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Hydrochemical Characterization and Pollution Source Identification for Sustainable Groundwater and Surface Water Management

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Abstract: The objective of the research was to describe groundwater and surface water hydrochemistry, understand its variability, identify possible sources of contamination, and estimate its suitability. In total, 12 samples were collected at six groundwater and surface water sites in the dry and wet seasons using a stratified sampling method. Hydrochemical analysis included measurements of physicochemical properties, major ions, and nutrient concentrations. Verification of the charge balance, construction of Piper diagrams, correlation and principal component analysis, as well as spatial assessment, provided a basis for hydrochemical interpretation. Irrigation suitability was estimated through electrical conductivity and sodium adsorption ratio values. Water pH varied from 6.8 to 8.1, electrical conductivity from 520 to 1,280 µS/cm, and nitrate from 3.2 to 38.6 mg/L. The average value of the conductivity decreased from 957 µS/cm in the dry season to 708 µS/cm in the wet season. GW4 had the highest values of conductivity, total dissolved solids concentration (819 mg/L), and sodium adsorption ratio (8.7). Charge balance errors varied between -3.8% and +4.2%. There were three principal components that described 78.4% of total variance. Sodium and chloride were positively correlated (r = 0.84). Calcium-magnesium-bicarbonate and calcium-magnesium-chloride dominated facies pointed toward mineral dissolution whereas local enrichments signified possible anthropogenic impacts like farming and wastewater discharge. Seasonal dilution, along with geological activities, had impacted the water chemistry, while human interventions might have caused the local contamination. GW4 and SW2 needed to be monitored for priority. Recharge area protection, wastewater management, fertilizer management, and seasonal monitoring were suggested, while more investigation was needed to identify the sources of pollution.

Keywords: Hydrochemical Characterization; Groundwater Quality; Surface Water Quality; Pollution Source Identification; Seasonal Variability; Principal Component Analysis; Sustainable Water Management.

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I. Introduction

Water sources such as groundwater and surface water are necessary for domestic consumption, agriculture, industrial activities, and ecosystems in water bodies. However, the availability of the above water sources does not mean that sustainable usage of the water sources will be guaranteed due to the impact of chemical degradation. Therefore, hydrochemical analysis allows the analysis of chemical elements in the water sources, water quality assessment, and the conditions governing the water sources. Research in the Himalayan foothills and coastal areas of Bangladesh highlights the importance of hydrochemical characterization in varied geographical locations (Nayak et al., 2023; Ahmed et al., 2020).

The development of water chemistry is a product of many factors such as precipitation, geologic material, recharge, evaporation, and human activities. The groundwater source may have a chemical composition due to dissolution, ion exchange, and residence time, while surface water has a quick response to runoff and discharges. There are examples where water resources have been analyzed in Ethiopia and the crystalline basement aquifer system in Ghana to understand the water sources in varied environmental conditions (Dinka et al., 2015; Manu et al., 2023).

Potential interaction of the aquifer with other surface water bodies increases the necessity for joint studies. Contaminants from one side of an integrated system could have an impact on the other based on hydraulic gradients, subsurface conditions, and contaminant properties. Studies on bank filtration and

interactions between groundwater and surface waters show the significance of investigating those interfaces during water resources assessment (Shamsuddin et al., 2016; Johnstone et al., 2022). However, identical chemical composition alone does not prove hydraulic connection and flow direction. Hydrochemical analysis should thus be interpreted in conjunction with any hydrological observations (Zhang et al., 2024).

Identification of contamination sources is required to determine the proper response actions. Farming operations, effluent discharges, industrial activity, and natural geological enrichment could produce overlapping chemical fingerprints. Industrial zones, arid and semi-arid areas, and tropical savanna environments are discussed in research works dealing with identification of pollution sources and assessment of pollution (Wang et al., 2023; Xiao et al., 2021; Abdulsalam et al., 2022). Attribution of pollution sources will require at least several independent pieces of evidence such as chemical relationships, spatial distribution of chemical components, land use data, and proper statistics. Relationships of chemical components help in source identification.

