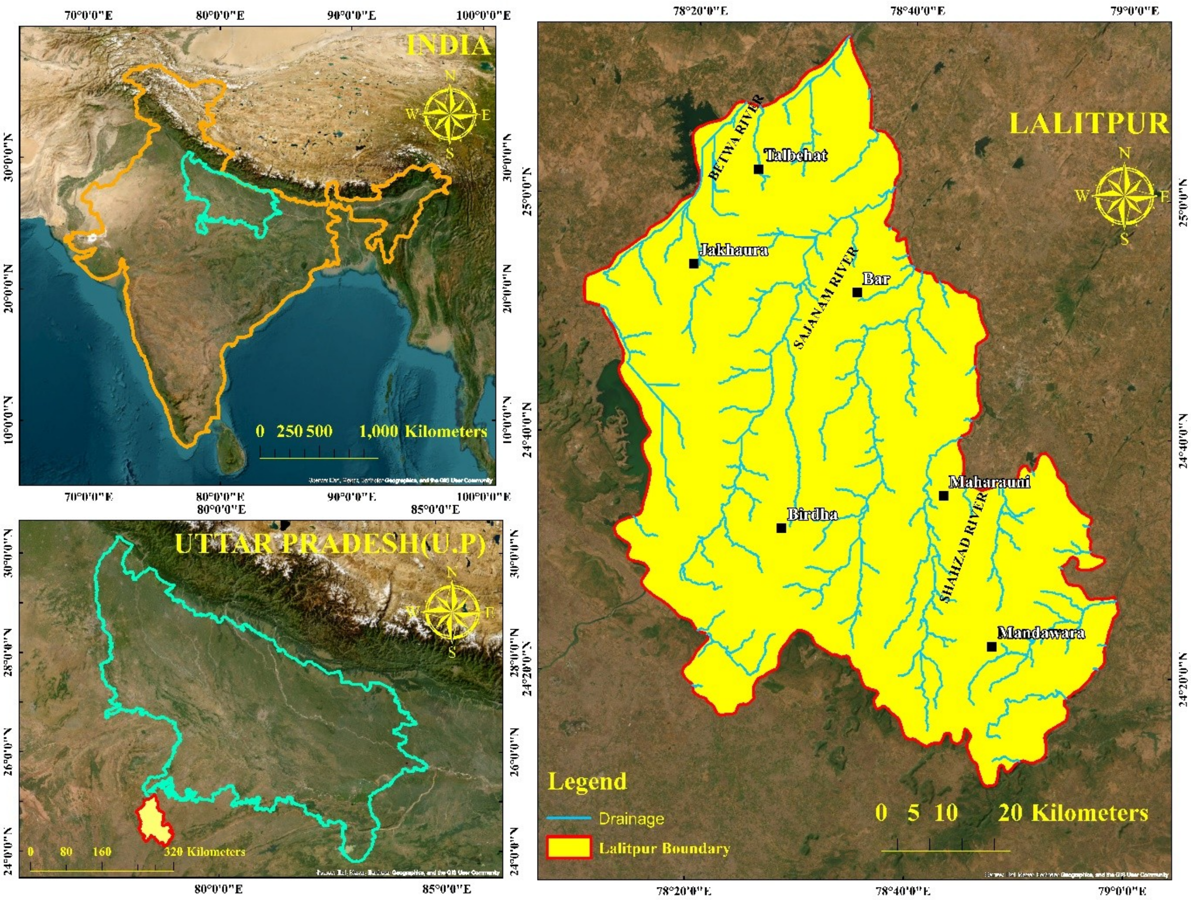

Figure 1. Study area location map along with the drainage pattern.

4. Geohydrological and Physiochemical Parameters

4.1. Physiochemical Parameters

The pH and TDS values were determined by a portable TDS instrument to evaluate the nature of the solution at the sample location point. According to the BIS 2012 standard of drinking water, the pH values must range from 7–5–8.5. In most cases, the results on pH value remain in the suitable range, and the nature of the pH is alkaline in most regions (Figure 2A). Acidic water can occur due to geology, buffering capabilities of the water system or due to the role of bicarbonates [22].

Total Dissolved Solids (TDS) is the total number of salts/minerals dissolved in the solution. A high amount of TDS can lead to an unpleasant taste in the water. According to the BIS drinking standards, the TDS value up to 500 mg/L is suitable for intake. But, in the study area, the values of TDS range from 200 to 1254 mg/L. The higher side TDS values are reported from Lalitpur and Maharauni blocks, and a few regions in the Bar block and in Talbehat (Figure 2B). The maximum concentration of EC was 2521 µS/cm, with a mean of 886 µS/cm. The EC values are showing a sympathetic relationship with the TDS. Higher values are mainly located in the Central and southern regions of the study area, which may be due to the dissolution of ions (geogenic) and agricultural activities.

4.2. Cations (Calcium and Magnesium) Distributions

Calcium is present as the highest concentration among all the cations in the study area. Its values range from 10.65 mg/L to 249.4 mg/L. BIS standard suitability for Ca^{2+} is up to 75–200 mg/l for drinking. However, Ca^{2+} concentrations are an area of concern in the Bar, Lalitpur and Maharauni blocks (Figure 3A). High solubility of Ca^{2+} makes it favourable to be present in most of the rock types. The occurrence of Ca^{2+} in high concentrations in the groundwater in the study area is due to the presence of water–rock interaction and mineral dissolution of Ca-bearing minerals such as dolomite, calcite, augite, plagioclase, and hornblende present in the rocks of the study area. Mg^{2+} is the second most abundant cation in the study area. The maximum and minimum concentrations of Mg^{2+} in the study area range between 82.4 mg/L and 0.04 mg/L (Figure 3B). BIS drinking suitability for Mg^{2+} is from 30 mg/L to 100 mg/L. Hence, Mg^{2+} is within the suitability range. High Na^{+} were found at some places coming from the rock water interaction of the Alkali feldspar and Sodic plagioclase, although their concentration in general remain very much in suitable standards. The cation–anion balance was measured, which showed an accuracy of 4.38% in the study.

4.3. Anions (Chloride, Carbonates and Bicarbonates) Distributions

Chloride is one of the dominant anions present in the study area, where its concentration ranges from 7.31 mg/L to 352.42 mg/L. The suitable concentration for drinking purposes for chloride is 250 mg/L, which is not the case if we look at the regions of Lalitpur block, Bar and Maharauni block (Figure 4A). The presence of higher concentrations is possibly due to anthropogenic activities or the breakdown of the apatite minerals during the erosive activities. High amounts of chloride intake can lead to osteoporosis, renal stones and other heart-related issues [23]. Carbonates range in concentration from 0 to 330 mg/L, and bicarbonates range from 1.36 to 292 mg/L (Figure 4C and 4B). Bicarbonates are responsible for bringing the impurities along with them to the groundwater from recharging points.

