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GIS-Based Mapping of Groundwater Contamination in Lucknow District, Uttar Pradesh

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Abstract: *Groundwater is an essential source of drinking water in urban regions; however, rapid urbanization, industrial growth, and anthropogenic activities have significantly deteriorated groundwater quality in many Indian cities, including Lucknow. The present study aims to evaluate the spatial variability of groundwater quality in Lucknow district using Geographic Information System (GIS)-based techniques and Water Quality Index (WQI) approaches. Major physicochemical parameters including pH, electrical conductivity (EC), total hardness, calcium (Ca^{2+}), magnesium (Mg^{2+}), chloride (Cl^{-}), fluoride (F^{-}), nitrate (NO_3^{-}), and sulphate (SO_4^{2-}) were analyzed for groundwater quality assessment.*

Spatial interpolation of groundwater parameters was performed using the Inverse Distance Weighting (IDW) method in GIS to generate thematic distribution maps and identify contamination hotspots. Two groundwater quality assessment approaches, namely Arithmetic Water Quality Index (AWQI) and Weighted Water Quality Index (WWQI), were applied to evaluate overall groundwater suitability for drinking purposes. The results revealed significant spatial variability in groundwater quality across Lucknow district. Elevated concentrations of hardness, EC, nitrate, chloride, and sulphate were observed in several urbanized and densely populated regions, indicating strong anthropogenic influence on groundwater systems.

The AWQI and WWQI hotspot maps indicated that eastern and southeastern parts of Lucknow district exhibited comparatively poor groundwater quality, while northern and western regions showed relatively better water quality conditions. Comparative analysis demonstrated that WWQI provided a more realistic and reliable assessment because parameter-specific weighting improved sensitivity toward critical contaminants. GIS-based hotspot mapping successfully delineated vulnerable groundwater zones and highlighted areas requiring immediate monitoring and management intervention.

The study demonstrates that integration of GIS and WQI techniques is highly effective for groundwater quality assessment, contamination hotspot identification, and sustainable groundwater resource management. The findings of this study can support policymakers and environmental planners in developing targeted groundwater protection and remediation strategies for rapidly urbanizing regions..

Keywords: Groundwater Quality, Water Quality Index (WQI), Arithmetic Water Quality Index (AWQI), Weighted Water Quality Index (WWQI), Geographic Information System (GIS), Spatial Interpolation, IDW Technique, Groundwater Contamination, Hotspot Analysis, Lucknow District

I. INTRODUCTION

Groundwater is one of the most important and reliable freshwater resources used for drinking, irrigation, domestic, and industrial purposes throughout the world. In developing countries such as India, rapid urbanization, industrialization, population growth, and agricultural intensification have significantly increased pressure on groundwater systems, leading to continuous deterioration in groundwater quality. Urban groundwater contamination has become a major environmental

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concern because pollutants from sewage discharge, industrial effluents, agricultural runoff, and landfill leachates gradually infiltrate aquifers and alter groundwater chemistry (Todd and Mays, 2005).

In rapidly expanding urban regions such as Lucknow, groundwater serves as a primary source of potable water for a large population. However, increasing anthropogenic activities and unplanned urban development have resulted in elevated concentrations of physicochemical contaminants including nitrate (NO_3^-), chloride (Cl^-), fluoride (F^-), sulphate (SO_4^{2-}), hardness, and dissolved solids. High concentrations of these parameters negatively affect groundwater suitability for drinking and may create severe public health risks (Kumar et al., 2016). Groundwater contamination is often difficult to detect visually because subsurface pollution occurs gradually and remains hidden for long periods, making it a silent environmental threat (Subba Rao, 2017).

Traditionally, groundwater quality assessment is performed by analyzing individual physicochemical parameters separately. However, interpretation becomes complex when multiple hydrochemical variables collectively influence water quality. To simplify this process, Water Quality Index (WQI) techniques are widely used to convert large hydrochemical datasets into a single numerical value representing the overall groundwater quality condition (Brown et al., 1972). WQI methods provide an efficient approach for categorizing groundwater into different quality classes such as excellent, good, poor, and unsuitable for drinking purposes.

Among the various WQI approaches, the Arithmetic Water Quality Index (AWQI) and Weighted Water Quality Index (WWQI) methods are commonly applied in groundwater quality studies. The AWQI method generally assigns equal importance to all parameters, whereas the WWQI method incorporates relative parameter weights according to drinking water standards and health significance. Consequently, WWQI provides comparatively more realistic and scientifically reliable groundwater quality assessment because critical contaminants receive greater influence during index computation (Ramakrishnaiah et al., 2009).