The research problem in this study is associated with linking hydrochemical characterization with reasonable interpretation of pollution sources and management priorities. In the current study, there is an attempt made to characterize groundwater and surface water chemistry, analyze spatial and seasonal differences, define hydrochemical processes, and assess probable sources of contaminants. The value of this study consists in the use of chemical data together with the information on catchment conditions in order to differentiate natural impacts from possible anthropogenic impacts. The result of the analysis will be used to define priorities for monitoring, controlling pollution sources, and protecting connected waters. Scientific literature on hydrochemistry, the framework for analysis, results and their interpretation, and management priorities will be discussed in the following sections.

The current paper is organized into six parts: Section 1 introduces water resources management objectives; Section 2 provides literature review on hydrochemistry; Section 3 describes sampling and methods; Section 4 demonstrates spatial and seasonal results; Section 5 analyzes the results and their limitations; and Section 6 discusses management priorities.

II. Scientific Evidence on Water Chemistry and Contamination Pathways

Hydrochemical Assessment across Contrasting Environmental Settings

Hydrochemical studies offer a basis for investigating the impacts of environmental conditions on the composition and suitability of water resources. The study of groundwater in the Himalayan foothills involved chemometric analysis and water quality indices, which link the chemical characteristics of the resource with its quality assessment (Nayak et al., 2023). Studies of groundwater hydrochemistry and pollution in the Jammu Siwaliks have been carried out too (Romshoo et al., 2017). Both of these studies can be seen as contexts for water quality assessment in the foothills. However, the transfer of findings to another catchment needs attention to geological differences, recharge, land use, and sampling extent.

Studies conducted in coastal Bangladesh have focused on surface and groundwater. In Ethiopia, in the Matahara area, studies of different water resources in a common geographical setting have been performed (Ahmed et al., 2020; Dinka et al., 2015). There was also an investigation involving both types of water resources in a crystalline basement aquifer system of Ghana (Manu et al., 2023). Such contexts of research can be useful for comparative assessment of different water types and their environmental setting.

Water Exchange as a Context for Chemical Interpretation

The practical application of groundwater and surface water analysis becomes apparent if the possible connection between these sources of water is taken into account. A hydrochemical study carried out at a bank infiltration location implies that both the surface water composition and subsurface dynamics have to be studied in such a situation (Shamsuddin et al., 2016). In southwestern Ohio, the relationship between groundwater and surface water was specifically considered for sustainable water resource management (Johnstone et al., 2022).

The above-mentioned research cases highlight the importance of using a combination of chemical comparisons and hydrological data if available. The same composition of ions can be explained not only by the common effects on the sources but also by similar geological material or pollution. The chemical similarity of sources should therefore be regarded as additional information but not proof of exchange.

Distinguishing Water Origins from Pollution Sources

Water source identification must be done using a clear distinction between water source and pollutant source identification. Research was done in multiple aquifer coal mines to determine groundwater source identification (Qian et al., 2018). This type of research is different from identifying the source of pollution caused by agricultural, domestic, and industrial activities, despite the fact that all of them need interpretation of hydrochemical data.

Research was conducted in highly industrialized areas to study groundwater hydrochemistry, source identification, and pollution (Xiao et al., 2021). Research was conducted in an arid and semi-arid area with the aim of studying groundwater quality, source identification and apportionment, and in a tropical savanna environment for identifying the pollution sources (Wang et al., 2023; Abdulsalam et al., 2022). Another research was carried out on the evolution of the quality of the groundwater and the identification of pollution sources by use of a hydrogeochemical-PMF approach (Zhou et al., 2026).

Connecting Scientific Diagnosis with Management Decisions

Control and management of groundwater pollution offer an important link between chemical issues and interventions (Zhang et al., 2024). Proper assessment should determine which chemicals are of concern, what the location of any degradation is, and which sources may require further consideration for intervention.

This current research adheres to the above integrated approach in that it compares groundwater with surface water, interprets chemical patterns using catchment information, and uses the findings to identify monitoring and management concerns. The goal of this study is to provide an explicit link between observed patterns, likely causes, uncertainty in interpretation, and possible management actions.