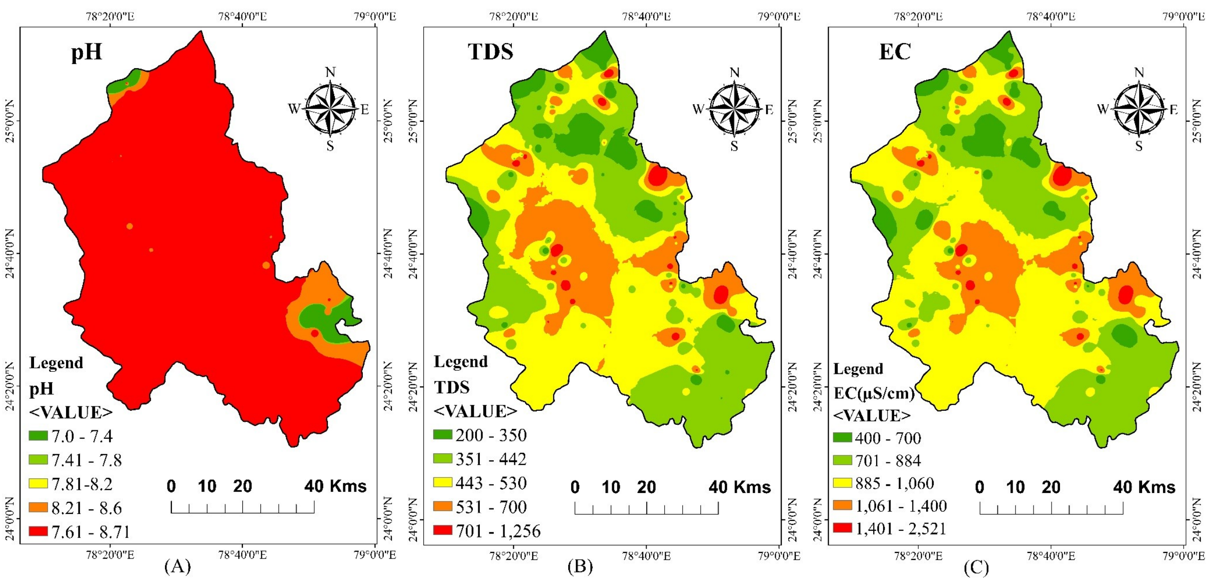

Figure 2. Spatial distribution of the physiochemical parameters (**A**) pH, (**B**) TDS, and (**C**) EC in the study area.

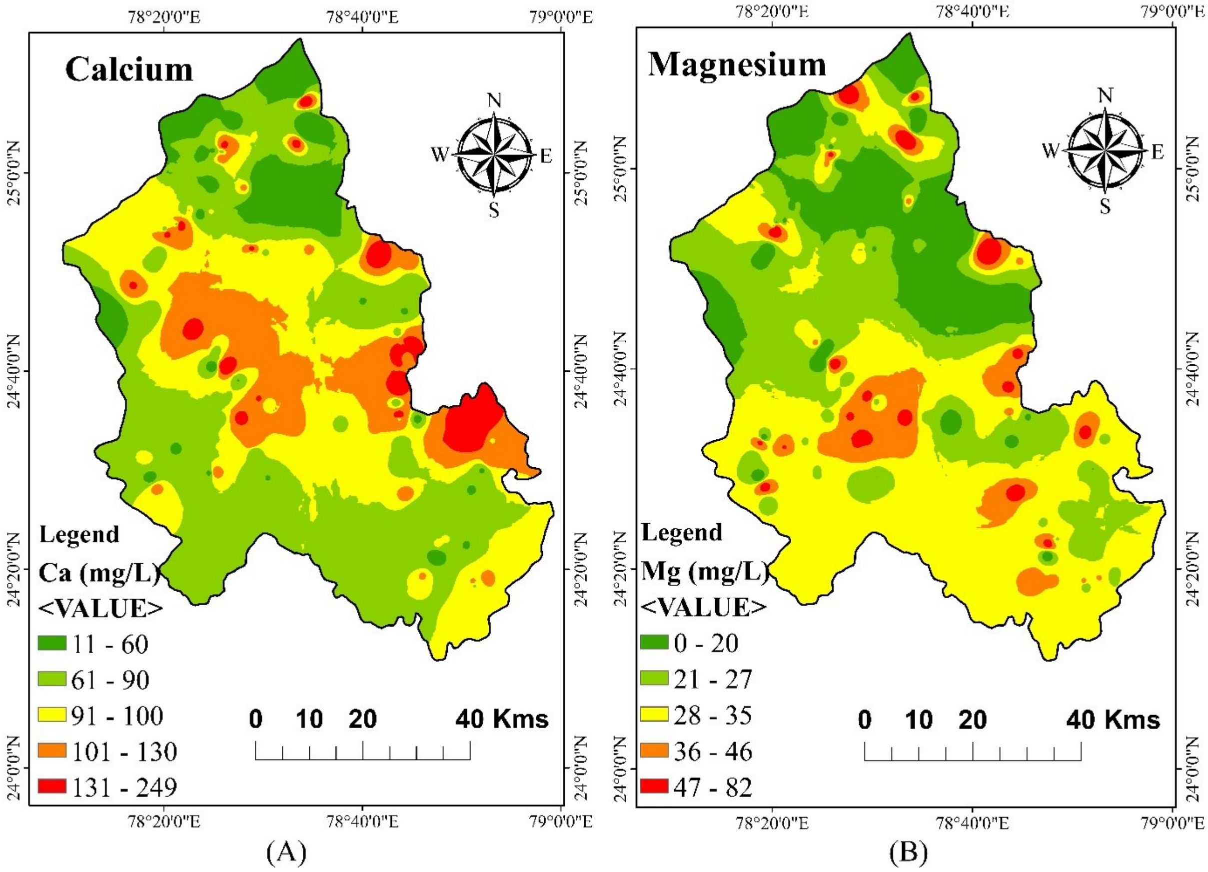

Figure 3. Spatial distribution map of the Cations: (**A**) Calcium and (**B**) Magnesium variation in the study area.

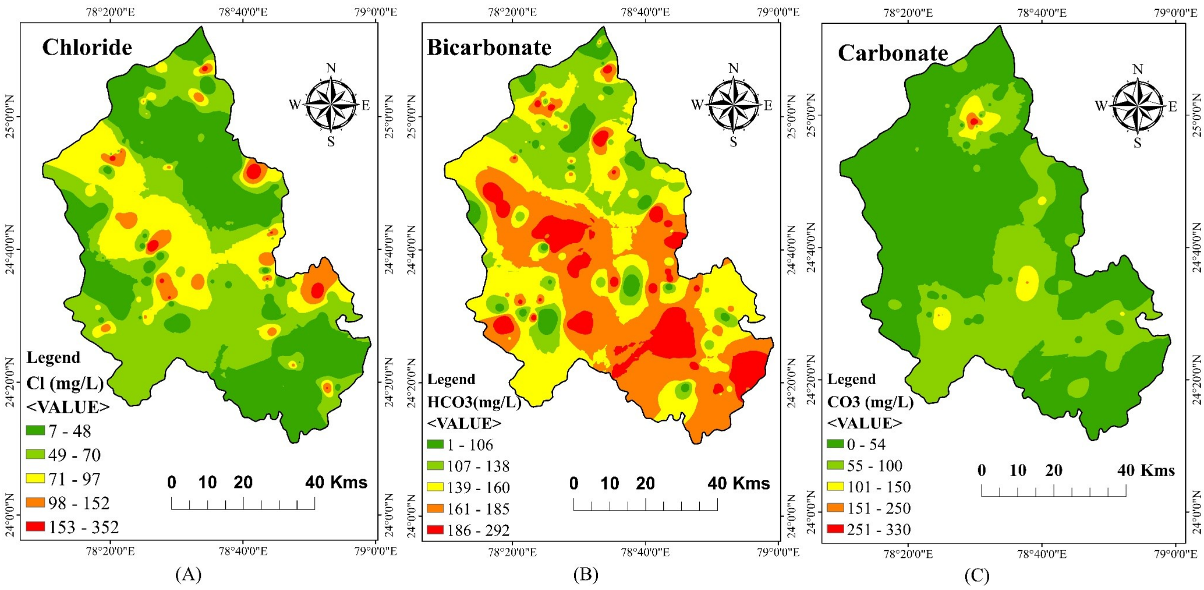

Figure 4. Spatial distribution map of the anions: (**A**) Chloride, (**B**) Bicarbonate and (**C**) Carbonates in the study area.

Nitrate concentrations in the study area were mostly found to be under safe drinking standards, less than 45 mg/L. Although at few regions in the study area, unsuitable concentrations of nitrate levels were observed, mainly in the northern region (Figure 5D). The maximum concentration of nitrate was found to be 51 mg/L. The source of the nitrate is mostly found to be coming from agricultural practices. Fluoride source in groundwater can be both geogenic and anthropogenic. Concentrations of fluoride in the study area ranges from 0 to 2.08 mg/L (Figure 5E). The northern region of the study area mostly showing elevated values, although most of the groundwater samples showed a suitable drinking concentration for fluoride. Fluoride is a lithophile element that has affinities towards rock-forming minerals (amphibole and biotite) [24]. Geogenic processes determine concentrations of sulphate in the groundwater of the study area. Maximum SO_4^{2-} concentration was 137 mg/L, with a mean value of 27.25 mg/L.