Recent advancements in Geographic Information System (GIS) technology have significantly improved groundwater quality assessment and spatial hotspot identification. GIS enables integration, visualization, and analysis of spatial hydrochemical datasets, thereby facilitating better understanding of groundwater contamination patterns. Spatial interpolation techniques such as Inverse Distance Weighting (IDW) are widely used to transform discrete groundwater observations into continuous spatial distribution maps (Magesh et al., 2011). These GIS-based approaches help identify contamination hotspots, vulnerable zones, and regional groundwater quality trends.

Several researchers have successfully integrated GIS and WQI approaches for groundwater quality assessment in different regions of India and abroad. Magesh et al. (2011) demonstrated that GIS-based groundwater quality mapping effectively identifies areas affected by high salinity and hardness. Panneerselvam et al. (2020) reported that hydrogeochemical processes and anthropogenic activities strongly influence groundwater quality in urban environments. Similarly, Verma et al. (2021) observed elevated groundwater contamination in urban regions due to sewage infiltration and rapid land-use change.

In the present study, groundwater quality in Lucknow district was evaluated using both AWQI and WWQI approaches based on major physicochemical parameters including pH, hardness, calcium (Ca^{2+}), magnesium (Mg^{2+}), chloride (Cl^-), fluoride (F^-), nitrate (NO_3^-), and sulphate (SO_4^{2-}). GIS-based IDW interpolation was employed to generate spatial hotspot maps and identify vulnerable regions affected by groundwater contamination. Comparative evaluation of AWQI and WWQI provides insight into groundwater quality variability and the effectiveness of different WQI methods for sustainable groundwater management and environmental planning.

II. METHODOLOGY

Groundwater quality assessment for Lucknow district was carried out using hydrochemical analysis, Water Quality Index (WQI) techniques, and Geographic Information System (GIS)-based spatial mapping. The overall methodology adopted in the study is presented below.

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1. Data Collection

Groundwater quality data were collected from different sampling locations across Lucknow district. The dataset included geographical coordinates (latitude and longitude) and major physicochemical parameters such as pH, electrical conductivity (EC), total hardness, calcium (Ca^{2+}), magnesium (Mg^{2+}), chloride (Cl^{-}), fluoride (F^{-}), nitrate (NO_3^{-}), and sulphate (SO_4^{2-}). The collected data were organized in spreadsheet format for further analysis.

2. Data Preprocessing

The collected groundwater dataset was cleaned and preprocessed before analysis. Missing values, duplicate records, and non-numeric entries were removed to ensure data accuracy and consistency. All hydrochemical parameters were converted into uniform numerical formats suitable for GIS and statistical analysis.

3. GIS Database Preparation

A spatial database was developed using Geographic Information System (GIS) techniques. The latitude and longitude coordinates of groundwater sampling locations were converted into spatial point layers. Administrative boundary data for Lucknow district were obtained in GeoJSON format and integrated into the GIS environment for spatial analysis and mapping.

4. Spatial Interpolation using IDW

Inverse Distance Weighting (IDW) interpolation was applied to generate continuous spatial distribution maps of groundwater quality parameters. IDW estimates unknown values based on nearby sampling points and assumes that closer points have greater influence than distant points (Magesh et al., 2011). The interpolation process transformed discrete groundwater observations into continuous spatial surfaces for identifying contamination patterns and hotspot regions.

5. Water Quality Index (WQI) Calculation

Two groundwater quality assessment methods were used in this study:

5.1 Arithmetic Water Quality Index (AWQI)

The Arithmetic Water Quality Index method calculates groundwater quality by considering equal importance for all parameters. Quality rating values were computed using drinking water standards, and the overall AWQI was obtained through arithmetic averaging of parameter quality indices.

5.2 Weighted Water Quality Index (WWQI)

The Weighted Water Quality Index method assigns relative weights to groundwater parameters according to their significance and permissible drinking water standards. Parameters with greater health impacts were given higher weights, resulting in a more realistic representation of groundwater quality conditions.

6. WQI Classification

The computed WQI values were classified into different groundwater quality categories such as Excellent, Good, Poor, Very Poor, and Unsuitable for drinking purposes. Standard WQI classification ranges were used for interpretation and comparison of groundwater quality conditions.

7. Hotspot Analysis and Mapping

Spatial distribution maps of AWQI and WWQI were generated using GIS-based IDW interpolation. The thematic maps helped identify groundwater contamination hotspots and vulnerable zones across Lucknow district. Areas showing elevated WQI values were considered contamination-prone regions influenced by urbanization, sewage infiltration, and anthropogenic activities.

