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Seasonal Variability of Groundwater Quality Using Entropy Weighted Water Quality Index (EWQI) in Uttar Pradesh, India

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Abstract. Groundwater serves as a major source of freshwater for domestic consumption, irrigation, and industrial utilization in India, especially in highly populated regions such as Uttar Pradesh. In recent decades, groundwater quality has been increasingly threatened by rapid urban growth, intensive agricultural activities, industrial discharge, and natural hydrogeochemical interactions. Moreover, seasonal changes associated with monsoon rainfall significantly affect groundwater composition and contaminant distribution. In this context, the present study evaluates seasonal variations in groundwater quality using the Entropy Weighted Water Quality Index (EWQI) and hydrogeochemical interpretation techniques. Groundwater quality data for premonsoon and postmonsoon periods were collected from the Central Ground Water Board (CGWB), Uttar Pradesh. To maintain the accuracy and reliability of the dataset, quality assessment was performed using the Ion Balance Error (IBE) method. EWQI was calculated independently for both seasons to determine the suitability of groundwater for drinking purposes. The analysis revealed noticeable seasonal fluctuations in important physicochemical parameters such as Electrical Conductivity (EC), Total Dissolved Solids (TDS), Total Hardness (TH), nitrate, and fluoride. Higher concentrations of dissolved constituents were generally observed during the premonsoon season due to limited recharge and increased evaporation, whereas postmonsoon groundwater exhibited comparatively improved quality because of rainfall-induced dilution and aquifer recharge. Seasonal groundwater quality was evaluated using EWQI classification and hydrogeochemical analysis. The results indicated substantial seasonal variation in groundwater quality across the study area. The outcomes of the study indicate that the integration of EWQI and hydrogeochemical analysis provides an effective framework for groundwater quality assessment under varying seasonal conditions.The developed methodology can assist policymakers and water resource authorities in groundwater monitoring, pollution assessment, and sustainable groundwater management practices.

Keywords: Groundwater quality; Seasonal variability; Entropy Weighted Water Quality Index (EWQI); Hydrogeochemistry; Groundwater assessment; Uttar Pradesh.

I. Introduction

Groundwater is a critical natural resource that supports domestic, agricultural, and industrial water demands across the world. In India, groundwater contributes significantly to drinking water supply and irrigation, particularly in densely populated states such as

Uttar Pradesh. The increasing population, rapid urbanization, industrialization, and excessive agricultural activities have resulted in significant deterioration of groundwater quality over the past few decades. Contamination by dissolved solids, fluoride, nitrate, and other hydrochemical constituents has emerged as a major environmental and public health concern.

Groundwater quality is strongly influenced by hydrogeological conditions, climatic variations, geological formations, and anthropogenic activities. Seasonal fluctuations associated with monsoon rainfall significantly alter groundwater chemistry through dilution, recharge, leaching, and water–rock interaction processes. During the premonsoon season, groundwater generally exhibits higher concentrations of dissolved ions due to evaporation and limited recharge conditions. In contrast, postmonsoon groundwater quality may improve because of dilution caused by rainfall recharge, although agricultural runoff and surface contamination may increase the concentration of certain pollutants.

Assessment of groundwater quality traditionally relies on laboratory analysis of multiple physicochemical parameters. However, interpretation of large datasets containing numerous hydrochemical variables can be difficult. To simplify groundwater quality assessment, Water Quality Index (WQI) methods are widely used. Among these approaches, the Entropy Weighted Water Quality Index (EWQI) is considered more objective because it assigns parameter weights based on information entropy rather than subjective judgment.

The major objectives of the study are:

- To analyze seasonal variability in groundwater quality between premonsoon and postmonsoon seasons.
- To compute Entropy Weighted Water Quality Index (EWQI) for both seasons.
- To identify seasonal changes in groundwater suitability for drinking purposes.

The proposed framework provides a reliable and scalable approach for seasonal groundwater quality assessment and hydrogeochemical interpretation under varying climatic conditions.