4.4. Geohydrological Parameters and Preparation of Groundwater Potential Map (GWP)

Geological study on Lalitpur district point out three distinct variety of rock formations [25–28]. The Vindhyan, Bijawar and Deccan volcanics rocks are mostly present in the southern part of Lalitpur, while central and northern parts of study area is occupied by Archean to Neoarchean crystalline rocks known as Bundelkhand Gneissic Complex (BnGC) (Figure 6A). About 80% of the total area of Lalitpur district comprises the rocks of BnGC, which includes pink granite, grey granite, quartz reefs, and granite-gneissic complex [29]. The Vindhyan sedimentary rocks deposited as sedimentary cover on the craton consist 18% of the area and are mostly quartzite, sandstone, limestone and shale. 2% of the region is covered by the volcanic cover of the Deccan Trap. Three giant crustal-scale structural features, NE-SW, NW-SE, and N-S trending giant shears. The NE-SW trending quartz reefs and NW-SE trending mafic dykes and swarms are present in the study area and affect the groundwater quality and quantity. Lalitpur district has a dendritic drainage pattern, with the region falling in high drainage density, suggesting impermeable terrain with high runoff, which leads to high concentrations of solutes in the groundwater resources (Figure 6C). Regions with high vegetation and less built-up area led to both good water potential and good water quality zones (Figure 7G). High lineament density creates better rock-water interaction regions (Figure 7F). Groundwater potential zone delineation is an important study for groundwater resource assessment [30].

Using GIS and AHP technique, Weightage were given to 7 thematic layers, such as geology (20%), geomorphology (30%), lineament density (11%), drainage density (6%), slope (7%), rainfall (17%) and LULC (9%) based upon their importance in the study area for the preparation of groundwater potential map (Figure 8). Groundwater potential is mostly very good to good in the southern region due to the occurrences of Vindhyan rocks (Table 1). Moving towards the northern part of the study area, the GWP is decreasing because of the occurrences of massive granite-type hard rock that makes it difficult for water to percolate beneath the surface and recharge the groundwater. The TDS and water contamination values are mostly low in the high GWP areas, whereas higher TDS in the low potential zones. In other words, good groundwater potential areas represent less contamination and vice versa. Regions located in the northern and the central region of the study area, due to hard rock terrain, low lineament density, high drainage density and low rainfall, make it a region of low recharge. Low recharge zones lead lessen the dilution, more so in the hard rock terrain, which is found in the study area. Hence, leads to an increase in the concentration of the contamination, which is shown in the WAWQI map.

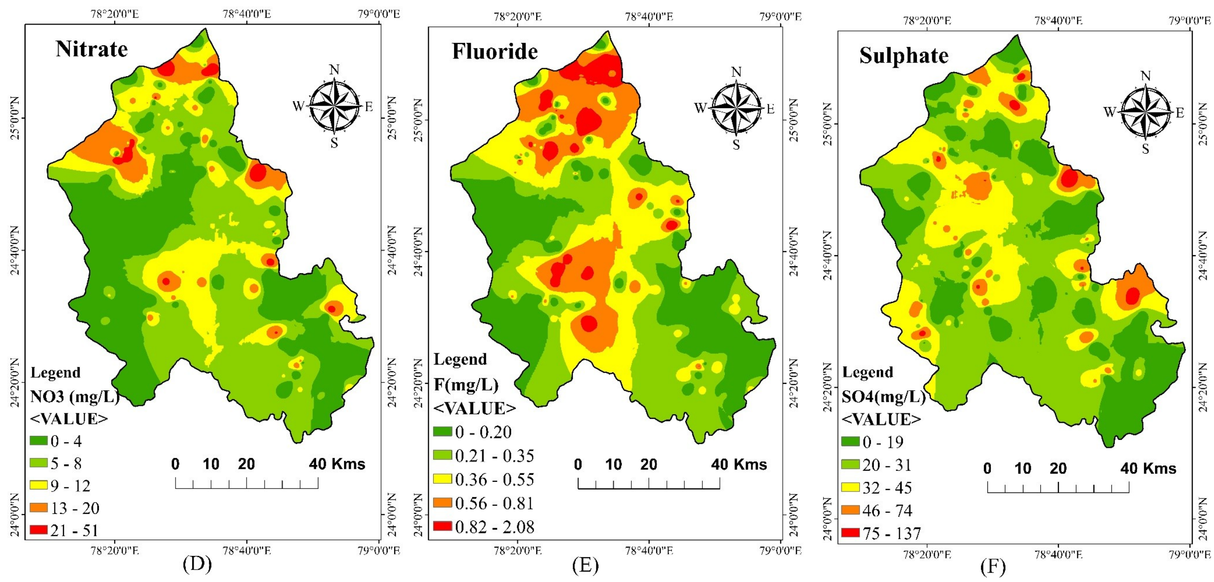

Figure 5. Continuation Figure 4: **(D)** Nitrate, **(E)** Fluoride, and **(F)** Sulphate.

