RGNZ/MGPB

Use of the Groundwater Quality Index, Multivariate statistics and Hydrogeochemistry for Groundwater Assessment in the Malabar Volcanic Area, Indonesia

Rudarsko-geološko-naftni zbornik
(The Mining-Geology-Petroleum Engineering Bulletin)
UDC: 556.3
DOI: 10.17794/rgn.2024.5.3

Original scientific paper

Rizka Maria[1*], Anna Fadliah Rusydi[2], Dyah Marganingrum[3], Retno Damayanti[4], Heri Nurohman[5], Hilda Lestiana[6], Riostantieka Mayandari Shoedarto[7], Asep Mulyono[8], Yudi Rahayudin[9], Taat Setiawan[10], Teuku Yan Walliana Muda Iskandarsyah[11], Bombom Rachmat Suganda[12], Hendarmawan Hendarmawan[13]

[1] *National Research and Innovation Agency (BRIN), Research Center for Geological Resources, Sangkuriang, Dago, Bandung. https://orcid.org/0000-0002-5659-7657*

[2] *National Research and Innovation Agency (BRIN), Research Center for Limnology and Water Resources, Jakarta-Bogor, Cibinong, Bogor. https://orcid.org/0000-0002-0682-1008*

[3] *National Research and Innovation Agency (BRIN), Research Center for Environmental and Clean Technology, Sangkuriang, Dago, Bandung. https://orcid.org/0000-0002-3148-6301*

[4] *National Research and Innovation Agency (BRIN), Research Centre for Mining Technology, Sutami, Lampung Selatan. https://orcid.org/0009-0009-8026-5095*

[5] *National Research and Innovation Agency (BRIN), Research Center for Geological Resources, Sangkuriang, Dago, Bandung. https://orcid.org/0000-0002-3089-512X.*

[6] *National Research and Innovation Agency (BRIN), Research Center for Geological Resources, Sangkuriang, Dago, Bandung. https: //orcid.org/0000-0002-2039-5439.*

[7] *National Research and Innovation Agency (BRIN), Research Center for Geological Resources, Sangkuriang, Dago, Bandung. https://orcid.org/0000-0003-1324-7865.*

[8] *National Research and Innovation Agency (BRIN), Research Center for Environmental and Clean Technology, Sangkuriang, Dago, Bandung. https://orcid.org/0000-0001-5999-4247.*

[9] *Jl. Sudirman, Bandung (Polytechnic of Energy and Mining, Ministry of Energy and Mineral Resources, Bandung 40211) Indonesia. https://orcid.org/0000-0001-9205-3078*

[10] *Geological Agency, Ministry of Energy and Mineral Resources, Groundwater Conservation Office, Center for Groundwater and Environmental Geology, Tongkol, Jakarta. https://orcid.org/0000-0002-9770-1131*

[11] *Universitas Padjadjaran, Faculty of Geological Engineering. https://orcid.org/0000-0002-7583-9244*

[12] *Universitas Padjadjaran, Faculty of Geological Engineering. https://orcid.org/0000-0001-7689-9970*

[13] *Universitas Padjadjaran, Faculty of Geological Engineering. https://orcid.org/0000-0003-0900-3331*

Abstract

The South Bandung basin has had significant population growth in the last ten years, particularly in the regions that border West Java. Consequently, there was an increase in the demand for groundwater, an essential resource for numerous uses. On the other hand, human activities have given impact significantly on the change of groundwater quality in the Bandung basin, the Malabar volcanic area. In the Bandung basin, the Malabar volcanic area has become an important location for urban water supply recharge. Within the current investigation 27 water samples were collected during the dry and wet seasons. The purpose of this study was to analyze the seasonal variability of parameters using different approaches. The comprehensive methods involving the application of multivariate statistics, geographical modelling, and the groundwater quality index. The spatiotemporal variability showed that the dilution effect of precipitation during the rainy season contributed to the significant seasonal variations. The hydrogeochemical facies was determined as Ca-Cl, CaMg-Cl, CaMg-HCO_3, and NaK-HCO_3. The Ground Water Quality Index (GWQI) analysis indicated that physicochemical factors influence water quality classifications from unsuitable to excellent. According to the conceptual model, the upstream area has excellent GWQI; however, the downstream area has decreased GWQI due to anthropogenic influence and the dissolution process. The results suggest that NH_4^+-N, Fe^{2+}, and Mn^{2+} have significant impact on GWQI. The novelties of this research include sensitivity analysis of each parameter to GWQI while conceptual model differentiates its findings from previous research. This conceptual model can be applied in various geographic environments to determine groundwater quality and its distribution regarding seasonal and land use changes.

Keywords:
groundwater; hydrogeochemical characteristics; GWQI; multivariate statistics; conceptual model

1. Introduction

Volcanoes provide many benefits to local communities in terms of soil fertility and abundant water resources. One of the available water resources is groundwater

---

Corresponding author: Rizka Maria
e-mail address: rizk002@brin.go.id

(**Hendrayana et al., 2023**). As a beneath-the-surface reserve, groundwater plays a significant function. It provides clean water which is important for agriculture, coastal populations and fragile ecosystems. Its very matter influences the foundation of these dynamic ecosystems (**Nguyen & Huynh, 2023b; Sukri et al., 2023**). The prospective for groundwater in volcanic aquifers in tropical nations is substantial due to the high intensity of precipitation that serves as the principal source of aquifer recharge (**Aouati et al., 2023; Razi et al., 2024**).

Numerous studies have been carried out on the geochemical processes because of their complexity in volcanic aquifer systems (**Hartanto et al., 2021; Selmane et al., 2022**). Hydrogeochemical investigations conducted in volcanic aquifers play a crucial role in understanding the relationship between groundwater and the minerals present in the aquifer (**Maria et al., 2021; Gountié Dedzo et al., 2023**). Prior hydrogeochemical investigations have shown that the chemical composition and overall quality of groundwater may go through modifications due to different geogenic variables as it moves from recharge to discharge areas (**Kopić et al., 2016; Zecevic, 2019; Shafiq et al., 2021**) and fluctuations in both the wet and dry seasons are subject to the impact of rainfall levels and alterations in land use, as indicated by previous studies (**Yousuf et al., 2022; Aouati et al., 2023**).

The physicochemical quality of groundwater is not only influenced by geological factors, but is also significantly impacted by human activities (**Hasan et al., 2022**). The variation in groundwater quality during increased precipitation can be attributed to the influence of domestic and agricultural waste disposal practices, underlining the role of human actions in this process (**Sabino et al., 2023**). The geochemical processes of groundwater are subject to the influence of precipitation levels (**Aouati et al., 2023**). The weathering and dissolution of primary ions during the rainy season, as well as the dilution that occurs during the dry season, have a significant influence on the physical and chemical characteristics of groundwater (**Frei et al., 2020; Li et al., 2022**).

The Malabar volcanic area has been identified as a prospective water source in West Java, with the potential to supply tap water to the Bandung basin (**Resubun et al., 2019; Harja et al., 2021**). The presence of diverse lithologies influences the hydrogeochemical processes in volcanic regions hosting hydrothermal systems. The study area has witnessed a rise in human-induced activity, particularly from the establishment of plantations and livestock farming, leading to the generation of residues that affect the hydrogeochemical composition of groundwater (**Rusydi et al., 2023**).

Numerous hydrogeochemical investigations conducted on a global scale have provided evidence that the generation of major ions is influenced by both anthropogenic and natural processes (**Gaikwad et al., 2020; Singh et al., 2020; Nguyen & Huynh, 2023a**). This study distinguishes itself from prior research by comprehensively analyzing hydrogeochemical patterns within volcanic facies, considering both spatial and temporal variations across various seasons. Hydrogeochemical parameters exhibit seasonal changes due to the impact of processes linked to groundwater movement, mineral dissolution and deposition, and the interaction of several factors affecting water quality (**Wheeler et al., 2021; Wu et al., 2021**).

Furthermore, in addition to hydrogeochemical analyses, a number of studies have utilized multivariate statistical analysis in order to differentiate between different sources of contamination and to define the development of groundwater (**Mishra et al., 2023; Pant et al., 2023**). Recent advances in the use of geographic information systems (GIS) have expanded its functionality for spatiotemporal data to determine the spatial distribution of groundwater quality parameters and map groundwater quality assessment (**Bouteraa et al., 2019**). Water quality can be evaluated by comparing physicochemical characteristics to international permitted limits (**WHO, 2022**). The spatial distribution of the water quality index can be visualized the representation of potential zones and estimate the severity of the problem (**Ma et al., 2020**).

Several indices are used to assess the quality of water resources, and the most effective for summarizing and presenting water quality data is with GWQI and WQI. The Water Quality Index (WQI) and Ground Water Quality Index (GWQI) are indicators used to determine the quality of surface and groundwater (**Barbosa Filho & de Oliveira, 2021; Masood et al., 2022**). The WQI was developed to measure the overall quality of surface water, including rivers, lakes, and streams (**Pande et al., 2020; Kayemah et al., 2021; Pant et al., 2023**). The GWQI is specifically designed to evaluate approaches to conveying the quality of drinking or irrigation water resources, as it is one of the most effective tools for summarising and presenting water quality data on groundwater sources, such as aquifers and wells (**Kawo & Karuppannan, 2018; Bouteraa et al., 2019; Masood et al., 2022; Mohamed et al., 2022; Nguyen & Huynh, 2023; Sajib et al., 2023; Francis et al., 2024**). However, both WQI and GWQI measure water quality. WQI is implemented for surface water, and GWQI is implemented for groundwater, with preferences based on the natural system and the sources of contamination.