II. Materials and Methods

Study Area

The present study was conducted in Uttar Pradesh, India, which is located in the northern part of the country between 23°52′–30°24′ N latitude and 77°03′–84°39′ E longitude. Uttar Pradesh covers an area of approximately 243,286 km² and is one of the most populous states in India. The climate of the region is predominantly subtropical, characterized by hot summers, cool winters, and monsoon rainfall.The average annual rainfall in the state ranges between 800 mm and 1000 mm, with nearly 85–90% of rainfall occurring during the southwest monsoon season from June to September. The hydrogeology of the state is largely dominated by Indo-Gangetic alluvial plains composed of sand, silt, clay, and gravel deposits. In the southern Bundelkhand region, hard rock formations such as granite, gneiss, sandstone, and basalt are present.The study area is shown in Fig. 1.

Groundwater is the primary source of drinking and irrigation water in Uttar Pradesh. However, rapid urbanization, agricultural intensification, industrial development, and excessive groundwater extraction have significantly affected groundwater quality across several districts.

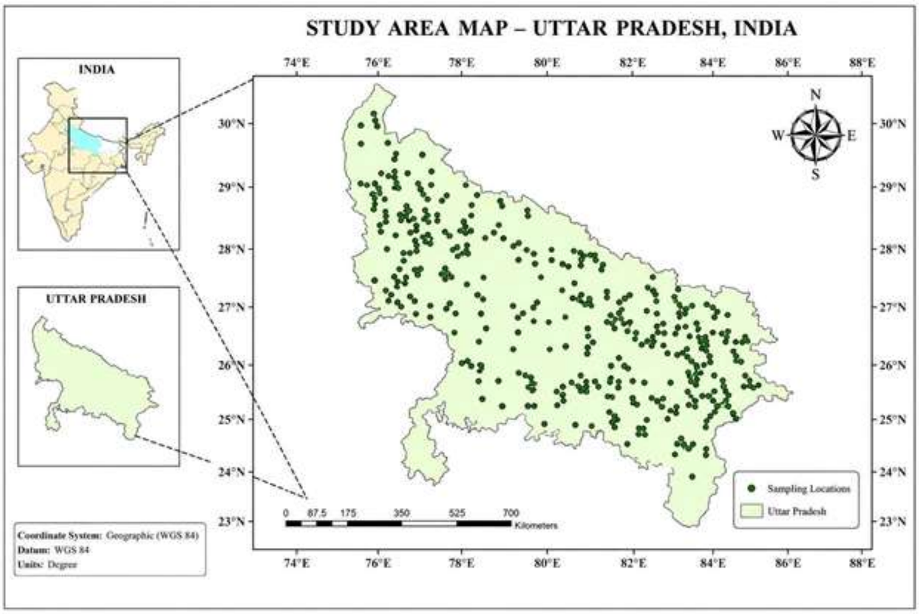

Fig.1. Study Area Map -Uttar Pradesh, India

Data Collection

Groundwater quality data for premonsoon and postmonsoon seasons were collected from the Central Ground Water Board (CGWB), Northern Region, Lucknow. The datasets consisted of groundwater samples collected from observation wells distributed across different hydrogeological regions of Uttar Pradesh.

The analyzed physicochemical parameters included: pH, Electrical Conductivity (EC), Total Dissolved Solids (TDS), Total Hardness (TH), Calcium (Ca^{2+}), Magnesium (Mg^{2+}),Sodium (Na^{+}), Potassium (K^{+}), Bicarbonate (HCO_3^{-}), Chloride (Cl^{-}), Sulfate (SO_4^{2-}), Fluoride (F^{-}), Nitrate (NO_3^{-}). Standard analytical procedures recommended by APHA were followed for groundwater quality analysis.

Entropy Weighted Water Quality Index (EWQI)

The Entropy Weighted Water Quality Index (EWQI) was computed separately for premonsoon and postmonsoon datasets to evaluate groundwater suitability for drinking purposes.

The EWQI methodology involves the following steps:

- Data normalization
- Entropy value calculation
- Entropy weight computation
- Quality rating calculation

The methodological framework is illustrated in Fig. 2.