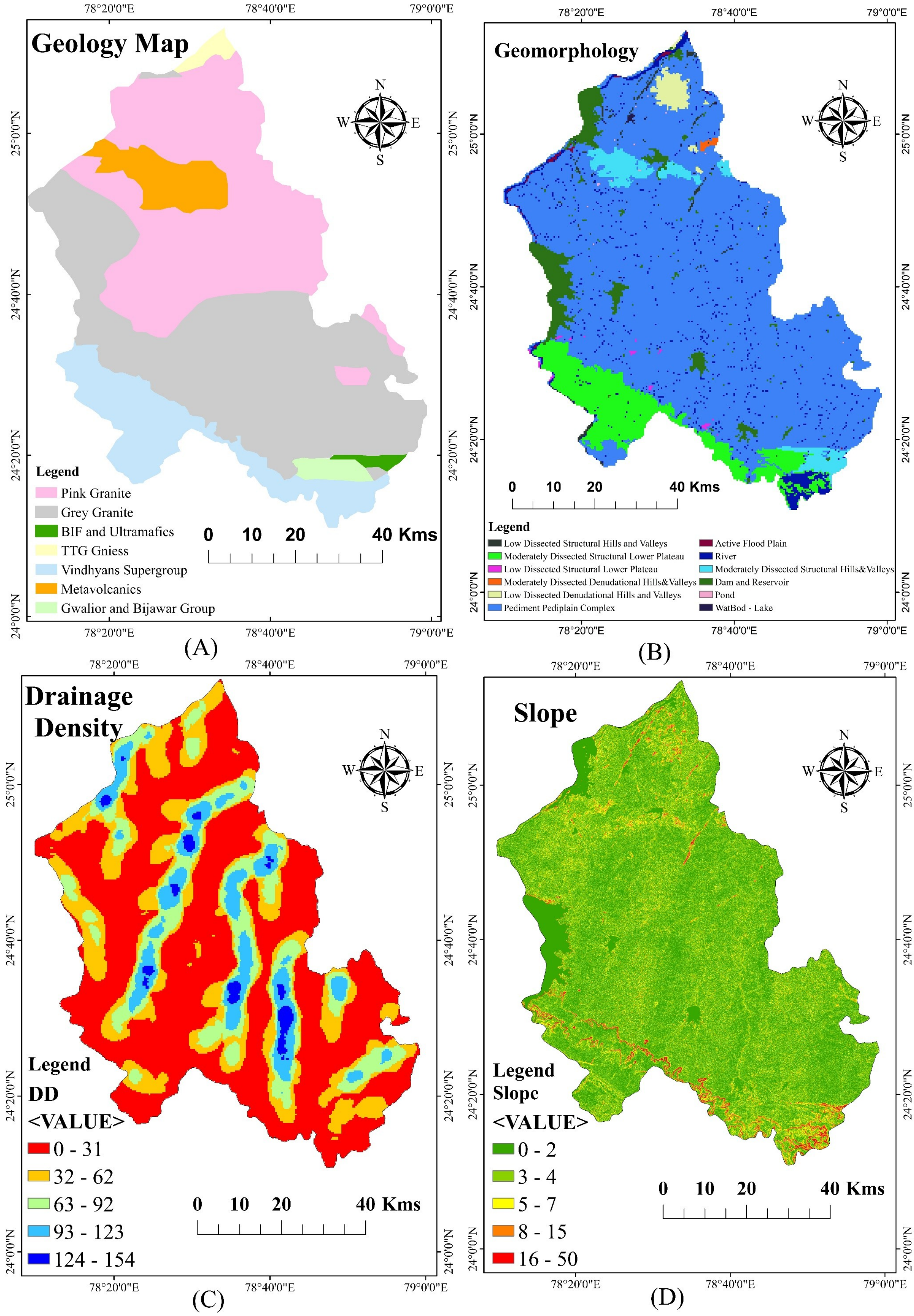

Figure 6. Thematic maps of the parameters used for groundwater potential zone delineation: (**A**) Geology; (After [31]) (**B**) Geomorphology, (**C**) Drainage Density (km/km^2), and (**D**) Slope.

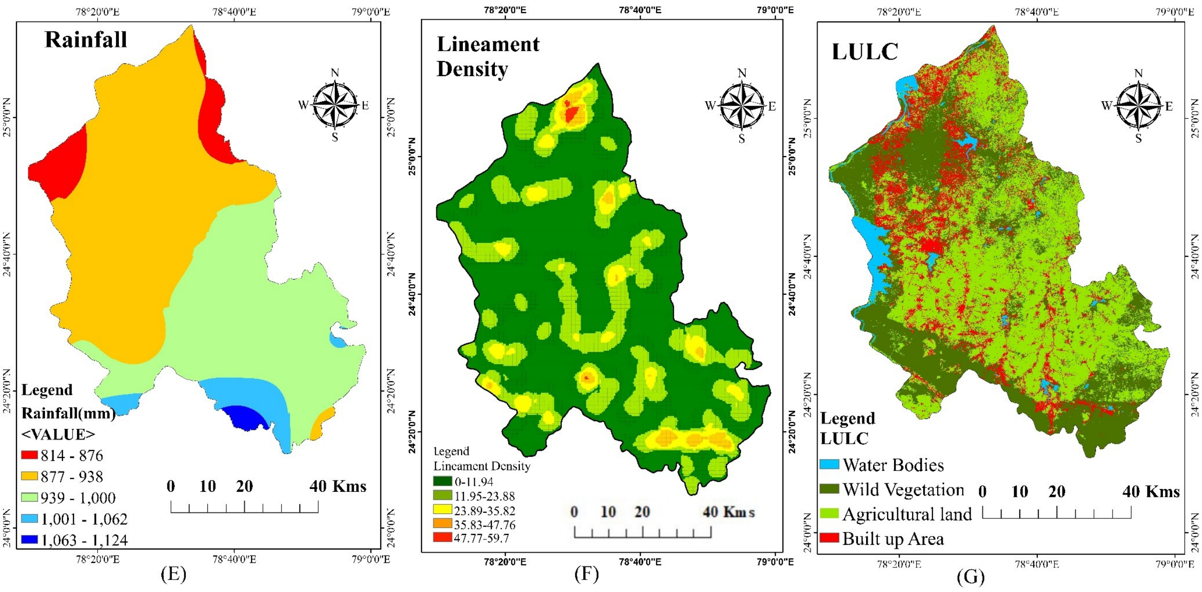

Figure 7. Continuation of Figure 5: (**E**) Rainfall, (**F**) Lineament density and, (**G**) Land use land cover.

Table 1. CGWB stations and their groundwater level depth data (mbgl) in the study area.

Station	Coordinates	Average Groundwater Level Depth (mbgl) Based on CGWB Observatory Wells	Validation Status
Amjhara ghati	24.37° N, 78.40° E	1.48	Validated
Lalitpur	24.67° N, 78.40° E	1.62	Validated
Talbehat New	25.05° N, 78.43° E	1.67	Validated
Bansi	24.87° N, 78.47° E	2.84	Validated
Jakhlaun	24.55° N, 78.32° E	3.02	Validated
Bar	24.86° N, 78.59° E	4.99	Validated
Talbehat-III	25.05° N, 78.47° E	4.37	Validated
Betna	24.48° N, 78.52° E	6.63	Partial
Silawan	24.57° N, 78.62° E	7.53	Validated
Hisar Kalan	25.07° N, 78.57° E	6.61	Validated
Digwar	24.36° N, 78.62° E	3.92	Validated

4.5. Preparation of Groundwater Quality Index Map

4.5.1. Calculation of Weighted Arithmetic WQI

The Water Quality Index (WQI) was calculated using the Weighted Arithmetic Water Quality Index (WAWQI) method. Key parameters analysed included pH, Total Dissolved Solids (TDS), Electrical Conductivity (EC), Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, Cl^{-}, SO_4^{2-}, F^{-}, and NO_3^{-}. The parameter values were compared against drinking water standards set by Bureau of Indian Standards and World Health Organisation (WHO) (Table 2). Each parameter was assigned a weight based on its significance in assessing water quality within the study region (Table 3). The relative weights for each parameter were calculated using Equation (1). The resulting WQI values were then classified into five categories: Very Good (5–50), Good (51–60), Moderate (61–70), Poor (71–90), and Very Poor (91–141).

$$\text{Relative weight (RW)} = \frac{AW}{\sum_{i=1}^{n} AW} \tag{1}$$

Here, AW represents the assigned weight.

$$\text{Quality Rating (Qi)} = \text{MP/SV} \tag{2}$$

(MP = Measured parameter; SV = Standard value)