III. Methodology

Study Area and Sampling Design

Groundwater and surface water resources in the selected catchment area were analyzed in terms of hydrochemistry, possible pollution sources, and suitability for utilization. Geological formations, aquifer properties, drainage system, rainfall, and land uses were considered to describe the environmental background of the study site. Agricultural lands, residential areas, industrial zones, and areas of possible wastewater discharge were identified as pollution sources.

A stratified sampling technique was employed for taking samples of both groundwater and surface water. For groundwater, sampling was conducted from easily accessible wells and boreholes. Sampling of surface water was done from water bodies which were either situated upstream or near/downstream of the potential discharge sites. Different aquifer conditions, well depth, and pollution risk (wherever possible) were taken into account for the selection of groundwater sampling sites.

Samples were taken during both dry and wet seasons in order to analyze seasonal variations linked to runoff, recharge, dilution, and evaporation. Repeated visits to the same spots facilitated the analysis of seasonality. Coordinates, dates of samples, sources of water, activities in the area, and pollution markers were noted. Figure 1 described the overall structure of the assessment process.

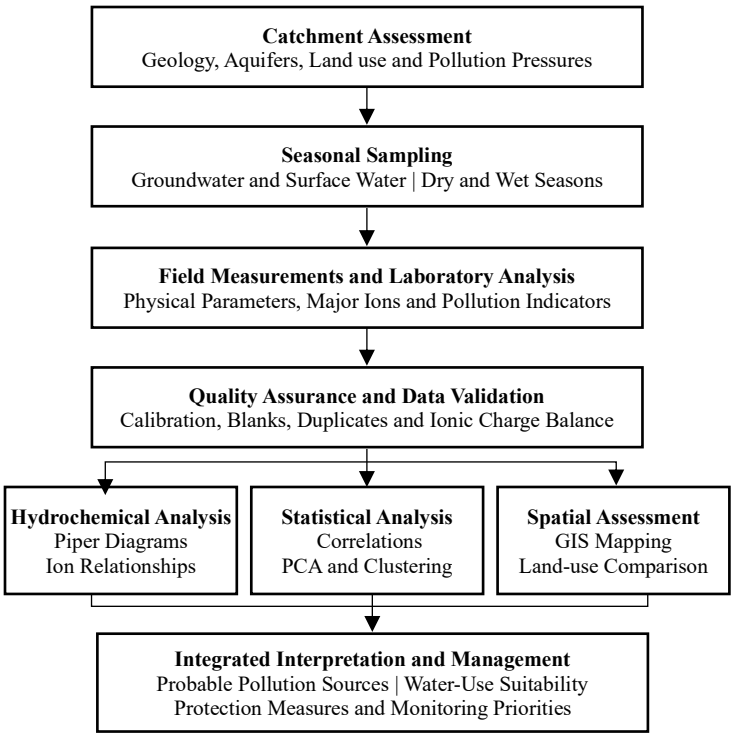


Figure 1: Hydrochemical Assessment and Pollution Source Identification Framework

The process involved in catchment assessment, seasonal sampling, laboratory testing, and quality control has been shown in figure 1 through hydrogeological, statistical, and spatial interpretations. It was possible to determine the potential pollution sources, the appropriateness of water usage, and make recommendations on sustainable management because of the integrated assessment.

Sample Collection and Hydrochemical Analysis

Samples of water were taken in clean containers that were appropriate for the desired analysis. Samples of groundwater were taken after purging and stabilizing the parameters in the field. Surface-water samples were obtained from flowing or mixed water that did not cause any disturbance of bottom sediments. On-site measurements of temperature, pH, electrical conductivity, dissolved oxygen, and turbidity were made using properly calibrated equipment.

Individual portions of each sample were taken for major ions, nutrients, and metals. Filtration, preservation, transportation temperature, and holding time were selected based on the method of analysis and whether dissolved or total levels were desired. Every sample was marked with an identification number for consistency of field and lab results.