This study intends to integrate several approaches from past studies. The present research requires the combination of different methods from prior investigations. The main aim is to assess the seasonal variability of comprehensive hydrogeochemical methods using the groundwater quality index and multivariate statistics. Then the distribution of GWQI is described spatially using the GIS method. The process will examine the contrasting conditions observed during the rainy and dry seasons. We hypothesize that a reduction in water infiltration during the dry season is correlated with increased concentrations of different water chemical parameters observed during the wet season. This phenomenon can

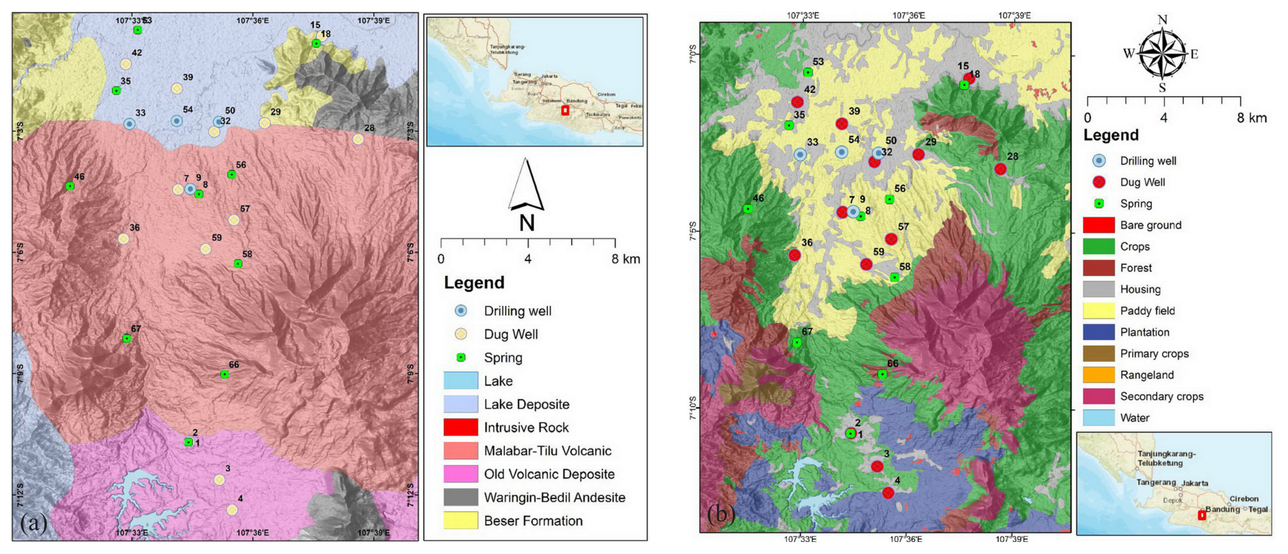

Figure 1: (a) Study area and geological condition in the Malabar volcanic area (modification from **Alzwar et al., 1992**); (b) Land use in the Malabar volcanic area (**Ministry of Environment and Forestry Republic of Indonesia, 2019**).

be attributed to resuspension, lack of dilution, and heightened evaporation. In this case, we focused on examining the variability of water quality in the aquifer, specifically in agricultural and industrial zones. However, this research is more comprehensive considering it includes GWQI parameter results with high sensitivity and conceptual models in both seasons as the novelty updates to the research findings.

2. Study area

The Bandung basin is delimited by volcanic mountains exclusively in its southern region, resulting from subduction processes. The demarcation line separating the Bandung Zone and the South Mountains is delineated by a sequence of volcanic formations, namely Patuha, Tilu, Malabar, Papandayan, and Cikurai (**Dam & Suparan, 1992**). The study was carried out in the Malabar volcanic region within the South Bandung volcanic area, located in West Java, Indonesia. The Malabar volcanic region is situated within the geographical coordinates of 107°30′E–107°40′E and 7°00′S–7°10′S (see **Figure 1a**). The average annual rainfall intensity ranges from 1,500 to 2,000 mm/year (**Adzhani & Tayubi, 2019**).

The lithological composition of the Malabar volcanic region comprises several distinct units (**Alzwar et al., 1992**) (see **Figure 1a**). The Beser Formation (Tmb) represents the earliest geological formation during the late Miocene period, composed of various types of rocks, including lava, tuffaceous breccias, andesite, and basalt. The ancient volcanic deposits (Qopu) are comprised of andesite lava deposits, aged pumice dacite, and tuff breccia. The Malabar Tilu volcanic rocks (Qmt) in the formation of more recent lava deposits, were subsequently overlain by more recent layers of sediment and volcanic materials of a fragmental nature. The Qd unit, comprised of lake deposits, is considered the most recent formation within the Holocene age.

The primary water supply for agricultural, domestic, and industrial purposes in the Malabar volcanic region primarily relies on springs channelled through gravity flow pipes and the utilization of dug and drilled wells. The Malabar region exhibits diverse land cover types, including bare ground, cultivated areas, residential settlements, paddy fields, plantations, primary crops, rangelands, secondary crops, and forests (**Indonesian Geospatial Information Agency, 2019**). **Figure 1b** illustrates the spatial arrangement of land use and land cover in the vicinity of the Malabar volcanic area. The relationship between land use and climate change has consistently influenced significant alterations in various aspects of the hydrologic cycle (**El-Magd et al., 2022**). Furthermore, modifications in land cover have been observed to impact the hydrogeochemical characteristics of groundwater (**Zhang et al., 2019**).

3. Materials and methods

3.1. Sampling and water quality analysis

A flowchart of the research approach utilised to achieve the study's aims is presented in **Figure 2**.

A total of 27 location points were taken for this study consisting of 13 dug wells, 4 drilling wells, and 10 springs that are distributed around of Malabar volcanic area. The distribution of the 27 sampling location points can be seen in **Figure 1**. Two samples were taken at each location point. One sample was taken in the dry season and another sample in the rainy season. All collected water samples were stored in a 500 mL clean plastic bottle and sent to the laboratory of National Research and Innovation Agency (BRIN) for analysis.

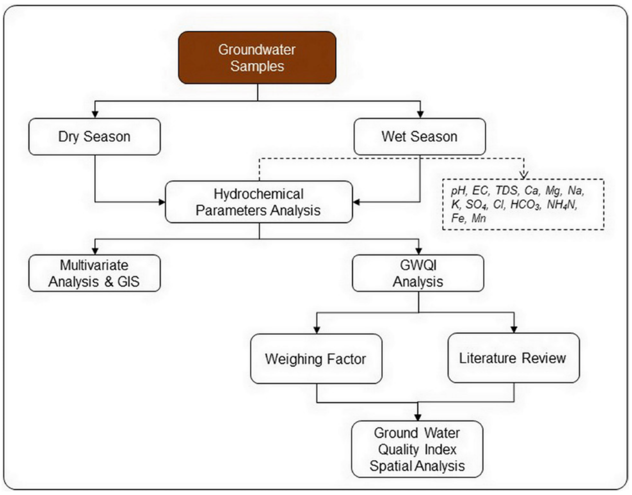

Figure 2: The flowchart illustrates the methods implemented to achieve the objectives of the research

In many cases around the world, groundwater is more abundant and of higher quality than surface water. Therefore, that is the reason groundwater is considered the most appropriate choice for human consumption (**Sajib et al., 2023; Francis et al., 2024; Kumar et al., 2024; Tabi et al., 2024**). As population growth and development occur, the quantity and quality of groundwater can be changed. Even though the study location is a rural area, it is in peri urban zoning (**Jupri & Mulyadi, 2017; Putri et al., 2022**). Consequently, an assessment of changes in the main indicators of groundwater quality is required to anticipate potential effects on public health in the research area. The main parameters that are usually used to assess the groundwater quality are pH, EC, TDS, Ca^{2+}, Mg^{2+}, Na^+, K^+, HCO_3^-, Cl^-, SO_4^{2-}, and NO_3^- (**Kumar et al., 2024**). In this study, iron (Fe) and manganese (Mn) parameters were added to see geogenic changes. The parameters TDS, NO_3^-, Cl^-, and SO_4^{2-} have a more important effect than other parameters such as Ca^{2+}, Mg^{2+}, Na^+, K^+, and HCO_3^- in defining drinking water quality (**Francis et al., 2024**). Then, Fe and Mn are as vital trace elements for human health (**Rushdi et al., 2023**).

EC and pH were measured in situ using a Horiba U-10 water quality checker. The quantification of TDS values was performed using gravimetric methods (**Kenkel, 2013**). Ca^{2+}, Mg^{2+}, Na^+, K^+ were determined using an Atomic Absorption Spectrophotometer (AAS) by the flame photometer method (AA-7000 SHIMADZU). The estimation of HCO_3^- was conducted using wet analysis by means of titration with H_2SO_4 (**Kenkel, 2013**). The chloride ion (Cl^-) was quantified through the application of a titrimetric method involving the standard titration of silver nitrate ($AgNO_3$). The analysis of sulphate was conducted utilizing a Shimadzu UV-VIS 1700 spectrophotometer.

The values were quantified in milligrams per liter (mg/L), except for pH (measured in units) and electric conductivity (EC; measured in µS/cm). The accuracy of laboratory results is examined by charge balance error (CBE) between total cations (as Ca^{2+}, Mg^{2+}, Na^+, K^+) and total anions (HCO_3^-, Cl^-, SO_4^{2-}, and NO_3^-). Tolerable CBE value is less than 5% (**Domenico & Schwartz, 1990**). The calculation of the Charge-Balance Error (CBE) was performed utilizing **Equation 1**.

$$CBE = \frac{\sum Zm_c - \sum Zm_a}{\sum Zm_c + \sum Zm_a} \times 100 \qquad (1)$$

Where:

Z – notation represents the valence of the ion,
m_c – the cation molality,
m_a – the anion molality.

The laboratory test data were analysed utilizing graphical techniques, bivariate evaluation, and correlation analysis. The combination of graphical and statistical interpretation produces a distribution that enhances the accuracy of research (**Navarro et al., 2020**).

3.2. Statistical analysis

The first statistical analysis we carried out was descriptive statistical analysis. Descriptive statistical analysis of groundwater includes summarising the key features of groundwater data (**Cooksey, 2020**). This approach sheds light on the central tendency, dispersion, and distribution of the data (**Morcillo, 2023**). Box plots are one type of data visualization that displays the frequency distribution of each parameter. It depicts the median, quartiles, and probable outliers for each parameter (**Williamson et al., 1989**). Within this study a multivariate statistical analysis was used to investigate the variables that influence the spatial and temporal characteristics of crucial factors. The Pearson correlation coefficient method was commonly employed to establish the correlations between many geochemical parameters. According to **Gaikwad et al. (2020)**, a coefficient (r) greater than 0.7 is indicative of a strong correlation. Coefficients falling between 0.5 and 0.7 are considered to represent a moderate correlation, while coefficients below 0.3 are suggestive of a weak correlation. The PCA approach was employed to conduct factorial research in order to identify the underlying factors contributing to variations in water quality (**Wheeler et al., 2021**). The Principal Component Analysis was employed as a means to streamline extensive geochemical data sets, hence facilitating the identification of previously undetected variations through the extraction of many components (**Rakotondrabe et al., 2018**). The utilization of several methodologies facilitated the evaluation of seasonal quality in order to elucidate the underlying factors contributing to fluctuations in mineral content within groundwater. The statistical analysis was conducted using the SPSS Version 26 program.

3.3 Groundwater quality index

The general status of groundwater quality in the study area, based on the major cations, major anions, ammonium, and metals contents, is understood using the water quality index calculation. The water quality assessment using GWQI which involves many comprehensive points and seasonal differences, is a reliable way to understand the yearly patterns, spatial and temporal changes, and trends in water quality (**Brown et al., 1972; Bora & Goswami, 2017; Chidiac et al., 2023; Nguyen & Huynh, 2023**).

The calculation of GWQI was conducted through the following steps: (i) assigning weights (wi) to each parameter based on their respective significance to water quality; (ii) determining the weight (Wi) and ranking the quality (qi) using Equation 2; (iii) calculating the subindex (SIi) for each parameter using Equations 3 and 4 calculating GWQI using Equation 5.