$$\text{Sub-Indices (SI)} = Qi \times RW \tag{3}$$

$$WQI = \sum_{i=1}^{n} SI \tag{4}$$

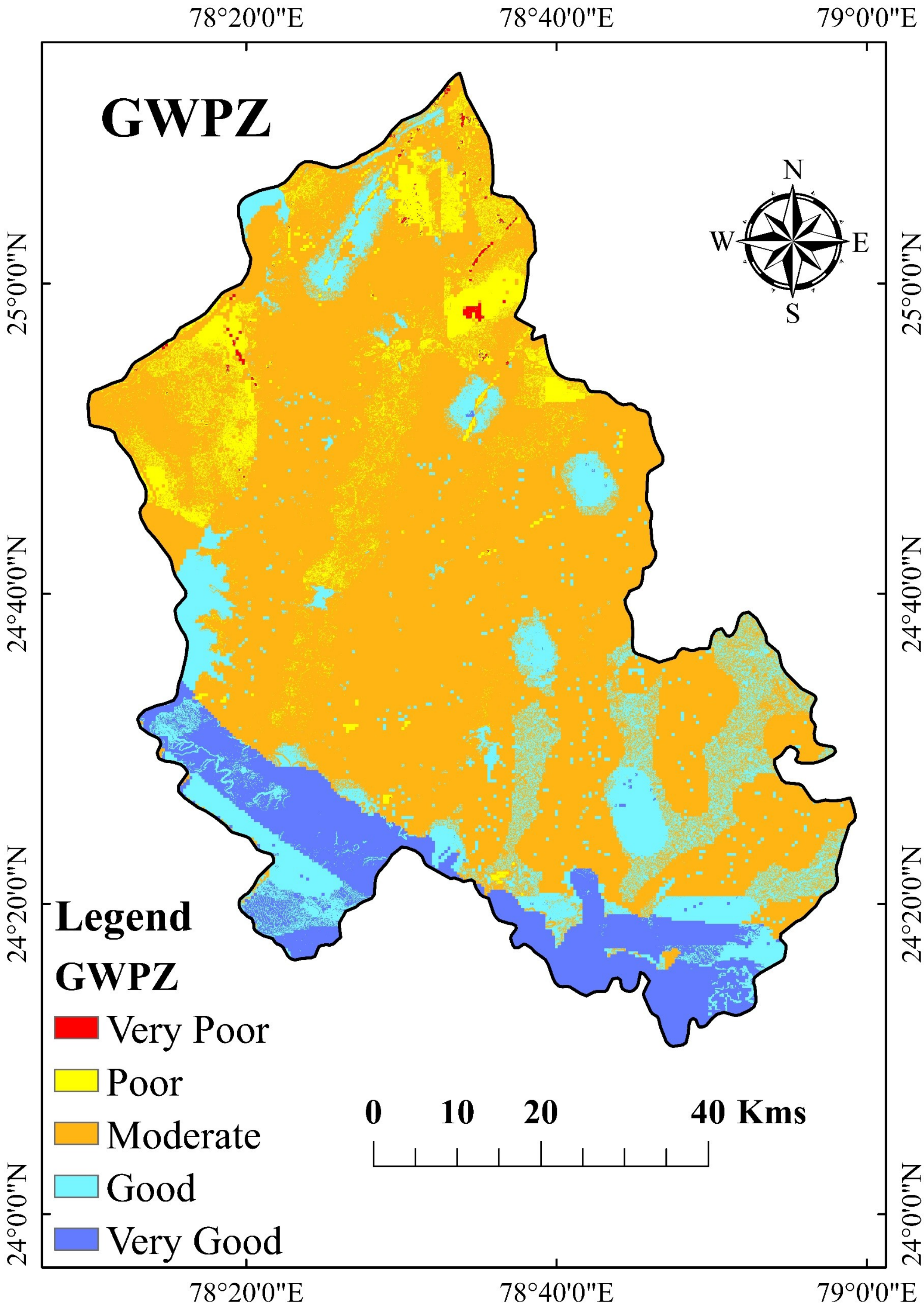

Figure 8. Groundwater potential map along with delineated zones in the study area.

Table 2. Statistical values of the physiochemical parameters obtained after the analysis and tabulation and compared to the drinking suitability standards.

Parameters	Minimum Value (mg/L)	Average Value (mg/L)	Maximum Value (mg/L)	BIS Standards (2012) (mg/L)	WHO Standards (2009) (mg/L)
pH	7.39	8.02	8.72	6.5–8.5	6.5–9.2
TDS	200	432.60	1260	300	500
EC (µS/cm)	410	854.93	2530	750	750
Ca^{2+}	9.7	85.42	255.7	75	100
Na^{+}	0.4	41.17	188.2	–	200
Mg^{2+}	4.99	26.55	87	30	150
K^{+}	0	2.28	50.2	–	200
Cl^{-}	7.09	57.32	354.53	250	250
SO_4^{2-}	0	27.25	137	250	200
F^{-}	0.15	0.72	2.10	1.0	0.5
NO_3^{-}	0	4.90	54.56	45	50

Table 3. Assigning weightage to the parameters for WAWQI calculations.

Parameters	Standards	Assigned Weight	Relative Weights
pH	8.5 *	9	0.1364
TDS	500 **	11	0.1667
EC	750 *	10	0.1515
Na^{+}	200 **	4	0.0606
K^{+}	200 **	3	0.0455
Ca^{2+}	75 *	8	0.1212
Mg^{2+}	30 *	7	0.1061
SO_4^{2-}	250 *	2	0.0303
F^{-}	1.5 *	1	0.152
Cl^{-}	250	6	0.0909
NO_3^{-}	45 *	5	0.0758

* denotes to BIS drinking standards and ** denotes WHO drinking standards.

5. Results and Discussion

5.1. Integration of Geospatial Data & Preparation of GWQI

To calculate the GWQI, values of pH, TDS, Ca^{2+}, Mg^{2+}, Cl^{-}, HCO_3^{-}, CO_3^{2-}, F^{-}, SO_4^{2-}, NO_3^{2-} and Groundwater Potential Zones (GWPZ) were taken into consideration because they are more influential in comparison to other physiochemical parameters, which were analysed regarding the hydrochemistry of groundwater in the study area. Other parameters, such as Na^{+} and K^{+}, were not considered for the AHP analysis as they were mostly found in safe drinking concentrations and showed very little variation in the study area. The groundwater characterisation suggests that the study area is characterised by Ca–Mg–HCO_3 water type facies conditions.

5.2. MCDM Technique and Analytical Hierarchical Process (AHP)

AHP is a mathematical multi-criterion decision-making technique is proposed by Thomas Saaty in 1970 at the Wharton High School of the University of Pennsylvania. AHP helps in assigning values representing the preference given to the given alternatives against other alternatives [32]. To carry out the Analytical Hierarchy Process, a multi-criteria decision-making technique, eleven thematic layers—pH, TDS, Ca^{2+}, Mg^{2+}, Cl^{-}, HCO_3^{-}, CO_3^{2-}, F^{-}, SO_4^{2-}, NO_3^{-}, and GWPZ were processed to delineate groundwater quality zones in the study area.

5.3. Pairwise Comparison Matrix Development

The Analytical Hierarchy Process was carried out to assign weightage to the eleven layers using the Multi-Criteria Decision-Making method (MCDM). Thematic layers for pH, TDS, Ca^{2+}, Mg^{2+}, Cl^{-}, HCO_3^{-}, CO_3^{2-}, F^{-}, SO_4^{2-}, NO_3^{-} and GWP were generated. The Groundwater samples for physiochemical parameters were analysed in Groundwater Analytical Research Centre, Bundelkhand University, Jhansi. Parameters found in high concentrations are considered for this study. The water potential mapping was done using several thematic layers using GIS and the AHP method.

5.4. Weight Assignment Rationale

To carry out the Analytical Hierarchy Process, a multi-criteria decision-making technique was used, where 11 thematic layers, such as pH, TDS, Ca^{2+}, Mg^{2+}, Cl^-, HCO_3^-, CO_3^{2-}, F^-, SO_4^{2-}, NO_3^- and Groundwater Potential, were prepared. The groundwater potential layer comprising 7 layers (Table 4) is a spatial integration for MCDM in the AHP-GIS. They were given weightage based on their impact on groundwater potential. Saaty's scale (1–9) (9 extremely important, 8 very strong importance, 7 extremely important, 6 strong importance, 5 strong importance, 4 moderate importance plus, 3 moderate, 2 weak, 1 equal importance) is used according to the relative importance of the factors. A pairwise comparison matrix was prepared for all 11 parameters, as shown in Table 5. To check consistency, the Consistency Index (CI) and Consistency Ratio (CR) were calculated using Equations (5) and (6) and values assigned in Table 6.

Consistency Analysis Consistency Index

$$CI = \frac{\lambda max - n}{n-1} \tag{5}$$

(n is the number of parameters used)

$$\begin{aligned} CI &= \frac{11.753 - 11}{11-1} \\ CI &= 0.075 \\ CR &= \frac{CI}{RCI} \end{aligned} \tag{6}$$

(Here, RCI is the Random consistency index)

CR $= 0.050$

According to Saaty, a consistency ratio less than 0.1 is suitable for further analysis.

Table 4. Comparison matrix for the GWQI.