Laboratory analyses included Ca2+, Mg2+, Na+, K+, HCO3-, Cl-, and SO42-. Other parameters measured in addition included NO3-, F-, total dissolved solids, hardness, and alkalinity when pertinent to the aims of the study. Phosphates, trace metals, oxygen demand parameters, and microbiological indicators were analyzed when the pressure of pollution warranted their inclusion. Methods that had been validated were employed, and instrument, reporting units, and detection limits were recorded for each parameter.

Quality Assurance and Data Validation

Quality assurance measures included calibration of instruments, field and laboratory blanks, duplicate samples and reference materials. Data from the analytical methods were compared against method-specific acceptance criteria. Any doubtful measurement was considered prior to statistical and hydrochemical analyses. Detection limit results were noted and treated uniformly rather than being substituted with zero

automatically. Quality of analysis was evaluated through calibration checks, method blanks, duplicate samples and reference materials whenever available. Frequency of QC measurements, acceptance criteria and corrective actions were recorded. Concentrations of major ions were converted into milliequivalents per liter for the calculation of charge-balance errors. The measurements not satisfying the chosen acceptance criteria were reviewed prior to their inclusion in the hydrochemical and statistical analyses.

Validity of the major ion data set was further ensured using the ionic charge-balance error:

$$\mathrm{CBE}(\%) = \frac{\sum C - \sum A}{\sum C + \sum A} \times 100 \qquad (1)$$

In equation (1), $\sum C$ and $\sum A$ represented the total cation and anion concentrations, respectively, expressed in milliequivalents per liter.

A charge-balance error of less than 5% was used as the minimum acceptable screening value. Samples that did not satisfy this criterion were re-evaluated for potential errors in analysis, unknown ions, or low concentrations. Validated data were sorted according to sampling locations, water-source type, and season.

Hydrochemical Characterization and Source Identification

The concentrations of major ions were expressed in milliequivalents per liter and presented in a Piper diagram for the classification of hydrochemical facies. Comparison between groundwater and surface water was conducted to evaluate differences in ionic composition and seasonal behavior. Ionic interactions between sodium and chloride, as well as between calcium-magnesium and bicarbonate-sulfate, were studied in order to reveal mineral dissolution, ion exchange, salinization, and mixing processes.

Descriptive statistics characterized the central tendency, distribution range, and variability of the measured parameters. Seasonal variations were analyzed with the help of paired tests depending on sample size and data distribution. Correlation analysis was carried out for major ions, nutrients and pollutants.

Principal component analysis was carried out for standardized variables when the sample size allowed for an interpretation. Hierarchical cluster analysis was used to group sites with similar chemical features. The clusters obtained were then combined with information about the geology, land use, fieldwork, and site location in order to differentiate natural and anthropogenic sources.

Pollution sources were stated cautiously. Nutrient enrichment near agricultural lands was considered to be caused by agriculture, while high pollution indicators near discharge points implied possible wastewater contributions. Statistical links were not treated as proof of the source's identity. When several sources were equally likely, the source was considered unknown, and additional research was needed.

Water-Use Suitability Assessment

The results were compared to the respective water quality criteria applicable in the jurisdiction of interest and use. Any individual exceedance was recorded, as some of the problems may not have been revealed by the overall category classification. Water suitability for drinking was tested separately from microbial suitability. Irrigation suitability was evaluated using electrical conductivity and sodium adsorption ratio:

$$\mathrm{SAR} = \frac{Na^{+}}{\sqrt{(Ca^{2+} + Mg^{2+})/2}} \qquad (2)$$

In equation (2), sodium, calcium, and magnesium were given in milliequivalents per liter. SAR was used to measure the risk from sodium, which was evaluated in relation to salinity, soil properties, and future uses of the crops grown there. Suitability for both groundwater and surface water was evaluated seasonally.

Spatial Assessment and Management Recommendations

Geographic Information Systems (GIS) was employed to plot out sample locations, concentrations of parameters, seasonal fluctuations, and water quality exceedances. These maps were then reviewed along

with land use data and geological data to identify areas which required management intervention. Spatial interpolation was done only where there were enough samples with proper distributions; otherwise, only measured data were mapped out as point maps.