EWQI Range	Rating of Groundwater Quality	Usage Possibilities	Grading
0 – 25	Excellent water quality	Drinking, irrigation, and industrial purposes	A
25 – 50	Good water quality	Suitable for drinking and domestic purposes	B
50 – 100	Medium water quality	Suitable for irrigation and limited domestic use	C
100 – 150	Poor water quality	Treatment required before drinking use	D
> 150	Unsuitable for drinking purposes	Restricted use; proper treatment required before use	E

Table 1. Classification of groundwater quality based on Entropy Weighted Water Quality Index (EWQI).Source: Modified after Kumar et al. (2021) and Wang et al. (2020).

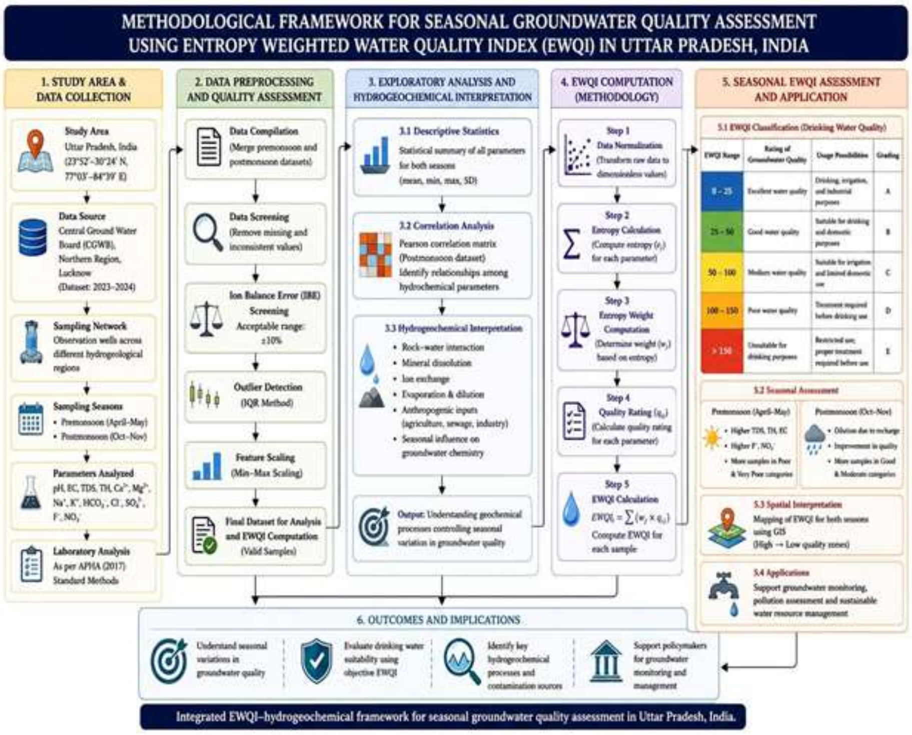

Fig.2. Flowchart of the methodological framework adopted for seasonal groundwater quality assessment using EWQI.

III. Results and Discussion

Seasonal Variability of Groundwater Quality
The statistical analysis revealed considerable seasonal variation in groundwater quality parameters between premonsoon and postmonsoon seasons.

During the premonsoon season, groundwater generally exhibited higher concentrations of dissolved constituents such as TDS, EC, TH, nitrate, and fluoride. The increase in concentration may be attributed to high evaporation rates, low groundwater recharge, and prolonged water–rock interaction.

In contrast, postmonsoon groundwater showed relatively lower concentrations of dissolved ions due to dilution caused by rainfall recharge. However, certain regions exhibited elevated nitrate concentrations after monsoon due to agricultural runoff and infiltration of contaminants.

The seasonal variability demonstrates the strong influence of climatic and hydro geochemical factors on groundwater quality.

Correlation Analysis
Correlation analysis of the postmonsoon dataset revealed significant relationships among various groundwater quality parameters, indicating the influence of hydrogeochemical processes and anthropogenic activities on groundwater chemistry. Strong positive correlations were observed between EC and TDS, suggesting that dissolved ionic constituents are the primary contributors to groundwater salinity during the postmonsoon season. Similarly, Total Hardness (TH) showed strong association with calcium and magnesium concentrations, reflecting the dissolution of carbonate and silicate minerals within the aquifer system.