	GWP	TDS	pH	HCO_3^-	Cl^-	CO_3^{2-}	Ca^{2+}	Mg^{2+}	NO_3^-	SO_4^{2-}	F^-
GWP	1	2	3	4	5	9	7	8	6	9	9
TDS	1/2	1	2	3	4	8	6	7	5	9	9
pH	1/3	1/2	1	2	3	7	5	6	4	8	9
HCO_3^-	1/4	1/3	1/2	1	2	6	4	5	3	7	8
Cl^-	1/5	1/4	1/3	1/2	1	5	3	4	2	6	7
CO_3^{2-}	1/9	1/8	1/7	1/6	1/5	1	1/3	1/2	1/4	2	3
Ca^{2+}	1/7	1/6	1/5	1/4	1/3	3	1	2	1/2	4	5
Mg^{2+}	1/8	1/7	1/6	1/5	1/4	2	1/2	1	1/3	3	4
NO_3^-	1/6	1/5	1/4	1/3	1/2	1/2	2	3	1	5	6
SO_4^{2-}	1/9	1/9	1/8	1/7	1/6	1/2	1/4	1/3	1/5	1	2
F^-	1/9	1/9	1/9	1/8	1/7	1/3	1/5	1/4	1/6	1/2	1

Table 5. Normalised comparison matrix and final weightage.

	GWP	TDS	pH	HCO_3^-	Cl^-	CO_3^{2-}	Ca^{2+}	Mg^{2+}	NO_3^-	SO_4^{2-}	F^-	Wt (%)
GWP	0.3277	0.4049	0.3832	0.3414	0.3013	0.2673	0.2390	0.2157	0.1964	0.1651	0.1429	28
TDS	0.1639	0.2024	0.2555	0.2560	0.2411	0.2227	0.2049	0.1888	0.1745	0.1651	0.1429	21
pH	0.1092	0.1012	0.1277	0.1707	0.1808	0.1782	0.1707	0.1618	0.1527	0.1468	0.1429	15
HCO_3^-	0.0819	0.0675	0.0639	0.0853	0.1205	0.1336	0.1366	0.1348	0.1309	0.1284	0.1270	11
Cl^-	0.0655	0.0506	0.0426	0.0427	0.0603	0.0891	0.1024	0.1079	0.1091	0.1101	0.1111	8
CO_3^{2-}	0.0364	0.0253	0.0182	0.0142	0.0121	0.0218	0.0114	0.0135	0.0111	0.0367	0.0476	2
Ca^{2+}	0.0468	0.0337	0.0255	0.0213	0.0201	0.0223	0.0341	0.0539	0.0655	0.0734	0.0794	4
Mg^{2+}	0.0410	0.0289	0.0213	0.0171	0.0151	0.0148	0.0171	0.0270	0.0436	0.0550	0.0635	3
NO_3^-	0.0546	0.0405	0.0319	0.0284	0.0301	0.0873	0.0683	0.0809	0.0445	0.0917	0.0952	6
SO_4^{2-}	0.0364	0.0225	0.0160	0.0122	0.0100	0.0089	0.0085	0.0090	0.0109	0.0183	0.0317	1
F^-	0.0364	0.0225	0.0142	0.0107	0.0086	0.0074	0.0068	0.0067	0.0073	0.0092	0.0159	1

Table 6. RCI values (33).

Matrix Order (*n*)	**RCI Value**
1	0.00
2	0.00
3	0.58
4	0.90
5	1.12
6	1.24
7	1.32
8	1.41
9	1.45
10	1.49
11	1.51

Furthermore, the groundwater quality categories were categorised into Very Good, Good, Moderate, Poor, and Unsuitable. The water quality was calculated using Equation (7). Weightage and ratings were given to the parameters on the ArcGIS.

$$\text{WQI} = \sum_{i=1}^{n} p * W_i \tag{7}$$

Here, p is the parameter, W_i is the weightage given to each parameter.

5.5. GIS-Based Weighted Overlay Analysis

All 8 rasterised thematic layers underwent weightage overlay on the ArcGIS platform, where the concentration of each parameter was categorised into five sections based on their effect on groundwater quality in the study area. Based upon that, they were given a ranking on a scale of 1–9.

5.6. Spatial Distribution Analysis GWQI

All 11 thematic layers (pH, TDS, Ca^{2+}, Mg^{2+}, Cl^-, $HCO_3{}^-$, $CO_3{}^{2-}$, F^-, $SO_4{}^{2-}$, $NO_3{}^-$ and GWPZ) were processed using AHP, and respective weightage was assigned based upon their importance to the groundwater quality. Finally, the GWQI map was generated (Figure 10B). The resulting GWQI map reveals that central and southern Lalitpur, as well as parts of the Bar block, fall into 'unsuitable' to 'moderate' zones. The northern regions mostly show 'Good' to 'Very Good' quality, some localised hotspots of degradation persist. Integrating geospatial data in the preparation of the GWQI offers several advantages over relying solely on arithmetically calculated WQI values.

Groundwater potential and groundwater quality are not always directly related; however, in some specific circumstances and associated studies, it was found that a region with poor groundwater quality is found in regions with poor groundwater potential zones. The groundwater quality and quantity both depend upon the aquifer mineralogy, topography and anthropogenic activities. Geohydrological factors often control the quality of the groundwater. In hard rock terrains, such as those in the study area, high lineament density, favourable geomorphology, and dilution of dissolved ions result in better water quality. In the study area, both groundwater potential and groundwater quality are closely related. The study fills the research gap of limited works done in the Bundelkhand region of India for the interdependency of both the quality and quantity of groundwater at the disposal for the population.

5.7. Validation

To validate the study results, several random samples with known physiochemical parameter values from the Water Quality Index (WQI) assessment were selected. The WQI status based on the arithmetic method, the GWQI status derived from the AHP approach, and the corresponding water potential zones were evaluated for each sample. For instance, sample ID L019 exhibited a TDS value of 1080 mg/L, along with high concentrations of chloride (Cl^-), nitrate ($NO_3{}^-$), and calcium (Ca^{2+}) levels, making it unsuitable for drinking according to standard guidelines Table 3. Similarly, water quality index for samples L0349a, L0187, and L027 based on physiochemical data were classified in the "Very Poor" category (WQI Arithmetic method) and were classified as "Unsuitable" GWQI (integration geospatial AHP method) and were located in the Moderate to Poor water potential zone, Table 7.

Conversely, samples such as L065, L0769, L0568, and L05601 results estimation of "Good" WQI (Arithmetic method) and Very Good (GWQI), which are in Moderate to Very Good water potential zones. These observations demonstrate strong agreement between the estimated WQI, GWQI data, and the sample locations under the respective GWPZ. The correlation between WAWQI and GWQI and the water potential zones is in good agreement in Table 8. The findings suggest that higher groundwater potential improves the dilution of dissolved salts in groundwater, a trend clearly observed in this study.

Table 7. Categories and Classification of parameters (in mg/L).

Parameters	Very Good	Good	Moderate	Poor	Unsuitable
Water Potential	Very High	High	Moderate	Low	Very Low
pH	7.8–8.2 & 8.21–8.6,	7.4–7.8	7.0–7.4 & 8.6–8.7	–	–
TDS	200–255	256–505	506–755	756–1004	1005–1254
Magnesium	0.04–20.39	20.4–27.5	27.51–34.6	34.61–45.58	45.59–82.4
Calcium	10.65–63.07	63.08–86.47	86.48–103.3	103.4–132.3	132.4–249.4
Bicarbonate	1.36–106.38	106.39–138.34	138.35–160.03	160.04–185.14	185.15–292.44
Carbonate	0.02–54	55–100	101–150	151–250	251–330
Chloride	7.31–47.91	47.92–69.56	69.57–96.63	96.64–152.12	152.13–352.42
Nitrate	0–4 & 5–8	9–12	13–20	21–51	–
Sulphate	0–19 & 20–31	32–45 & 46–74	75–137	–	–
Fluoride	0–0.2 & 0.21–0.35	0.36–0.55	0.56–0.81	0.82–2.08	–

Table 8. Status of WAWQI, GWQI and Water Potential at different known sample sites.