8. Comparative Analysis

A comparative analysis between AWQI and WWQI was performed to evaluate the sensitivity and effectiveness of both methods in groundwater quality assessment. Differences in hotspot identification and groundwater quality classification were analyzed to determine the most suitable approach for groundwater monitoring and sustainable management.

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III. RESULTS AND DISCUSSION

1. Spatial Distribution of Groundwater Parameters

The spatial distribution maps generated using GIS-based IDW interpolation revealed significant spatial variability in groundwater quality across Lucknow district. The hydrochemical parameters showed noticeable differences between urbanized central regions and peripheral areas, indicating the influence of both geogenic and anthropogenic factors on groundwater chemistry.

The pH values ranged between slightly alkaline conditions, indicating bicarbonate buffering and mineral dissolution processes. Electrical conductivity (EC) showed comparatively higher concentrations in central and southeastern regions, suggesting elevated dissolved ionic content and possible influence of urban wastewater infiltration. Total hardness values were observed to be relatively high in several urbanized zones, indicating the dominance of calcium and magnesium ions in groundwater.

Calcium (Ca^{2+}) and magnesium (Mg^{2+}) concentrations showed moderate spatial variation across the study area and contributed significantly to groundwater hardness. Chloride (Cl^{-}) concentrations were comparatively higher in densely populated regions, which may be associated with domestic sewage intrusion and anthropogenic contamination. Fluoride (F^{-}) concentrations were generally within permissible limits, although localized elevations were observed in some areas due to geological influence.

Nitrate (NO_3^{-}) exhibited strong spatial variability and showed higher concentrations in agricultural and urbanized regions, indicating contamination from fertilizer application and sewage leakage. Sulphate (SO_4^{2-}) distribution also showed moderate variation and reflected both natural mineral dissolution and anthropogenic influence.

Overall, the spatial distribution maps clearly demonstrated that groundwater quality deterioration is more pronounced in urban and densely populated regions of Lucknow district.

Table 3.1 Spatial Characteristics of Groundwater Parameters

Parameter	Spatial Observation	Possible Source
pH	Slightly alkaline throughout district	Mineral dissolution
EC	Higher in central & southeastern regions	Urban wastewater infiltration
Hardness	Elevated in urban zones	Ca–Mg rich groundwater
Ca^{2+}	Moderate variation	Carbonate dissolution
Mg^{2+}	Higher in urban regions	Geological influence
Cl^{-}	Elevated in densely populated areas	Sewage contamination
F^{-}	Mostly within permissible limits	Geogenic source
NO_3^{-}	High in agricultural & urban areas	Fertilizers & sewage
SO_4^{2-}	Moderate variation	Natural + anthropogenic

2. Block-wise Variation Analysis

Block-wise variation graphs indicated noticeable differences in groundwater quality among different blocks of Lucknow district. Certain blocks such as Chinhat, Sarojini Nagar, and Mohanlalganj exhibited comparatively higher concentrations of hardness, nitrate, chloride, and EC, suggesting greater anthropogenic influence and groundwater contamination. In contrast, peripheral blocks such as Kakori and Mal showed relatively lower concentrations of most parameters, indicating comparatively better groundwater quality conditions.

The variation observed among different blocks highlights the localized nature of groundwater contamination and emphasizes the importance of regional groundwater monitoring instead of relying only on district-level averages.

Table 3.2 Block-wise Groundwater Quality Status

Block	Groundwater Condition	Major Concern
Chinhat	Poor	High nitrate & EC
Sarojini Nagar	Poor	Hardness & chloride
Mohanlalganj	Moderate to poor	Urban contamination
Kakori	Relatively good	Low contamination
Mal	Good	Lower anthropogenic impact

3. Comparison of Interpolation Methods

The comparative analysis of interpolation techniques revealed significant differences in spatial prediction and surface smoothness. IDW interpolation produced comparatively smooth and realistic spatial patterns while preserving local variability around sampling points. Linear interpolation generated simpler spatial surfaces but failed to capture localized variation effectively. Cubic interpolation produced highly smooth surfaces but introduced unrealistic oscillations and exaggerated spatial gradients in some regions.

Among all methods, IDW was found to be the most suitable interpolation technique for groundwater quality mapping in the present study because it balanced smoothness and local variability effectively.

Table 3.3 Comparison of Interpolation Methods

Method	Characteristics	Limitation
IDW	Smooth & realistic patterns	Depends on sampling density
Linear	Simple interpolation	Poor local variation representation
Cubic	Highly smooth surface	Unrealistic oscillations

4. AWQI and WWQI Analysis

The Arithmetic Water Quality Index (AWQI) and Weighted Water Quality Index (WWQI) methods were applied to evaluate overall groundwater suitability for drinking purposes. The computed AWQI and WWQI values indicated that groundwater quality in Lucknow district ranges from good to poor categories depending on the sampling location.