The GWQI value was calculated utilizing the algorithms (**Nguyen & Huynh, 2023**):

$$Wi = \frac{wi}{\sum_{i=1}^{n} .wi} \tag{2}$$

$$qi = Ci / Six100 \tag{3}$$

$$SI_i = Wixqi \tag{4}$$

$$GWQI = \sum SI_i \tag{5}$$

Where:

w_i – weight of each indicator,
W_i – relative weight,
q_i – ranking for each parameter,
w_i – weight for each indicator was determined according to the value of importance to water quality,
C_i – measured concentration,
S_i – guideline value according to the drinking water quality guidelines (**WHO, 2022**).

Each water quality parameter's weight value (w_i) was established based on how significant it is to the overall quality of the water suitable for human consumption. Determination the weighting for each parameter based on references that based on analysis of each parameter effects on human health (see **Table 1**).

Table 1: Weight of chemical parameters of the GWQI

Parameter	S_i^a	Weight (wi)	Relative weight (*Wi*)
pH	6.5	4^b	0.09
EC	1000	4	0.09
TDS	500	4	0.09
Ca^{2+}	75	2^b	0.04
Mg^{2+}	30	2^b	0.04
Na^+	200	2^b	0.04
K^+	10	2	0.04
SO_4^{2-}	250	4^b	0.09
Cl^-	250	3^b	0.07
HCO_3^-	120	3^b	0.07
NH_4^+-N	27.18	5	0.11
Fe^{2+}	0.3	5^b	0.11
Mn^{2+}	0.08	5^b	0.11

^aS_i guideline value according to the *WHO Guidelines for Drinking Water Quality* (**WHO, 2022**). ^{b}Weight of each parameter according to (**Şener et al., 2017**)

The GWQI was calculated using characteristics that were relevant to both natural geological processes and potential anthropogenic influences. Parameters like nutrients and heavy metals (Fe and Mn) were given the highest weight due to their significant impact on water quality, particularly for drinking purposes. The presence of Fe and Mn accumulations in water can indicate natural or man-made sources, potentially posing health risks if reaching toxic levels. Fe and Mn are the most important considerations because both parameters are commonly found in volcanic areas and their excessive presence can affect taste, colour and health significantly (**Yang et al., 2002; Bibi et al., 2007**). Ammonium (NH_4^+-N) is a crucial biomarker of organic contamination and agricultural runoff. Nitrogen compounds exist in water as ammonium (NH_4^+-N) ions, with nitrite being more harmful to both animals and humans compared to nitrate (**Varol & Davraz, 2015**). High ammonium levels in water consumption can lead to various health issues such as blue babies or methemoglobinemia disease in infants, gastric carcinomas, abnormal pain, birth defects in the central nervous system, and diabetes (**Varol & Davraz, 2015; Ardhaneswari & Wispriyono, 2022**). pH, SO_4, EC and TDS were assigned a weight of 4. pH indicates whether water is acidic or alkaline, which influences the solubility and toxicity of pollutants. EC reflects the ability of water to conduct electrical current, which is proportional to the concentration of dissolved ions. TDS refers to the combined content of all inorganic and organic compounds in water. HCO_3^- and Cl^- were assigned a weight of 3 as medium considerations. The importance of considering these two parameters is to maintain the carbonate and osmotic balance in groundwater I. Calcium, magnesium, and sodium, on the other hand, were assigned the minimum weight of 2 due to their least importance in water quality. In general, major cations (Ca^{2+}, Mg^{2+}, Na^+, K^+) are crucial for determining the hardness and mineral content of water, while major anions (HCO_3^-, Cl^-, SO_4^{2-}) indicate water's buffering capability and probable contamination sources (**Kawo & Karuppannan, 2018**).

The GWQI values are classified and evaluated according to 5 levels. The Ground Water Quality Index (GWQI) score is classified into five groups depending on ground water quality to assist in determining when groundwater is suitable for various uses, such as drinking, agriculture, and industrial reasons (**Kate et al., 2020; Derdour et al., 2023**). It has been chosen from many methods available for assessing water quality status (see **Table 2**) (**Nguyen & Huynh, 2023**).

Table 2: GWQI Range, status and possible usage of the water sample

GWQI	Water quality status (WQS)	Possible usage
0 -25	Excellent	Drinking, irrigation and industrial
26 – 50	Good	Drinking, irrigation and industrial
51- 75	Poor	Irrigation and industrial
76 – 100	Very poor	Irrigation
Above 100	Unsuitable for drinking and fish culture	Proper treatment required before use

3.4. Groundwater geochemical facies

Groundwater geochemistry examination is a technological approach employed to study the quality of groundwater (**Pratama et al., 2023**). The study used Piper diagram analysis to illustrate the geochemical evolution of groundwater and establish the interrelationship among various dissolved ions. This analysis was performed using the trilinear Piper diagram method, facilitated by the Geochemist's Workbench 17 program (free community edition).

3.5. Spatial analysis

Kriging is a mathematical interpolation technique that uses a linear combination of data at neighbouring sampled sites to create predictions at locations that have not been sampled. Geographic proximity to the unsampled location, the spatial arrangement of the observations – such as clustering of observations in enhanced areas – and the pattern of spatial correlation of the data all have an impact on the kriging prediction. Kriging model development will be useful in the spatially linked data. It is possible to collect data recorded throughout several spatial supports and employ kriging to execute adjustments like downscaling or upscaling (**Orús et al., 2005**). In this study, the kriging method is employed to demonstrate the water quality data. In addition to the field of GWQI for drinking and water quality spatial distribution, kriging interpolation is found to be used in other fields, including global ionospheric maps and monthly temperature spatial modelling (**Oliver & Webstrer, 1990; Belkhiri et al., 2020; Khan et al., 2023**). Since the water quality parameters have been visualized, we continue to analyse the distribution results spatially and temporally.

4. Results

4.1. Physicochemical and water quality parameters

The geochemical entities were studied in terms of the physical and chemical features of the groundwater that they contained in order to determine the quality of the accessible water resources. **Figure 3** shows box and whisker plots indicating seasonal variations in major ion characteristics. The research region's physicochemical parameters were examined and compared to the WHO recommended values for human consumption and drinking water (**WHO, 2022**).

Table 3 presents the descriptive statistics that were derived from the in-depth calculations of water quality parameters that were carried out during the wet and dry seasons. In general, the concentration of water quality in the research region was higher during the wet season than during the dry season. The concentrations of Na^+, Ca^{2+}, and Mg^{2+} increased statistically significantly during rainy seasons, but declined statistically significantly during dry seasons.

During wet seasons, the concentrations of $HCO_3^-$and SO_4^{2-}increased by a significant percentage, whereas the

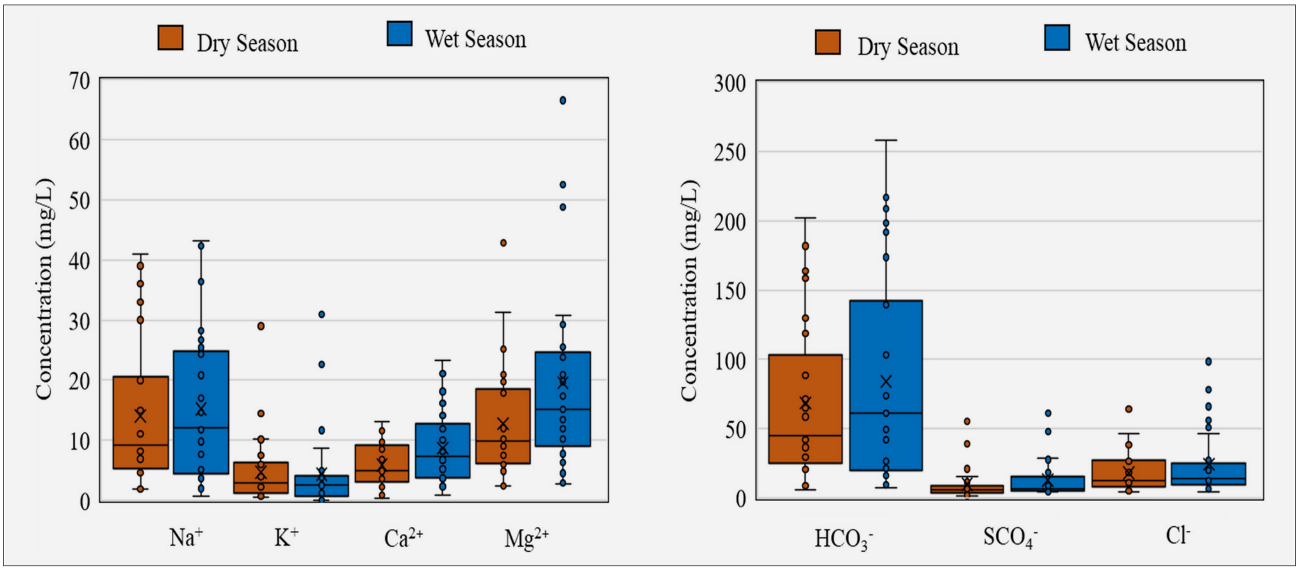

Figure 3: Box and whisker plots of the major ion in the seasonal variations

Table 3: Summary statistics of analytical data during rainy and dry seasons

Water quality parameter	Unit	Dry season			Wet season			WHO, (2022)
		Min	Max	Mean	Min	Max	Mean	
pH		5.19	7.96	6.72	5.28	7.9	6.78	6.5
EC	µS/cm	40.00	700.00	238.52	50	700	242.48	1000
TDS	mg/L	31.00	509.00	166.26	20	518	167.41	500
Na^+	mg/L	2.31	42.82	13.20	0.63	43.18	15.91	200
K^+	mg/L	0.36	13.05	5.94	0.25	30.91	4.54	10
Mg^{2+}	mg/L	1.89	40.84	14.59	0.91	23.26	8.84	30
Ca^{2+}	mg/L	0.54	28.99	4.86	2.77	66.54	20.14	75
Cl^-	mg/L	1.28	55.27	10.13	4.53	98.57	25.60	250
SO_4^{2-}	mg/L	4.64	64.02	18.97	4.26	61.51	13.62	250
HCO_3^-	mg/L	6.18	201.90	70.54	7.54	258.25	85.67	120
NH_4^+-N	mg/L	0.00	0.78	0.18	0.03	6.46	0.85	27.18
Fe^{2+}	mg/L	0.00	8.63	0.78	0	6.56	0.63	0.3
Mn^{2+}	mg/L	0.00	3.90	0.34	0	2.91	0.37	0.08