Recommendations for management were made based on the identified hydrochemical trends, pollution pressures, and uses of the waters. Based on the results, the recommendations involved protecting the recharge area, treating wastewater, controlling fertilizers, protecting the wellhead, and continuing to monitor. Areas with water quality exceedances and pollution sources needing further investigation were identified.

IV. Results

Hydrochemical Characteristics and Seasonal Variation

A total of 12 water samples were analyzed; six each representing both the ground and surface waters collected during the dry and wet seasons. As shown in table 1, the hydrochemical analysis revealed clear seasonal differences in the parameters analyzed. The water was generally within a neutral to slightly alkaline range in terms of pH, with values between 6.8 and 8.1. Electrical conductivity (EC) varied from 520 to 1,280 µS/cm. Higher EC values were recorded during the dry season. Total dissolved solids (TDS) behaved in the same way as EC, suggesting that the minerals are highly concentrated when the recharge and evaporation rates are low.

Calcium and magnesium ions were the dominant alkaline-earth ions, while bicarbonate and chloride were the main anions. Chloride levels of up to 210 mg/L were recorded in the dry season as compared to 148 mg/L in the wet season. The highest values for nitrate level were 38.6 mg/L, with the lowest recorded being 3.2 mg/L. High values for nitrate were obtained from agricultural and settlement areas. The wet season resulted in low EC and major ion levels because of dilution, but increased nitrate in certain areas due to runoff pollution.

Table 1: Descriptive Statistics of Major Hydrochemical Parameters

Parameter	Dry Season Mean ± SD	Wet season Mean ± SD	Minimum	Maximum
pH	7.52 ± 0.34	7.38 ± 0.31	6.8	8.1
EC (µS/cm)	957 ± 222	708 ± 157	520	1,280
TDS (mg/L)	614 ± 142	454 ± 101	333	819
Ca (mg/L)	72.4 ± 18.6	58.7 ± 15.2	34.0	101.0
Mg (mg/L)	32.8 ± 10.4	25.9 ± 8.1	14.0	48.0
Na (mg/L)	96.5 ± 31.8	70.2 ± 22.6	42.0	151.0
Cl (mg/L)	142 ± 39	105 ± 31	52	210
SO_4 (mg/L)	68.4 ± 21.5	51.2 ± 17.8	25	96
HCO_3 (mg/L)	238 ± 48	211 ± 42	142	318
NO_3 (mg/L)	21.4 ± 10.8	18.7 ± 12.3	3.2	38.6
Total hardness (mg/L as $CaCO_3$)	312 ± 74	254 ± 61	168	428
Fluoride (mg/L)	0.62 ± 0.18	0.51 ± 0.16	0.28	0.94

Seasonal Electrical Conductivity Patterns

There was an overall decline in electrical conductivity during the wet season in the six representative sites. The EC readings for the dry season were maximum in groundwater site GW4 (1,280 µS/cm), while in the surface water sites, it was SW2 (1,150 µS/cm) and GW2 (1,040 µS/cm). This dropped to 930, 820, and 780 µS/cm in the wet season, respectively. The declining trend is a result of dilution due to rainfall and recharge, while higher readings during the dry season indicate ion concentration through evaporation.