Sample Site (Known)	Coordinates	TDS (mg/l)	F^- (mg/l)	NO_3^- (mg/l)	HCO_3 (mg/l)	Ca (mg/l)	Mg (mg/l)	Cl (mg/l)	Arthematically Calculated WAWQI	GWQI (AHP)	Water Potential
1. L019	25.1213 78.57	1080	0.15	51	244	208.7	4.72	198.54	Very poor	Unsuitable	Very Poor
2. L065	25.026 78.5364	390	0.7	14	122	67.2	21.54	38.29	Good	Good	Moderate
3. L0568	24.4804 78.4799	470	0.6	7	195.2	77.8	21.75	42.54	Moderate	Moderate	Moderate
4. L0349a	24.6759 78.4359	1260	0.08	30	268.4	250.06	67.06	14.18	Very poor	Unsuitable	Poor
5. L0769	24.3065 78.885	300	0.3	7	146.4	81.9	20.78	21.27	Good	Very Good	Very Good
6. L27	24.7097 78.7372	850	0.17	16.5	203.4	255.7	34.78	208.46	Very Poor	Unsuitable	Moderate
7. L0187	24.8608 78.6924	1150	0.5	36	146.4	194.1	75.61	246.75	Very Poor	Unsuitable	Poor
8. L17	24.886 78.5578	310	0.02	6	146.7	98.4	14.17	24.11	Very Good	Very Good	Good
9. L0216	24.8107 78.2817	590	0	25	231.8	137.5	26.13	73.74	Poor	Unsuitable	Poor
10. L0561	24.4871 78.3115	250	0.14	6	244	43.3	9.6	36.87	Very Good	Very Good	Very Good

5.8. Relationship between WAWQI and GWQI in Study Area

The hydrochemical facies of groundwater in Lalitpur district indicate that the majority of samples belong to the Ca–Mg–HCO_3 water type in the Piper diagram (Figure 9). The geohydrological setting of Lalitpur is characterized by hard rock-dominated terrain with low infiltration rates, moderate to high surface runoff, and high-rate evaporation. Groundwater potential mapping reveals that 67.69% of the area falls under moderate potential, while 23.08% is classified as good potential zones. Total dissolved solids (TDS) range from 200 to 1225 mg/L (moderate to high), accompanied by elevated chloride concentrations (up to 342 mg/L). Physicochemical parameters exhibit significant spatial variation (Table 7), suggesting that geological factors strongly influenced groundwater quality. Regions dominated by the rocks of the Bijawar Group metasedimentary and Vindhyan sandstones, active floodplains, and areas with moderate to high structural hills and valleys facilitate greater infiltration, leading to notable variations in GWQI values.

The Weighted Arithmetic Water Quality Index (WAWQI) and Geospatial Water Quality Index (GWQI) classify the study area into five quality categories in Table 9. The variation distribution patterns of WAWQI and GWQI are displayed in Figure 10, which represent different shapes and sizes. The WAWQI percentile distributions reveal that 11.41% of the area is classified as Very Good, 43.40% as Good, 32.41% as Moderate, 11.54% as Poor, and 1.22% as Very Poor categories. In contrast, GWQI percentile distributions results indicate 5.01% Very Good, 38.39% Good, 38.55% Moderate, 17.12% Poor, and 0.91% Very Poor. Discrepancies between WAWQI and GWQI percentile distributions are primarily due to the integration of hydrogeological layers (land use, geology, rainfall, and soil) within a GIS-based Analytical Hierarchy Process (AHP) framework. Similar findings have been reported in other regions [18, 19, 33]. It is suggested that GIS-integrated models demonstrate greater sensitivity to local variations, including lithology, recharge zones, and anthropogenic influences [34].

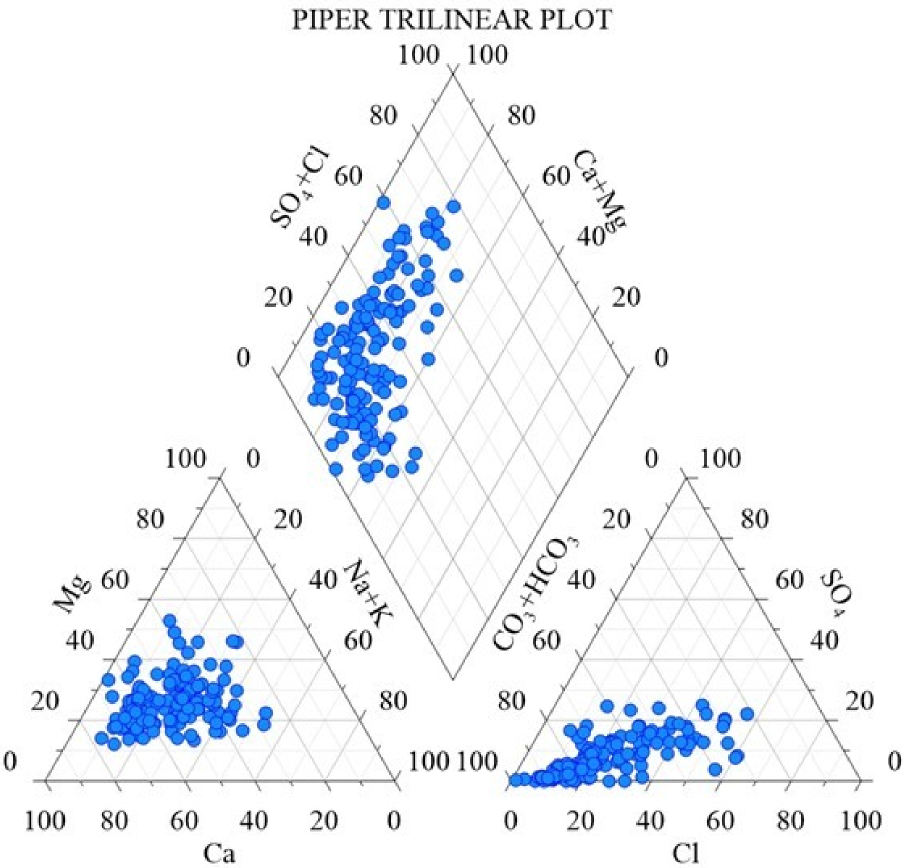

Figure 9. Piper trilinear plot representing the hydrochemical facies in the groundwater of the study area.

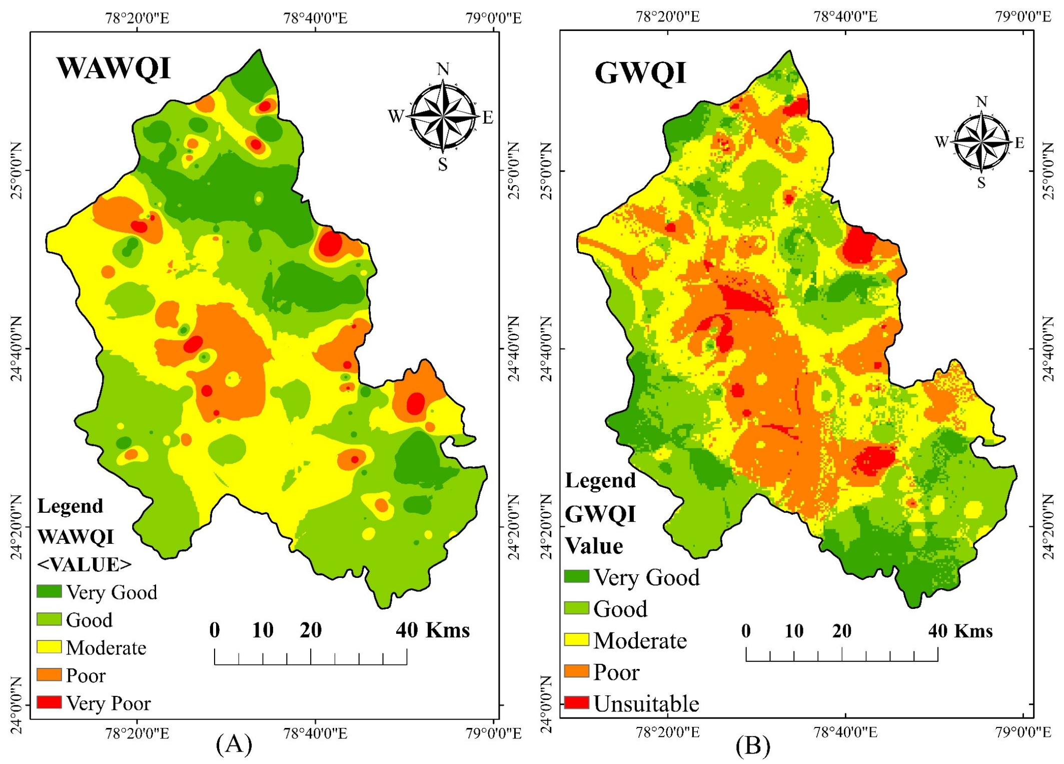

Figure 10. Thematic map of the (**A**) Weighted Aritmetical Water Quality Index (WAWQI) and (**B**) Geospatial Water Quality Index (GWQI) of the study area.