Table 4: Correlation Matrix of geochemical in the dry season

	pH	EC	TDS	Ca^{2+}	Mg^{2+}	Na^+	K^+	HCO_3^-	SO_4^{2-}	Cl^-	NH_4^+-N
pH	1										
EC	0.06	1									
TDS	0.02	0.99^{**}	1								
Ca^{2+}	0.17	0.92^{**}	0.89^{**}	1							
Mg^{2+}	0.02	0.83^{**}	0.82^{**}	0.84^{**}	1						
Na^+	0.33	0.87^{**}	0.85^{**}	0.77^{**}	0.71^{**}	1					
K^+	0.13	0.80^{**}	0.82^{**}	0.72^{**}	0.52^{**}	0.68^{**}	1				
HCO_3^-	0.41^{*}	0.82^{**}	0.78^{**}	0.83^{**}	0.81^{**}	0.92^{**}	0.65^{**}	1			
SO_4^{2-}	−0.06	0.45^{*}	0.48^{**}	0.51^{**}	0.290	0.16	0.42^{*}	0.10	1		
Cl^-	−0.30	0.78^{**}	0.81^{**}	0.64^{**}	0.56^{**}	0.50^{**}	0.69^{**}	0.37^{*}	0.43^{*}	1	
NH_4^+-N	−0.05	0.44^{*}	0.43^{*}	0.27	0.49^{**}	0.46^{*}	0.12	0.39^{*}	−0.07	0.34	1

*Significant at the 0.05 level (two-tailed); **Significant at the 0.01 level (two-tailed).

concentration of Cl^- decreased relatively slightly. The factors of dissolution and precipitation affect the ions Na^+, Ca^{2+}, Mg^{2+}, HCO_3^-, and SO_4^{2-}, whereas evaporation during the dry season impacts the Cl^- and K^+ ions. Pearson correlations in the Malabar volcanic area indicated the relationship among parameters within a specific season. **Tables 4** and **5** show correlation matrices for the dry and wet seasons, respectively. This correlation shows the relationship between variables where the correlation is positive signifies that as one variable increases, the other variable also increases. While, negative correlation indicates (in **Table 4** negative numbers are marked) that as one variable increases, the other decreases, as seen in the negative correlation between pH and Cl^-, SO_4^{2-}, and NH_4-N. Data processed with Pearson's correlation had a confidence level of 99% and 95%. The Pearson correlation studies elucidated the interdependence of many physicochemical factors. The specific characteristics and composition of the cations and anions present in the aqueous solution determined the correlation between TDS and EC. The association between TDS and Ca^{2+}, as well as a moderate correlation with Na^+, Mg^{2+}, and Cl, suggests that the dissolution of rock minerals altered groundwater geochemistry (**Moussaoui et al., 2023**).

Sodium ions (Na^+) exhibited a significant association with K^+, Mg^{2+}, Ca^{2+}, Cl^-, and HCO_3^-. This correlation suggests the potential occurrence of ion exchange processes in groundwater and the potential impact of human activities on the geochemical composition of groundwater (**Frei et al., 2020**). These human activities may include the presence of fertilizer residues and inadequate sanitation practices in the vicinity of point sources (**Nyarko et al., 2022**).

The correlation identified in groundwater between Mg^{3+}, Ca^{2+}, and HCO_3^- suggests that these ions interact through geochemical processes such ion exchange and mineral dissolution (**Dişli, 2018; Hu et al., 2013**). The moderate link observed between the occurrence of Cl^- and SO_4^{2-} ions and HCO_3^- ions can be attributed to the anthropogenic influence of agricultural practices. Sul-

Table 5: Correlation Matrix of geochemical in the wet season

	pH	EC	TDS	Ca^{2+}	Mg^{2+}	Na^+	K^+	HCO_3^-	SO_4^{2-}	Cl^-	NH_4^+-N
pH	1										
EC	0.36*	1									
TDS	0.39*	0.97**	1								
Ca^{2+}	0.36	0.87**	0.83**	1							
Mg^{2+}	0.15	0.72**	0.67**	0.69**	1						
Na^+	0.44*	0.87**	0.87**	0.66**	0.58**	1					
K^+	0.00	0.68**	0.71**	0.57**	0.43*	0.47**	1				
HCO_3^-	0.61**	0.80**	0.77**	0.72**	0.72**	0.78**	0.37*	1			
SO_4^{2-}	0.21	0.39*	0.37*	0.61**	0.21	0.07	0.32	0.13	1		
Cl^-	−0.33	0.55**	0.53**	0.54**	0.48**	0.38*	0.68**	0.07	0.33	1	
NH_4^+-N	0.43*	0.514**	0.39*	0.29	0.52**	0.58**	0.15	0.73**	−0.19	−0.09	1

*The correlation significant at the 0.05 level (two-tailed); ** The correlation significant at the 0.01 level (two-tailed).

phate (SO_4^{2-}) is derived through several natural processes, including mineral weathering, volcanic activity, decomposition and combustion of organic waste, and the oxidation of sulphides. In contrast, the anthropogenic causes can be attributed to the leaching of fertilizers from agricultural soils, as well as the runoff of agricultural and industrial wastewater (**Zak et al., 2021**).

4.2. *Groundwater hydrogeochemical facies analysis*

The research conducted by Piper revealed that the hydrogeochemical facies were categorized as Ca-Cl, Ca-MgCl, Ca-MgHCO$_3$, and Na-HCO$_3$, as depicted in **Figure 4**. The Ca-Cl facies were seen in the upstream region, where hydrothermal alteration influenced the elevated concentration of Cl^-. The presence of Ca-MgCl in the upstream region indicates the impact of volcanic rocks on the groundwater facies. In all regions, the Ca-MgHCO$_3$ facies were found to be predominant. The downstream occurrence of the Na-KHCO$_3$ facies was observed. During the rainy season, ion concentrations are elevated in the volcanic rocks due to dissolution processes and anthropogenic activity. Evaporation and the lack of dilution effects are responsible for the change in concentration during the dry season.

The downstream region exhibited a prevalence of silica weathering as the primary mechanism affecting groundwater, followed by cation exchange processes facilitating the absorption of Na^+ ions. Additionally, anthropogenic activities exerted an influence on the groundwater in this location. The hydrogeochemical evolution observed involved the transformation of the Ca^{2+} and Mg^{2+} cations into Na^+. The detection of HCO_3^- in the water sample suggests the occurrence of groundwater mixing, which can be attributed to the decomposition of organic substances. The observation of mineralization enhancement processes and dilution processes was conducted in order to detect the occurrence of natural min-

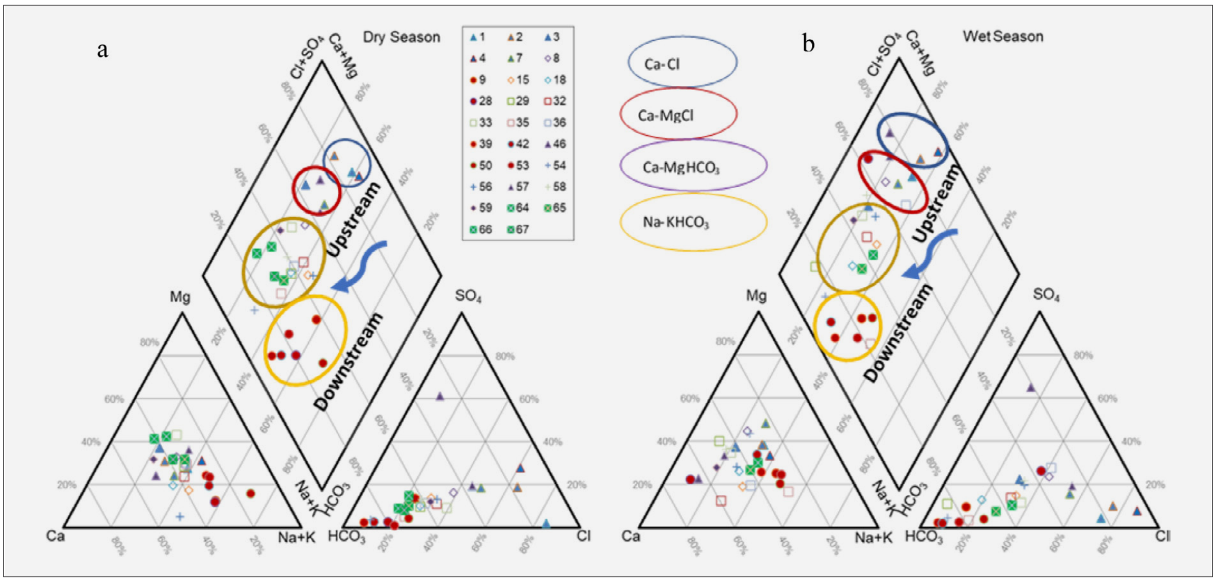

Figure 4: The Piper diagram during both the dry and wet seasons

eralization throughout the process of groundwater recharge in aquifer zones.

The hydrogeochemical investigations conducted during both rainy and dry seasons revealed distinct characteristics in the quantities of cations and anions as observed from upstream to downstream regions. The elevated precipitation level had a significant influence on the hydrogeochemical composition of groundwater, particularly concerning the process of mineral dissolution. The occurrence of precipitation was observed due to the solvent's involvement in the process of natural mineralization dilution.

The Ca-Cl facies in the upstream region, influenced by significant rainfall, exhibits complex relationships between geological formations and hydrological processes. Calcium and chloride are produced by geological processes, whereas rainfall, infiltration, and runoff influence the distribution and concentration of these ions in groundwater. In the Ca-MgCl facies, the presence of volcanic rocks exerted a discernible impact on the groundwater dynamics. Notably, this influence was shown to vary in response to the intake of rainwater during the wet seasons. Moreover, the Ca-$MgHCO_3$ facies exhibited dominance throughout all regions. In the downstream region, the Na-$KHCO_3$ facies was seen.

The downstream region experienced the accumulation of groundwater through the process of silica weathering, which was subsequently influenced by cation exchange mechanisms involving the absorption of Na^+ ions. Additionally, anthropogenic activities exerted an impact on the groundwater dynamics in this area. The presence of the HCO_3^- anion in rainfall suggests its incorporation through mixing processes, while the density of the Ca^{2+} cation can be attributed to the weathering of rocks. The Na-$KHCO_3$ facies was situated in the downstream region. According to **Koesoemadinata & Hartono (1981)**, the mineral composition of the volcanic sedimentary rock included Na-feldspar ($NaAlSi_2O_8$), Na-feldspar ($KAlSi_2O_8$), pyroxene, and olivine. The rock minerals that arise from the process of weathering serve as the source of Na^+ cations and HCO_3^- anions. The Na-$KHCO_3$ facies was generated as a result of the mineral dissolving process. During the rainy season, the ion concentrations were found to be elevated due to both dissolution processes occurring in volcanic rock cracks and anthropogenic activity. The observed rise in concentration for the dry season could perhaps be attributed to the processes of evaporation and the absence of dilution effects. The time period of groundwater-rock contact influences the physical and chemical characteristics. The duration of these interactions is critical in controlling the extent to which certain minerals dissolve in groundwater, impacting their overall chemical composition (**Wu et al., 2020**).