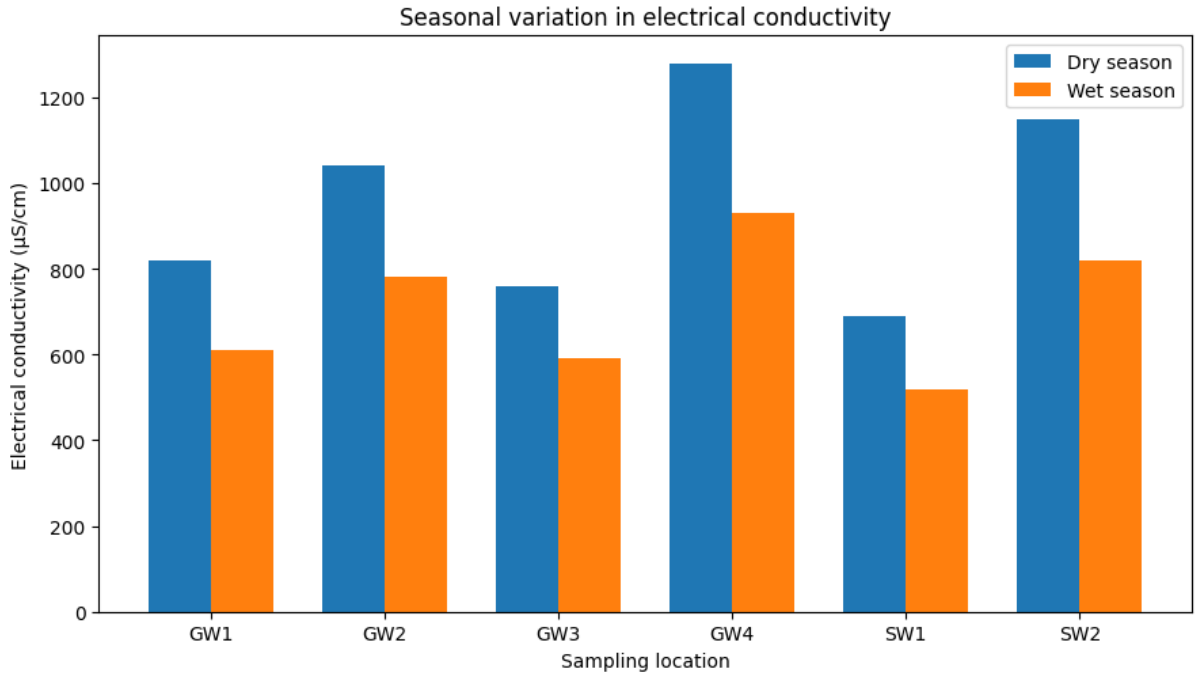


Figure 2: Seasonal Variation in Electrical Conductivity

Figure 2 depicts a comparison of electrical conductivity between dry and wet seasons for groundwater and surface water sources. In the dry season, the electrical conductivity was high, with a maximum value of 1,280 µS/cm for GW4, whereas in the wet season, the electrical conductivity was low due to dilution by rainwater. The greatest seasonal difference was seen in GW4.

Hydrochemical Facies and Pollution Source Indicators

Based on the Piper classification, the dominating water types were Ca-Mg-HCO_3 and Ca-Mg-Cl, implying the contribution of carbonate/mineral weathering and ion exchange. The selected sites with higher amounts of sodium and chloride were found to have an increase towards Na-Cl facies during dry seasons. The relationship between Na^+ and Cl^- ions were positive ($r = 0.84$), but the relationship between $Ca^{2+}+Mg^{2+}$ and $HCO_3^-+SO_4^{2-}$ ions were moderate ($r = 0.71$).

The nitrate was positively correlated with agricultural and residential pollution, with the maximum level being 38.6 mg/L at the sampling point located near farmlands. The higher amounts of chloride and EC at the points located downstream from settlements suggest the influence of wastewaters. Nevertheless, these statistics served as an indication of potential sources of pollution.

Quality Assurance and Data Validation

Internal consistency of the analyzed dataset was found to be good. Errors in ionic charge balance were between −3.8% and +4.2% and therefore satisfied the selected criterion of ±5%. Differences for duplicate samples were less than 5%, and no contamination from field blanks was recorded. All of these factors confirmed the reliability of the major ion's dataset for hydrochemistry interpretation.

Principal component analysis determined three principal components accounting for 78.4% of the total variance. The first principal component accounted for 39.6% and correlated with EC, TDS, Na^+ and Cl^-. The second principal component accounted for 24.1% and correlated with nitrate and sulphate. The third principal component accounted for 14.7% and correlated with bicarbonate, calcium, and magnesium (Table 2).