Moderate to strong positive correlations were also observed among sodium, chloride, sulfate, and bicarbonate ions, indicating the combined effects of mineral weathering, ion exchange processes, agricultural runoff, and anthropogenic contamination sources. The correlation between nitrate and other dissolved constituents suggests possible contamination from fertilizer application, sewage infiltration, and surface runoff during the monsoon period.

Compared to the premonsoon season, slightly lower correlation strengths were observed for certain parameters in the postmonsoon dataset, which may be attributed to rainfall-induced dilution and recharge effects. Monsoonal recharge alters groundwater chemistry by introducing fresh water into the aquifer system, thereby reducing the concentration of dissolved ions in several regions.

The correlation heatmap further demonstrated that EWQI exhibited strong positive relationships with TDS, TH, EC, bicarbonate, and sulfate, indicating that these parameters play a major role in controlling groundwater quality deterioration during the postmonsoon period. The analysis also helped identify the most influential hydrochemical variables controlling groundwater quality deterioration.

Overall, the correlation analysis highlights the seasonal influence of hydrogeochemical processes, monsoonal recharge, and anthropogenic activities on groundwater quality variability across Uttar Pradesh. The correlation matrix is presented in Fig. 3

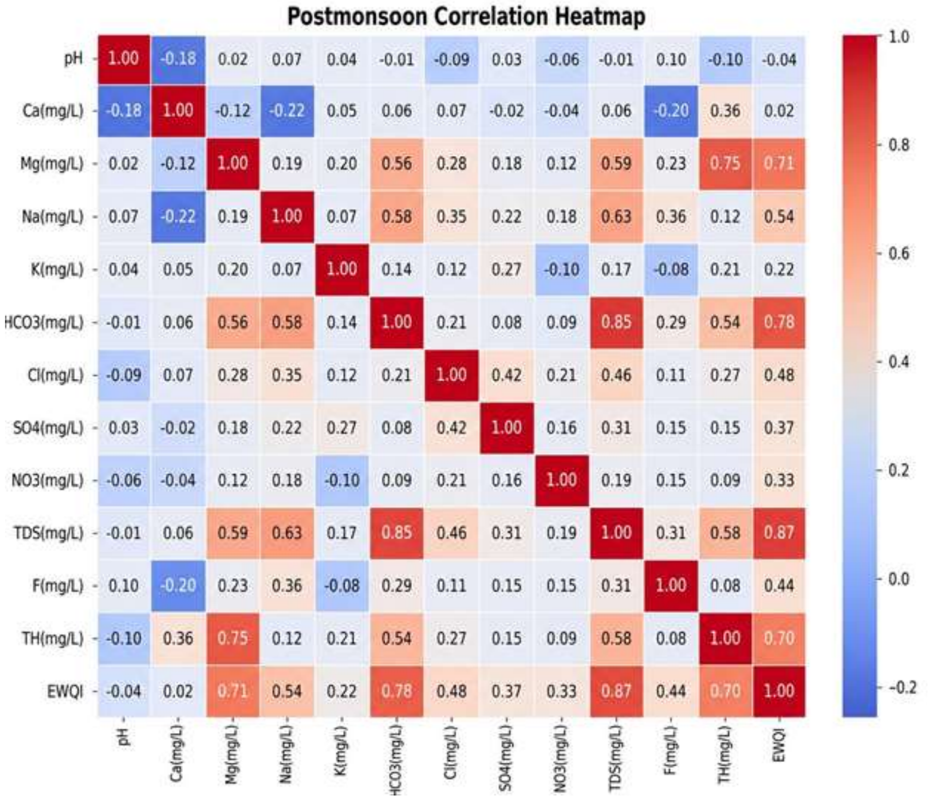

Fig.3. Correlation heat map of postmonsoon season

Hydrogeochemical Interpretation

Hydrogeochemical interpretation was carried out to understand the geochemical processes controlling groundwater chemistry and seasonal variations across Uttar Pradesh. The groundwater quality of the study area is influenced by a combination of natural hydrogeochemical processes and anthropogenic activities, including mineral weathering, ion exchange, agricultural runoff, sewage infiltration, and groundwater recharge conditions.