Table 6: The principal component loadings matrix of the geochemical data reflecting the groundwater quality

Parameters	Component					
	1		2		3	
	Dry	Wet	Dry	Wet	Dry	Wet
pH	0.13	0.44	-0.65	-0.57	0.57	-0.50
EC	0.99	0.97	-0.03	0.10	-0.08	-0.15
TDS	0.98	0.95	-0.00	0.08	-0.14	-0.17
Na^+	0.88	0.85	-0.17	-0.14	0.31	-0.13
K^+	0.79	0.64	-0.28	0.49	-0.27	-0.07
Mg^{2+}	0.88	0.84	0.21	-0.00	0.14	0.44
Ca^{2+}	0.93	0.88	-0.15	0.23	-0.07	-0.21
Cl^-	0.73	0.51	0.23	0.77	-0.48	0.23
SO_4^{2+}	0.41	0.37	-0.17	0.46	-0.67	-0.48
HCO_3^-	0.86	0.87	-0.20	-0.42	0.41	-0.07
NH_4-N	0.45	0.59	0.63	-0.61	0.38	0.17
Fe^{2+}	0.42	0.49	0.16	-0.55	0.24	0.41
Mn^{2+}	0.21	0.47	0.84	0.25	0.12	0.67
Total	6.88	6.59	1.84	2.38	1.60	1.49
% of Variance	52.91	50.70	14.19	18.27	12.27	11.49
Cumulative %	52.91	50.70	67.09	68.98	79.37	80.47

4.3. The Principal Component Analysis (PCA)

The PCA approach was employed to conduct factorial research in order to identify the underlying factors contributing to variations in water quality (**Wheeler et al., 2021**). This study involved the evaluation of many tested parameters. The present study employed PCA as a method to identify the primary components and sources of variation in groundwater quality throughout different periods, thereby providing a comprehensive assessment of the groundwater quality level. Three principal components (PC1, PC2, and PC3) were derived from the eigenvalues, which represent the point sample parameters observed during both seasons. During the wet and dry seasons, PC1 accounted for 52.91% and 50.70% of the overall divergence, respectively. PC2 accounted for 14.19% and 18.27% of the overall variation in the wet and dry seasons, respectively. Similarly, PC3 accounted for 12.27% and 11.49% of the variance in the wet and dry seasons, respectively (see **Table 6**). The variables that showed a substantial positive loading in PC1 were those that included EC, TDS, Na^+, K^+, Mg^{2+}, Ca^{2+}, Cl^-, and HCO_3^-.

During the dry period, Mg^{2+}, Cl^-, NH_4-N, Fe^{2+} and Mn^{2+} demonstrated positive relationships to the PC1 and PC2 axis, meanwhile pH, EC, TDS, Na^+, K^+, Ca^{2+}, Cl^-, SO_4^{2+} and HCO_3^- give positive relationships to the PC1 axis but have negative relationships to the PC2 axis. In the wet period, EC, TDS, K^+, Ca^{2+}, Cl^-, SO_4^{2-} and Mn^{2+} demonstrated positive relationships to the PC1 and PC2 axis, meanwhile pH, Na^+, Mg^{2+}, HCO_3^-, NH_4-N and Fe^{2+} give positive relationships to the PC1 axis but have negative relationships to the PC2 axis. The PCA graphs are depicted in **Figure 5**.

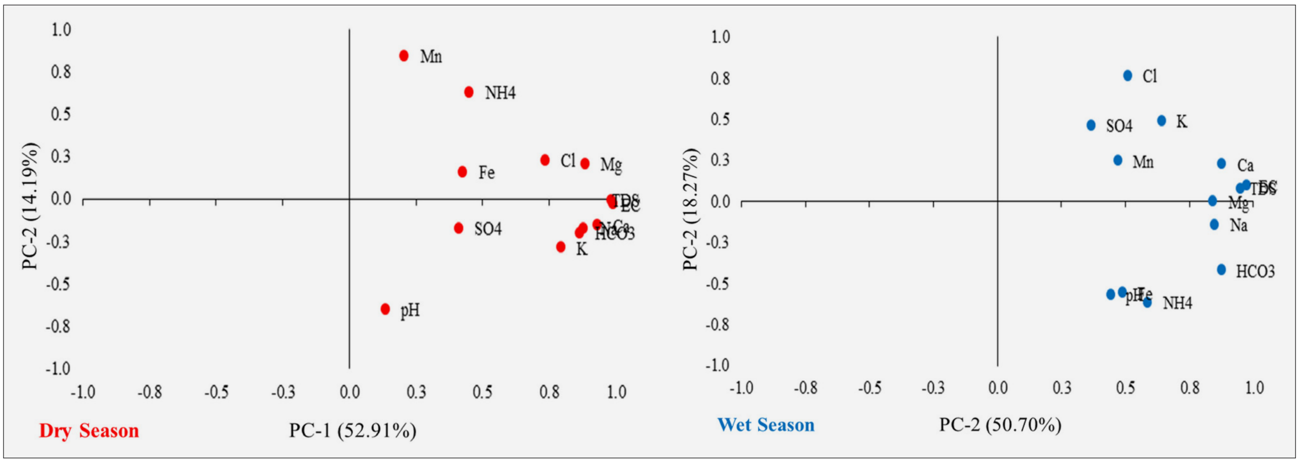

Figure 5: The PCA graph explains the changes in the parameters due to the dry and wet seasons

PCA was employed to analyze the physicochemical data. The quantification of groundwater hydrogeochemical was primarily determined by the conductivity, total dissolved solids (TDS), and the parameters of cations (Na^+, K^+, Mg^{2+}, Ca^{2+}) and anions (Cl^-, SO_4^{2-}, and HCO_3^-) in the principal component 1 (PC1). These processes were identified as the most crucial factors in assessing the hydrogeochemical characteristics of the groundwater. The dissolution process during the rainy season leads to an observed rise in the concentration of EC, TDS, K^+, Ca^{2+}, SO_4^{2-}, NH_4-N and Fe^{2+}minerals. In the arid season, the diluting mechanism of TDS minerals leads to an augmentation in their concentration. During both the dry and wet seasons, it was seen that the primary factor exhibited the most significant positive loadings with Na^+, K^+, Mg^{2+}, and Ca^{2+}. This suggests that the greater concentrations of these ions were mostly influenced by the aquifer structures, which resulted in the weathering of silicate minerals.

The presence of a significant amount of bicarbonate ions (HCO_3^-) indicated the alkaline characteristics of this component. PC1 exhibited a combination of varying levels of hardness and alkalinity across both seasons. In the interim, it is plausible that the secondary source of pollution could originate from residential and agricultural activities, corresponding to the rainy and dry seasons, respectively. The accounting measures implemented had a significant impact on the overall quality of groundwater hydrogeochemical, particularly in relation to both anthropogenic and geogenic influences. The positive PCA scores indicate that there are parameters with significant loadings on a certain element that has an influence on groundwater. Furthermore, a notable distinction existed between the dry and wet seasons in terms of the variables EC, TDS, K^+, Ca^{2+}, SO_4^{2-}, NH_4-N and Fe^{2+}.

5. Discussion

5.1. Spatiotemporal variation of physicochemical parameters

The spatial modelling of water quality parameters showed hydrogeochemical variation distribution pat-

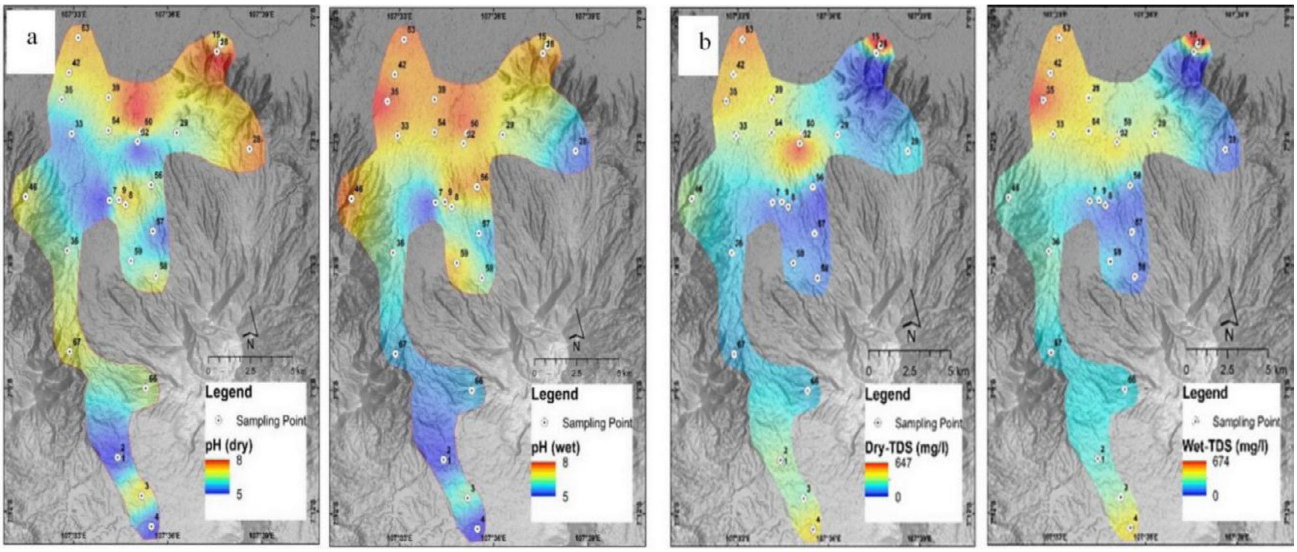

Figure 6: The spatiotemporal variation of (a) pH and (b) total dissolved solids (TDS)

Copyright held(s) by author(s), publishing rights belongs to publisher, pp. 41-62, DOI: 10.17794/rgn.2024.5.3