The comparative results showed that AWQI values fluctuated more significantly because equal importance was assigned to all groundwater parameters. In contrast, WWQI produced comparatively balanced and realistic groundwater quality assessment because parameter-specific weights were incorporated based on drinking water standards and health significance.

For example, some sampling locations showed AWQI values exceeding 100, indicating poor groundwater quality, whereas WWQI values for the same locations remained within the good category. This demonstrates that WWQI

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moderates the influence of less critical parameters and provides a more reliable assessment of groundwater quality conditions.

Table 3.4 AWQI and WWQI Comparison

Sample	AWQI	WWQI	Water Quality Status
1	67.66	57.30	Good
2	115.84	57.05	Poor (AWQI), Good (WWQI)
3	46.91	56.40	Excellent–Good
4	66.05	72.62	Good
5	58.97	68.78	Good

5. Hotspot Identification

The GIS-based hotspot maps generated from AWQI and WWQI clearly identified contamination-prone regions within Lucknow district. The eastern and southeastern regions exhibited relatively higher WQI values, indicating deteriorated groundwater quality conditions. These hotspot zones corresponded with areas showing elevated concentrations of nitrate, hardness, chloride, and EC.

The identified hotspots are likely influenced by rapid urbanization, sewage infiltration, agricultural runoff, and excessive groundwater extraction. Peripheral regions showed comparatively lower WQI values, indicating better groundwater quality and lower anthropogenic stress.

The hotspot analysis demonstrates the effectiveness of integrating GIS and WQI techniques for identifying vulnerable groundwater regions and supporting targeted groundwater management strategies.

Table 3.5 Groundwater Contamination Hotspots

Region	Dominant Contaminants	Possible Cause
Eastern Lucknow	NO_3^-, EC	Agricultural runoff
Southeastern Lucknow	Hardness, Cl^-	Sewage infiltration
Central urban region	EC, hardness	Urbanization & wastewater
Peripheral regions	Low contamination	Lower human impact

6. Overall Interpretation

The results indicate that groundwater quality in Lucknow district is controlled by both hydrogeochemical processes and anthropogenic activities. Urban expansion, wastewater infiltration, agricultural intensification, and population pressure are major contributors to groundwater quality deterioration in several regions of the district.

The integration of GIS-based spatial interpolation and WQI approaches proved highly effective for groundwater quality assessment, hotspot identification, and visualization of contamination patterns. Comparative analysis further demonstrated that WWQI provides comparatively more realistic and reliable groundwater quality evaluation than AWQI because of its weighted parameter approach.

The findings of this study provide a scientific basis for groundwater monitoring, contamination control, and sustainable groundwater resource management in rapidly urbanizing regions.

IV. CONCLUSION

The present study evaluated groundwater quality in Lucknow district using GIS-based spatial analysis and Water Quality Index (WQI) approaches. Spatial distribution maps generated through IDW interpolation revealed significant variability in groundwater quality across the study area, indicating the influence of both geogenic processes and anthropogenic activities on groundwater chemistry.

The hydrochemical analysis showed that parameters such as electrical conductivity (EC), hardness, nitrate (NO_3^-), chloride (Cl^-), and sulphate (SO_4^{2-}) exhibited elevated concentrations in several urbanized and densely populated regions. Higher contamination levels were primarily observed in the eastern and southeastern parts of Lucknow district, suggesting strong influence of sewage infiltration, urban runoff, agricultural activities, and rapid urbanization.

The comparative evaluation of Arithmetic Water Quality Index (AWQI) and Weighted Water Quality Index (WWQI) demonstrated noticeable differences in groundwater quality assessment. AWQI showed greater fluctuation because all parameters were treated equally, whereas WWQI provided comparatively more stable and realistic groundwater quality representation due to parameter-specific weighting. The results indicated that WWQI is more suitable for identifying contamination hotspots and evaluating groundwater suitability for drinking purposes.

GIS-based hotspot analysis successfully identified vulnerable groundwater zones requiring immediate monitoring and management intervention. The integration of GIS and WQI approaches proved highly effective for groundwater quality visualization, spatial interpretation, and contamination hotspot delineation.

Overall, the study highlights that groundwater quality in Lucknow district is under increasing environmental stress and requires sustainable management strategies. Regular groundwater monitoring, proper sewage management, controlled agricultural practices, and scientific groundwater planning are essential to protect groundwater resources and ensure safe drinking water availability for future generations.

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