Table 9. Percentile distribution of WAWQI and GWQI with the Physiochemical and Geohydrological characteristics.

WAWQI Distribution Area (%)	GWQI Distribution Area (%)	Physiochemical Characters	Geohydrological Characters
Very-poor (1.22%)	Very poor/Unsuitable (0.91%)	Unsuitable TDS high (>1000), chloride high (>200), carbonate and bicarbonate high	Pink granite, grey granite, high Built-up area with low agriculture and vegetation, less fractures, low infiltration rate, poor to very poor groundwater potential areas
Poor (11.54%)	Poor (17.12%)	Unsuitable TDS high (>600), chloride high (>150), carbonate and bicarbonate high	Massive pink granites, steep slopes, low lineament density, and low dissected structural hills and valleys, poor groundwater potential
Moderate (32.41%)	Moderate (38.55%)	pH is near to 7.5 Moderate TDS high (450–500), chloride low (>100), calcium moderate (100) moderate carbonate and bicarbonate moderate	Pediments and pediplain complex, hard rock terrain of pink granite, high drainage density, moderate structural hills and valleys, moderate water potential category
Good (43.40%)	Good (38.39%)	TDS low (<400), chloride high (<60), low carbonate and bicarbonate	Active flood plain, high-moderate-high structural hills and valleys, low runoff, leading to good water potential
Very Good (11.41%)	Very Good (5.01%)	low TDS (<300) chloride low (<50), carbonate and bicarbonate very low	Alluvial deposits, gentle slopes, high lineament density, good rainfall, rocks mostly fractured, ultramafics, Vindhyan sedimentary and Bijawar metasedimentary, excellent water potential

Integrating geospatial data into GWQI preparation offers significant advantages over relying solely on arithmetically derived WAWQI values. These improvements arise from the influence of geomorphology, lithology, drainage patterns, slope gradients, land use/land cover (LULC), and groundwater potential zones (GWPZ) are documented in Figure 10. It is also noted that the GWQI pattern has good agreement with GWPZ (Table 9). Multicriteria-based GWQI effectively reveals spatial clusters and gradations in groundwater quality that are obscured in purely arithmetic assessments.

Some recent research has highlighted an interdependent relationship between groundwater quality and potential across various regions [9, 35]; (however, high potential does not inherently guarantee a good groundwater quality index (GWQI). The findings of the present study from Lalitpur demonstrate that groundwater potential zones (GWPZ) align closely with GWQI. Notably, groundwater potential represents the availability and yield of the resource, whereas groundwater quality pertains to its chemical suitability for drinking, irrigation, and other purposes. High groundwater potential areas are typically characterised by favourable geo-hydrological parameters such as high recharge rates, significant porosity, and substantial aquifer thickness [10, 15], which facilitate the dilution of dissolved ions [13, 18]. Conversely, low potential zones are commonly characterised by limited recharge and slow water movement factors that enhance water–rock interaction, salinisation, and the concentration of dissolved ions.

Thus, GWQI displayed in Figure 10 and Table 9 provides a more detailed and realistic representation of groundwater quality, indicating that certain areas, especially in the good and moderate category water potential zone of Lalitpur, exhibit comparatively better performances than WAWQI. The Madawara area lies in the excellent/very good category for GWQI rather than the good category displayed by WAQWI. The ground report favours GWQI. These observations highlight the superiority of geospatial integration in evaluating groundwater suitability, and integration has produced a precise, reliable, and representative groundwater quality index. Thus, geospatial integration in WQI development delivers a comprehensive, visually intuitive, and actionable assessment of regional water quality in Lalitpur district.

6. Limitation and Scope

The current integration study can provide holistic and multi-dimensional results related to the sustainable groundwater qualitative and quantitative resource management, which will be crucial for resource planning in Bundelkhand-type rocky terrain. Areas around Lalitpur town, Maharauni, Jakhaura, and Birdha experienced deteriorating groundwater quality and poor GWPZ. To protect the deteriorating groundwater quality in these areas, immediate steps related to enhancing the GWPZ must be taken for the suitability and sustainability of groundwater resources. However, this approach may have limitations in heavy metal industries or mining areas where a variety of toxic metals, such as chromium, lead, iron, arsenic, mercury, etc., are mixed in the groundwater of thick aquifers. The present study area is mostly composed of hard rock terrain and is completely devoid of heavy chemical industries, metal mining, or heavy population stress. These are highly influential factors in groundwater contamination. To enhance this research work, an assessment of the Heavy Metal Index (HMI) and Health risk assessment must also be carried out in future work.

7. Conclusions

- The water quality assessment was conducted by separately analysing physicochemical and geohydrological parameters, followed by a multicriteria integration to estimate the Groundwater Quality Index (GWQI) for Lalitpur district.
- The Very Poor to Poor category for GWQI is characterised by high TDS (1000–600 mg/L), Cl^- (200–150 mg/L) and high HCO_3^-/CO_3^{2-} concentrations. These regions are dominated by hard rock terrain comprising pink and grey granites, low lineament density, and extensive built-up areas with very low to low agricultural land. Such conditions result in poor groundwater recharge and prolonged water–rock interaction.
- Moderate zones, with pH near 7.5, TDS (450–500 mg/L), low chloride ($<$100 mg/L), and moderate calcium/carbonates, align with pediments and pediplain complexes in hard-rock pink granitic terrains, supported by moderate drainage and structural features.
- Very Good to Good zones show low TDS (400–300 mg/L), chloride ($<$60 mg/L), and CO_3^{2-} concentrations in the groundwater. The terrain has active flood plains with high-moderate structural hills/valleys and low runoff, fostering good water potential through enhanced recharge, aided by good rainfall.
- The findings indicate a sympathetic relationship between groundwater potential and groundwater quality, wherein high-recharge zones promote contaminant dilution. This is evidenced by the spatial alignment of better GWQI classes with favourable geohydrological conditions.
- Geospatial integration in WQI development provides a comprehensive and actionable assessment of regional water quality in the Lalitpur district. GWQI is more effectively captures the complexity of hydrogeological systems than isolated arithmetic calculations, making it essential for sustainable groundwater management, contamination risk assessment, and long-term planning.

Author Contribution

U.B.: Conceptualization; Investigation; Methodology; Writing—original draft. S.P.S.: Visualisation; Validation; Supervision; Writing—review and editing.

Funding

This work was funded by a project from the Department of Science and Technology, Govt. of India.

Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

The data used for the research are available from the authors upon request.

Acknowledgement

S.P.S. gratefully acknowledges the financial support provided by the Department of Science and Technology (DST), New Delhi, under the research project NRDMS/01/201-Ext/2016 (G). An appreciation is extended to local communities and government officials who facilitated field work and data collection. We are sincerely thankful to E. Shaji for his valuable suggestions to improve our manuscript and to Rubal Singh for his valuable help in fieldwork and the lab.

Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Use of AI and AI-Assisted Technologies

No AI and AI-assisted technologies were used in the research work.

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