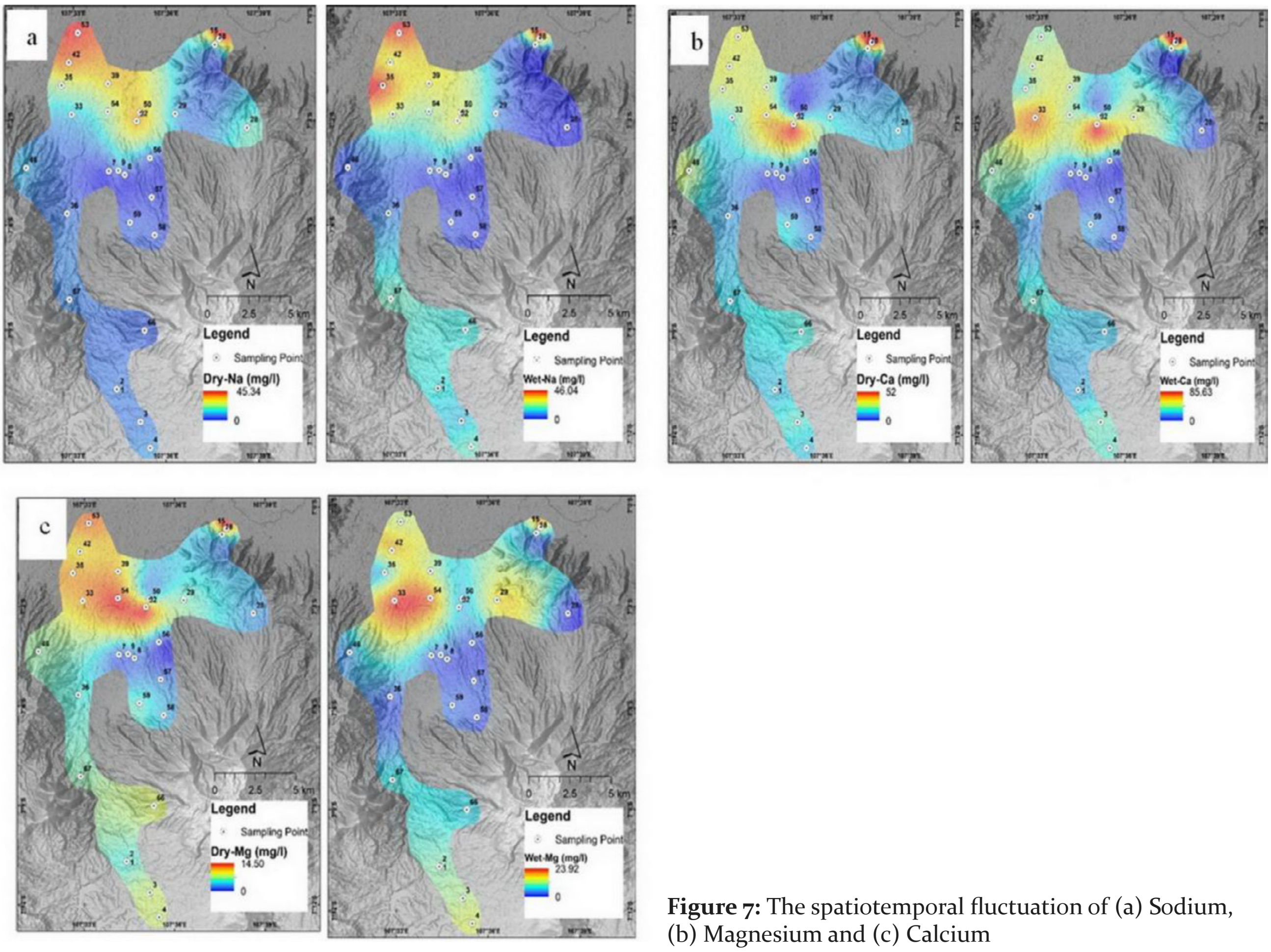

Figure 7: The spatiotemporal fluctuation of (a) Sodium, (b) Magnesium and (c) Calcium

terns. Spatial maps of pH show that the highest values are located in the downstream areas (see **Figure 6a**). The pH values ranged from 5.19 to 7.96 for the dry season and from 5.28 to 7.90 through the wet season. High pH concentrations were found at the locations relating to rice fields, plantations and residential areas. According to **Zrelli et al. (2018)**, the pH spatiotemporal variation was influenced by the quality and rate of groundwater infiltration in the recharge area and the interaction between rock and water.

The spatial distribution maps of TDS showed that the highest values characterized the northeastern and downstream areas of the study area (see **Figure 6b**). The TDS values ranged from 76 to 592 mg/l and in the dry season from 20 to 518 mg/l in the wet season. TDS concentrations were higher in the wet season than those in the dry season. The trend of increasing values occurs during the rainy season.

The high concentration of TDS was also to related to the paddy, plantations, and settlement areas. The assessment of TDS measurements can aid in categorizing water suitability for agricultural, drinking, and industrial purposes. According to **Ahmed et al. (2021)**, exceeding the established threshold for TDS concentrations can result in gastrointestinal complications within the human body. High TDS concentrations commonly arise from several environmental and geological factors and human activities, including using fertilizers and household and agricultural practices (**Fashae et al., 2019**).

The spatial distribution map of Na^+ indicated elevated values in the northwestern and northeastern regions of the investigated area. The Na^+ concentrations varied between 1.89 and 40.84 mg/l during the dry season and between 0.63 and 43.18 mg/l during the wet season (see **Figure 7a**). The attention of Na^+ was found to be usually higher during the wet season than during the dry season.

Na^+ concentrations increase in environments with paddy fields and residential structures. The increasing trend in Na^+ concentration in the studied area has been caused through anthropogenic activities such as agricultural residues and domestic sewage. According to **Ahmed et al. (2021)**, excessive consumption of Na^+ might adversely affect the human body, including exceptionally high blood pressure and toxemia in pregnant women. In this study, the Na^+ exhibited concentration increases in the highland south region. Furthermore, the lowland area had the highest Na^+ concentration level during the wet season.

The concentrations of Mg^{2+} ranged from 0.36 to 13.05 mg/l during the dry season and from 0.91 to 23.26 mg/l during the wet season (see **Figure 7b**). Magnesium concentrations are generally higher during the wet season

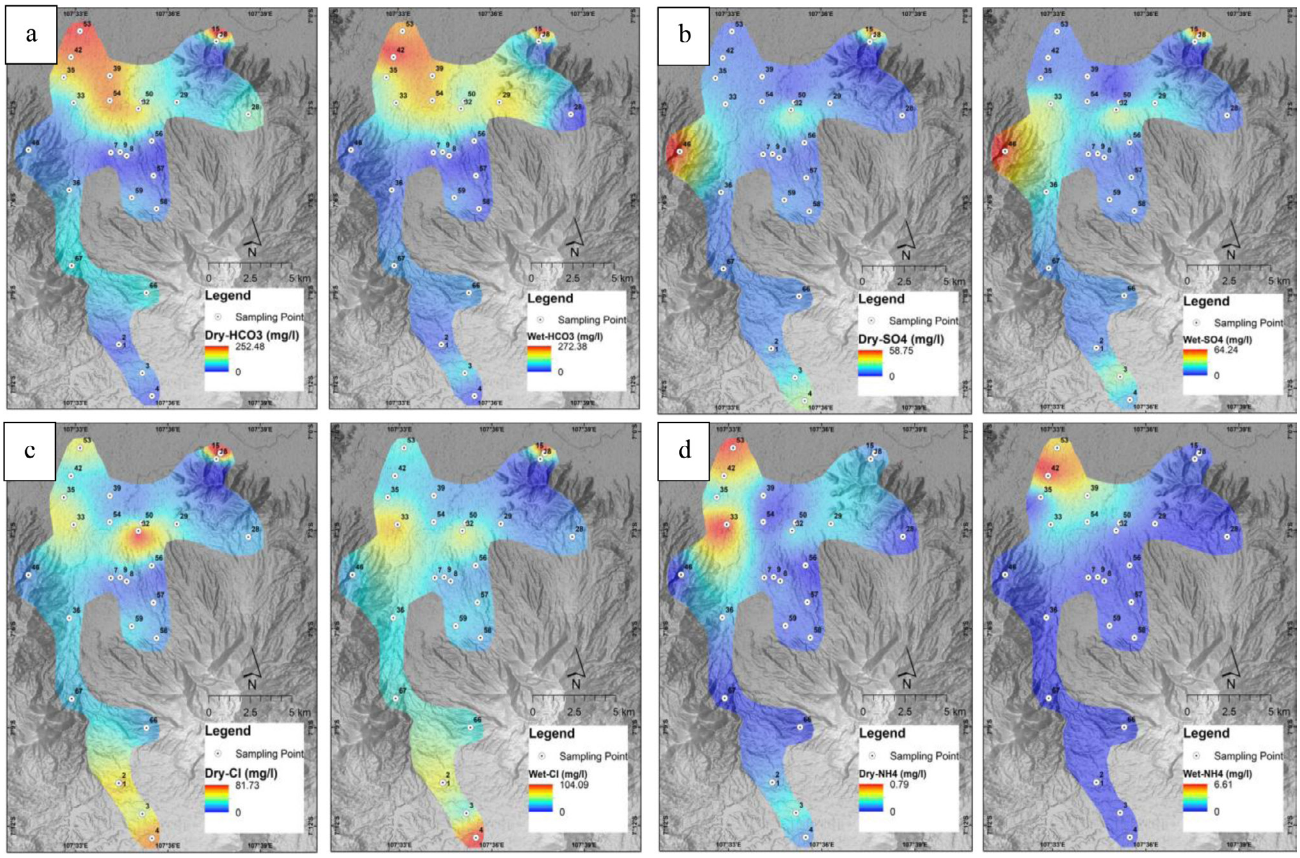

Figure 8: The spatiotemporal fluctuations of (a) HCO_3^-, (b) SO_4^{2-}, (c) Cl^-, and (d) NH_4-N

compared to the dry season. Mg^{2+} concentrations increase in locations with residences and paddy fields. Anthropogenic activities, such as domestic sewage and agricultural scraps, contributed to an increase in Mg^{2+} concentration in the study area. The presence of Mg^{2+} in its native state can be attributed to volcanic rocks that include basaltic to andesitic compositions (**Hem, 1985**). The naturally occurring Mg^{2+} content arises from the contact process between rock layers that groundwater traverses (**Sabino et al., 2023**). The presence of insufficient levels of magnesium in the body has been associated with a range of health hazards. These risks include atherosclerotic vascular disease, eclampsia in pregnant women, vasoconstriction, acute myocardial infarction, infection, and hypertension (**Eslami et al., 2022**).

The spatiotemporal distribution map of Ca^{2+} revealed its presence in the northern and northeastern regions of the designated study area. The Ca^{2+} concentrations exhibited a range of 2.31 to 42.82 mg/l during the dry season and 2.77 to 66.54 mg/l during the wet season (see **Figure 7c**). Calcium concentrations rise during periods with increased precipitation, indicating complex relationships between geological and environmental processes. Increasing calcium concentrations in paddy fields and settlements can have an impact on water quality. Ca^{2+} are classified as alkaline earth metals and play a crucial role in igneous minerals, particularly in pyroxene, amphibole, and feldspar silicate chains (**Hem, 1985**). According to **Ahmed et al. (2021)**, calcium is an essential component in regulating a wide variety of physiological processes that occur within the human body. Some of these activities include the constriction of blood vessels, the coagulation of blood, the transmission of nerve impulses, and the contraction of muscles. Additionally, elevated levels of Ca^{2+} are indicative of the presence of feldspar, pyroxene, and amphibole minerals (**Hem, 1985**). According to **Ticinesi et al. (2022)**, there is no significant correlation between calcium concentrations and the risk of osteoporosis, colorectal cancer, or kidney stones.