The dominance of major cations and anions indicates that groundwater chemistry is primarily governed by rock–water interaction processes. Calcium (Ca^{2+}), magnesium (Mg^{2+}), and bicarbonate (HCO_3^-) ions were found to dominate in several groundwater samples, indicating the prevalence of Ca–Mg–HCO_3 hydrochemical facies. This facies type is generally associated with carbonate mineral dissolution and natural groundwater recharge processes within alluvial aquifers.

In certain regions, elevated concentrations of sodium (Na^+) and chloride (Cl^-) were observed, particularly during the premonsoon season. The occurrence of Na–Cl type groundwater may be attributed to evaporation, ion exchange reactions, agricultural return flow, and anthropogenic contamination sources such as domestic sewage and industrial discharge. Increased salinity during the premonsoon season reflects reduced dilution and prolonged residence time of groundwater within the aquifer system.

The higher concentrations of Total Dissolved Solids (TDS), Electrical Conductivity (EC), and Total Hardness (TH) during the premonsoon period suggest intensified water–rock interaction and concentration of dissolved ions due to high evaporation rates and limited groundwater recharge. In contrast, postmonsoon groundwater quality exhibited comparatively lower ionic concentrations because of rainfall-induced dilution and aquifer recharge.

Fluoride enrichment in some groundwater samples may be associated with the dissolution of fluoride-bearing minerals present in aquifer formations. Similarly, elevated nitrate concentrations observed in several regions indicate the influence of anthropogenic activities, particularly excessive fertilizer application, agricultural runoff, septic leakage, and sewage infiltration. Postmonsoon increases in nitrate concentration in certain locations further suggest contaminant transport through monsoonal recharge and surface infiltration processes.

Correlation analysis revealed strong positive relationships among EC, TDS, TH, calcium, magnesium, bicarbonate, and sulfate ions, indicating their common geogenic origin and hydrochemical association. The observed seasonal variability demonstrates that groundwater chemistry in the study area is strongly controlled by climatic conditions, recharge processes, lithological characteristics, and human-induced contamination.

Overall, the hydrogeochemical interpretation indicates that both natural geochemical reactions and anthropogenic influences play significant roles in controlling groundwater quality across Uttar Pradesh. The integration of hydrogeochemical analysis with EWQI assessment provides a comprehensive understanding of seasonal groundwater quality dynamics and drinking water suitability in the region.

IV. Seasonal EWQI Assessment

The computed EWQI values indicated considerable spatial and seasonal variability in groundwater quality across Uttar Pradesh.

Premonsoon Season
A significant proportion of groundwater samples fell under poor and unsuitable groundwater quality categories during the premonsoon season. Elevated concentrations of TDS, hardness, fluoride, and nitrate contributed to groundwater quality deterioration.

Postmonsoon Season
Postmonsoon groundwater quality showed relative improvement due to dilution effects associated with monsoon recharge. The percentage of samples under good and moderate categories increased during this period.
However, some areas still exhibited poor groundwater quality due to anthropogenic contamination and hydrogeochemical conditions.

The EWQI analysis demonstrated that groundwater quality in Uttar Pradesh is strongly influenced by seasonal hydrological processes.

V. Conclusion

The present study investigated seasonal Variability in groundwater quality using the Entropy Weighted Water Quality Index (EWQI) in Uttar Pradesh, India. The results demonstrated significant seasonal variation in groundwater quality parameters between premonsoon and postmonsoon periods. Premonsoon groundwater exhibited relatively higher concentrations of dissolved constituents due to evaporation and limited recharge conditions, whereas postmonsoon groundwater quality showed improvement because of rainfall dilution and recharge.The EWQI analysis revealed that several regions of Uttar Pradesh fall under poor and very poor groundwater quality categories, indicating serious concerns regarding drinking water.

The integration of EWQI and hydrogeochemical analysis provides a reliable framework for seasonal groundwater quality assessment and drinking water suitability evaluation.The adopted EWQI-based framework can support groundwater monitoring, contamination assessment, and sustainable water resource management in regions experiencing similar environmental and hydrogeochemical conditions.

Future studies should incorporate long-term monitoring datasets, GIS-based spatial mapping, and hydrogeochemical modeling for improved groundwater management.
Declaration of Competing 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.

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