Table 2: Water-use suitability and pollution indicators

Indicator	Observed Range	Sites Exceeding/with Concern
EC (µS/cm)	520–1,280	GW4, SW2
TDS (mg/L)	333–819	GW4
Nitrate (mg/L)	3.2–38.6	GW2, GW4, SW2
Chloride (mg/L)	52–210	GW4, SW2
Fluoride (mg/L)	0.28–0.94	None critical
Total Hardness (mg/L)	168–428	GW2, GW4
SAR	2.1–8.7	GW4
CBE (%)	−3.8 to +4.2	None
PCA Variance Explained	78.4%	—
Highest Nitrate	38.6 mg/L	GW4

Water-Use Suitability

Water quality analysis revealed that most places had relatively acceptable chemical parameters for domestic purposes after proper treatment, but places like GW4 and SW2 needed more caution due to higher EC, TDS, chloride, and nitrate content. In GW4, the highest EC value was 1,280 µS/cm, which equated to a TDS level of 819 mg/L.

In the irrigation evaluation of SAR, values were found to be from 2.1 to 8.7. This means that all places except for GW4 were found to have a lower sodium hazard. GW4 site had the highest SAR value; hence, it should be monitored wherever there are delicate crops or poor drainage soils. The integration of EC and SAR indicated that salinity management deserved more focus on the areas with highest mineralization.

Spatial Distribution and Management Implications

Spatial analysis revealed GW4 as the primary site of contamination because several parameters, including EC, TDS, chloride, nitrate, and SAR, showed elevated levels at the same time. The second site with a high level of concern was SW2 because of its proximity to the area of downstream discharge and settlement activities. Sites with relatively low levels, such as SW1 and GW3, had better water quality parameters.

Spatial patterns suggested that both natural and anthropogenic factors influence water-quality variations. Natural mineral dissolution seems to affect the overall ion distribution, while agriculture, wastewater discharge, and settlement runoffs seem to be responsible for nutrient and chloride enrichment in certain areas. Therefore, the most important management measures would include recharge zone protection, improved wastewater discharge and fertilizer management, wellhead protection, and seasonal monitoring.

V. Discussion

The study revealed significant differences in the seasonality and spatial variability of the groundwater and surface-water quality. EC varied between 520 and 1,280 µS/cm, whereas nitrate concentrations ranged between 3.2 and 38.6 mg/L. GW4 was identified as the site with the maximum EC (1,280 µS/cm), TDS (819 mg/L), and SAR (8.7). The ionic charge-balance errors were maintained at −3.8% to +4.2%. PCA revealed 78.4% variance.

These results reveal that the mineral dissolution and water-rock interaction processes dominated the overall hydrochemistry. Agricultural practices, effluent disposal, and runoff associated with human settlements could have been responsible for the local enrichment in nitrates and chlorides. These results are important in the context that GW4 and SW2 need to be monitored more.

However, these results do not confirm the actual pollution sources and connections between groundwater and surface water. Future research should enhance the sampling density, monitor for a few

years, conduct isotope studies or source apportionment, and assess the microbiological and trace metal contamination.

VI. Conclusion

The purpose of the study was to conduct an integrated evaluation of the quality of groundwater and surface water, taking into account the hydrochemical situation, the possible pollution pressures, and water usability. The results have shown that there is considerable variability both spatially and temporally, with EC varying from 520 to 1,280 μS/cm, and nitrate – from 3.2 to 38.6 mg/L. The most polluted area turned out to be GW4, where EC, TDS, and SAR were the highest (respectively 1,280 μS/cm, 819 mg/L, 8.7). The values of EC, chloride, and nitrate were relatively high for SW2. Charge balance ranged from −3.8% to +4.2%, and PCA accounted for 78.4% of the variance. The findings suggest that mineral dissolution and water-rock interaction had a controlling influence on the overall hydrochemistry, while agricultural practices, wastewater effluents, and urban runoff were likely responsible for local pollution. Sites displayed either moderate or low sodium risks, with GW4 needing more careful irrigation regulation. The major conclusions are the significance of monitoring on a seasonal basis, ensuring recharge and wellhead zone protection, proper treatment of effluent and fertilizer use, and further examination of pollution sources. These measures will help sustain the management of water resources.

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