In the wet season, the mean concentration of HCO_3^- was recorded as 99.49 mg/l, while in the dry season, it was observed to be 87.01 mg/l. The spatial distribution map demonstrates that the downstream area has a prevalence of high values (see **Figure 8a**). Rainwater interacts with the environment, migrating and raising bicarbonate ions concentrations during intense precipitation. There is an elevated concentration of HCO_3^- in the paddy fields and settlement areas. In the dry season, the SO_4^{2-} values varied between 2.01 and 55.27 mg/l; in the wet season, they ranged from 4.35 to 61.51 mg/l. **Figure 8b** depicts the spatial distribution map, highlighting the elevated concentrations of SO_4^{2-} in the central and downstream regions of the investigated area. The significant attention of SO_4^{2-} is primarily observed in residential areas and is strongly associated with anthropogenic activities. In the

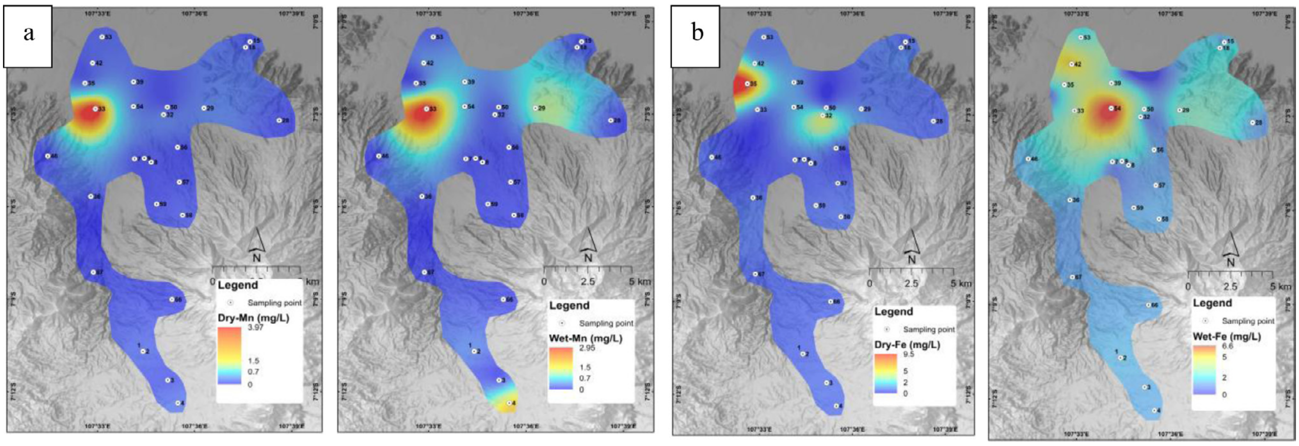

Figure 9: The spatiotemporal fluctuations of (a) Mn^{2+}, and (b) Fe^{2+}

dry season, the Cl^- range was 4.64 to 64.02 mg/l; in the rainy season, the range was 4.53 to 98.57 mg/l. The spatial distribution map depicted in **Figure 8c** demonstrates that the concentrations of Cl^- were elevated in both the central and distal facies. The attention of chloride ions (Cl^-) was usually higher during the wet season than the dry season.

During the rainy season, chloride ion (Cl^-) levels are often greater in rice fields and residential areas compared to the dry season. Ultimately, the NH_4^+-N readings exhibited a range of 0 to 0.78 mg/l during the dry season, whereas in the rainy season, the range extended from 0.03 to 6.46 mg/l. **Figure 8d** depicts a spatial distribution map showcasing the regions with the highest NH_4^+-N values, primarily observed in the distal area. The concentrations of Cl^-, SO_4^{2-}, HCO_3^-, and NH_4^+-N exhibited greater significance during the rainy season than the dry season, with higher abundance values seen in the downstream area. The parameters Cl^-, SO_4^{2-}, and NH_4^+-N exhibit associations with agricultural operations, volcanic activities, and alkali characteristics.

Manganese (Mn^{2+}) concentrations varied from 0 to 3.9 mg/l during the dry season and 0 to 2.91 mg/l during the wet season (see **Figure 9a**). Particularly, concentrations were often higher in the dry season than in the wet season. Manganese is naturally occurring in volcanic rocks and sediments. Manganese can be introduced into groundwater by weathering and leaching these minerals (**Hem, 1985**). Agricultural runoff and industrial processes may also contribute to high manganese levels in groundwater. The range of Fe^{2+} concentrations were 0 to 8.63 mg/l in the dry season and 0 to 6.56 mg/l in the wet season (see **Figure 9b**). The concentration of Fe^{2+} in groundwater within the Malabar volcanic area exhibits a noticeable seasonal variation, with higher levels observed during the dry season compared to the wet season. However, the range of Fe^{2+} concentrations indicates a potentially greater influence of local geological formations and human activities, such as agriculture, which can exacerbate iron concentrations. The elevated levels of Fe^{2+}, particularly in communities and paddy fields, suggest that the iron is likely sourced from both natural geological processes and anthropogenic activities. Volcanic rocks and lake deposits naturally contain iron compounds. When groundwater interacts with these rock strata, Fe^{2+} is released into the water (**Hem, 1985**). This natural leaching process is enhanced during the dry season due to lower dilution rates, resulting in higher concentrations of Fe^{2+}. The interaction of groundwater with iron-rich rocks, combined with the agricultural practices in paddy fields that may introduce additional iron through fertilizers and soil amendments, contributes to the observed seasonal fluctuations in iron concentrations. These findings highlight the need for regular monitoring groundwater to mitigate potential health risks associated with high iron.

High levels of manganese and iron exposure concurrently may have complementary or synergistic impacts on health, including Alzheimer's, Huntington's, Parkinson's, pigmentation changes, mitochondrial dysfunction, cardiovascular illness, and respiratory/neurological issues (**Okereafor et al., 2020; Awliahasanah et al., 2021; Rahman et al., 2021; Eslami et al., 2022; Rushdi et al., 2023**). Manganese mostly affects the neurological system, cause cognitive impairment, including lower math and IQ test scores, memory loss, attention issues, increased hyperactivity, aggressive behaviour, and motor dysfunction (**Emmanuel et al., 2018; Eslami et al., 2022**). Fe poisoning can lead to health issues including hemochromatosis, organ damage, hemosiderosis, joint discomfort, and weariness whereas iron overload largely affects the liver cirrhosis, and other organs, but both may have a role in inflammation and oxidative stress (**WHO, 2004; Ustaoğlu & Islam, 2020**).

5.2. *GroundWater Quality Index*

The computed GWQI values in the dry season vary between 12.97 to 575.63, and in the rainy season they range from 14.33 to 510.84, and have been divided into five categories based on water quality, ranging from "excellent" to "unsuitable for drinking". During the dry season, 29.63% of the samples tested were unsuitable for

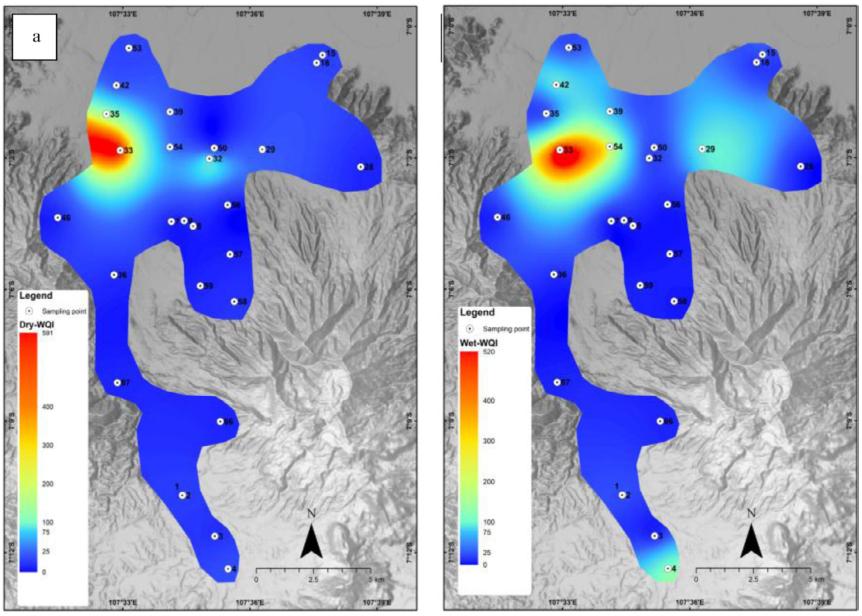

Figure 10: Variations in the GWQI in the Malabar volcanic region both (a) the dry and (b) wet seasons

drinking (specifically at sampling points 4, 29, 32, 33, 35, 39, 42, and 54,), 11.11% were poor or very poor, while 37.04% and 11.11% of groundwater samples were assessed as excellent and good. During the wet season, 25.93% of the samples tested were unsuitable for drinking (specifically at sampling points 4, 29, 33, 39, 42, 53, and 54), 11.11% were poor, and 14.81 were very poor whereas 25.93% and 22.22% of groundwater samples were classified excellent and good, respectively. The GWQI distribution map illustrates the overall water quality in **Figure 10**.

The wet season demonstrated the highest GWQI. In contrast, the dry season had the lowest seasonal GWQI, indicating that water quality conditions were poorer during the rainy season than during the dry season. Persistent and severe precipitation causes nonpoint pollutants to infiltrate into groundwater, contaminating it. The GWQI analysis found significant geographical differences between downstream and upstream sites. The GWQI rating for the upstream area was lower than that of the downstream area. This disparity can be attributable to the accumulation of contaminants from a variety of sources, including residences, agriculture, and other human activities.

Low concentrations of Na^+, K^+, Cl^-, and SO_4^{2-} in groundwater are due to silica weathering, groundwater-rock interactions, and residual fertilisers. Anthropogenic activities have altered groundwater downstream, leading to higher levels of Na^+, K^+, Cl^-, SO_4^{2-} Fe, Mn, and NH_4-N ions. The observed increase in physicochemical concentrations within the local region during the dry season is due to evaporation, and there are no dilution effects. During the rainy season, ion concentrations in fractured volcanic rocks and anthropogenic activities were found to be higher, owing mostly to dissolving processes. Assessment of anthropogenic influences on contamination levels of Cl^-, SO_4^{2-}, Fe, Mn, and NH_4-N was actualized from various sources, including septic tanks, residential wastewater, livestock, and agricultural waste.

The sensitivity of each parameter to GWQI results can have a major impact on water quality management measures. The following is a detailed breakdown of the sensitivity of various parameters and their impact. Ammonium (NH_4^+-N), iron (Fe) and manganese (Mn) have a highly sensitive significant impact on water quality index. Their respective presence in drinking water and other bodies of water can have serious consequences, especially in the case of agricultural runoff. Ammonium generally affects water for consumption sources from agricultural runoff, which includes fertilisers and animal manure. High ammonium concentrations in water bodies can lead to eutrophication, which depletes oxygen and has a negative impact on aquatic life. While ammonium is not particularly dangerous to humans, its presence in drinking water may signal contamination by other harmful compounds. Furthermore, ammonium can be oxidised to nitrate, which at high levels can induce methemoglobinemia or "blue baby syndrome" in neonates, resulting in impaired oxygen delivery in the blood (**Baldiris-Navarro et al., 2020; Ardhaneswari & Wispriyono, 2022; Nguyen & Huynh, 2023**). Iron (Fe) and manganese (Mn) are important water quality indicators because of their significant impact on environmental health and human consumption. Groundwater in volcanic locations may include higher levels of iron and manganese as a result of mineral dissolution from volcanic rocks. Chronic exposure to excessive manganese levels in drinking water has been linked to neurological disorders. Manganese toxicity can produce symptoms comparable to Parkinson's disease, such as tremors, difficulties walking, and facial muscle spasms. While iron is a necessary vitamin, excessive consumption can lead to health issues such as hemochromatosis, a condition in which the body accumulates too much iron, potentially causing liver damage, cardiac problems, and diabetes. Excessive manganese intake can also have an impact on brain development and function in newborns and young children (**Emmanuel et al., 2018; Okereafor et al., 2020; Awliahasanah et al., 2021; Rahman et al., 2021; Eslami et al., 2022; Rushdi et al., 2023**).

TDS, pH and EC are highly sensitive water quality indicators because they directly reflect mineral concentration and overall water quality. The principal ions in water (Ca^{2+}, Mg^{2+}, Na^{2+}, K^{+}, HCO_3^{-}, Cl^{-}, SO_4^{2-}) provide valuable information for analysing changes in water chemistry and have moderate sensitivity in water quality indicators. High TDS and EC values indicate a high concentration of dissolved ions, which might alter water flavour. pH levels can affect the solubility and toxicity of chemicals and heavy metals in water.

The principal ions in water (Ca^{2+}, Mg^{2+}, Na^{2+}, K^{+}, HCO_3^{-}, Cl^{-}, SO_4^{2-}) provide valuable information for analysing changes in water chemistry and have moderate sensitivity in water quality indicators. These ions influence the overall ionic equilibrium and hardness of water. Individuals on sodium-restricted diets should monitor their sodium and potassium levels. At high concentrations, chlorides and sulphates can provide a salty taste and laxative effects, respectively (**Gao et al., 2020; Kumar et al., 2024**). Understanding these sensitivities allows for better prioritisation of water quality management measures and a more accurate interpretation of GWQI results. By addressing these findings and implementing them into future studies and water management strategies, we can gain a better understanding of groundwater quality dynamics and develop practical solutions. The groundwater quality index method guarantees that water supplies are effectively managed, protecting both human health and the environment.

5.3. Groundwater conceptual model

A comprehensive groundwater conceptual model is created to improve our comprehension of the underground hydrogeological structure and the behaviour of groundwater movement. This model combines various geological, hydrological, and environmental data from GWQI, multivariate statistics, and GIS to illustrate the flow paths and directions within the study area. The model is divided into two distinct zones based on topography and hydrogeochemical analysis, as depicted in **Figure 11**. The upstream zone has significant structural influence, characterized by steep slopes, low primary ion concentrations, an electrical conductivity (EC) of 200 µS/cm or lower, and hydrogeochemical facies predominantly composed of Ca-Cl, Ca-MgCl, and Ca-$MgHCO_3$ types. The CaCl facies emerge due to the mineral weathering process occurring within porous volcanic rocks. However, it can also arise due to anthropogenic activity near aquatic environments. The dominant calcium-magnesium facies are formed from the weathering of silica minerals derived from basaltic andesitic volcanic rocks. The Ca-$MgHCO_3$ type facies arise due to the prolonged interaction between rock and groundwater. It was found that the upstream location had exceptionally high water quality when comparing the GWQI ratings of both the downstream and upstream sites.

Whereas upstream locations collect fewer pollutants than downstream areas, some areas have been discovered to be contaminated by crop residue and livestock sewage.

The downstream area has a significant downward gradient caused by prevailing structural features. The results show TDS greater than 200 mg/L and EC values more than 200 µS/cm. The hydrogeochemical facies is dominated by calcium-magnesium bicarbonate (Ca-$MgHCO_3$) and sodium bicarbonate (Na-HCO_3), resulting in low quantities of primary ions. The Ca-$MgHCO_3$ facies occur near subsurface water flow. Ca^2 is primarily elevated due to interactions with volcanic chemicals. The presence of HCO_3 indicates an interaction between shallow and deep groundwater, resulting in local recharge. Rock weathering produces Ca^{2+} cations. The $NaHCO_3$ facies is dominant in plain areas influenced by anthropogenic activities. The evolution of groundwater is characterised by a cation exchange process that results in an increase in Na ions and a decrease in Ca and Mg ions. Shallow and deep groundwater are blended, as shown by the Na-$KHCO_3$ groundwater facies. An intermediate flow regime is assigned to the groundwater flow system related to the Na-$KHCO_3$ facies. The downstream zone's GWQI value showed significant variation. Pollution in upstream habitats is facilitated by a variety of human-driven activities, including residential units, agricultural institutions, and industrial facilities.

The hydrological process of water infiltration into shallow aquifers significantly impacts seasonal variations. The GWQI analysis revealed that the majority of the samples have water quality ratings of unsuitable, very poor, poor, good, or excellent; this value is helpful in determining water suitability. This conceptual model shows that whereas upstream areas have generally good to exceptional GWQI levels, specific ones have low values due to the impact of plantation residues and animal waste.

Downstream locations have lower GWQI due to anthropogenic impacts and dissolution processes, resulting in GWQI values ranging from poor to unsuitable. There are no significant variations in GWQI values between rainy and dry seasons. In addition, this conceptual model can be implemented to help conserve groundwater reserves and make better use of water for consumption. This could assist with environmental monitoring and effective maintenance of groundwater supplies. This conceptual model of hydrogeology in the wet and dry seasons can be employed to represent a condition of groundwater quality through the QWQI and hydrogeochemical facies, and the results will become apparent by comparing the two seasons. The resulting findings peculiarity

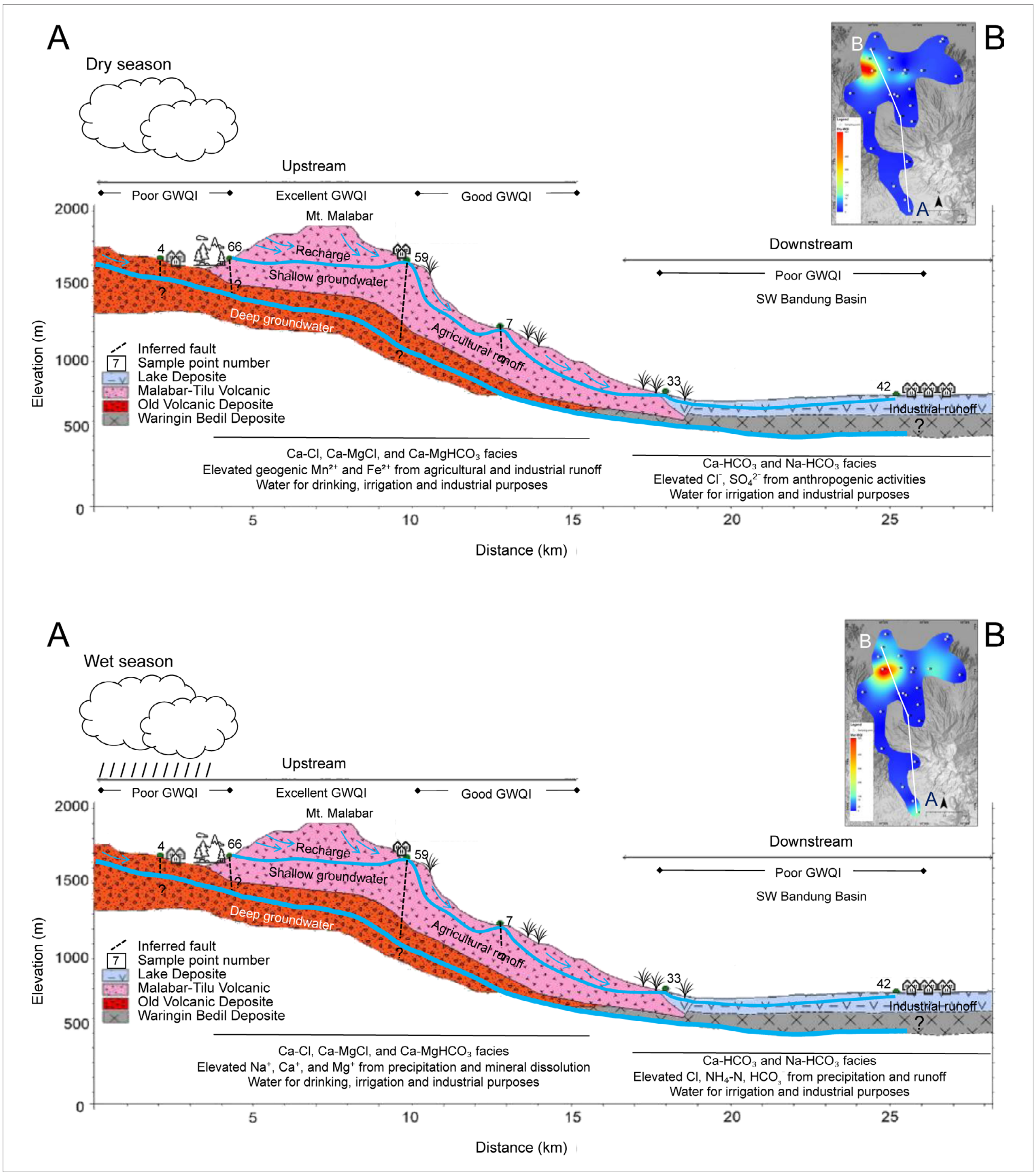

Figure 11: The conceptual model of groundwater hydrogeochemistry in the Malabar volcanic region. Generalized cross-sections are showing the different hydrogeochemical characteristics occurring in the study area during wet and dry seasons.

consists of the sensitivity GWQI parameters and the conceptual model, which could possibly be utilised in a variety of geographical settings to conduct groundwater assessments.

6. Conclusions

Analyzing the seasonal variability patterns of groundwater geochemistry is of the utmost importance in comprehending the underlying groundwater dynamics and identifying the influences of natural factors and human activities. The weathering of silicate minerals was the principal source of the elevated ion concentrations. Throughout both seasons, PC1 displayed varied amounts of hardness and alkalinity. Furthermore, household and agricultural runoff might be a secondary source of pollution. Positive PCA scores indicate that significantly weighted components are related to a specific component that has an impact on groundwater. There was a significant difference in EC, TDS, K^+, and Mg^{2+} buildup between the dry and wet seasons. Mineral dissolution within fractured volcanic rocks alters the hydrogeochemical facies of Ca-Cl, Ca-MgCl, Ca-$MgHCO_3$, and Na-$KHCO_3$, a process that intensifies throughout the rainy season. The conceptual model illustrates that the upstream area has an excellent level of GWQI, while localised areas have poor GWQI values with environmental conditions influenced by agricultural products and contaminants from animals' manure. In contrast, the downstream area has a GWQI value that fluctuates from good to unsuitable due to anthropogenic effects and the dissolution process. The sensitivity of each parameter on GWQI results could significantly impact water quality management methods. NH_4^+-N, Fe^{2+}, and Mn^{2+} have significant impacts on GWQI. pH, TDS, and EC are slightly sensitive since they directly reflect overall mineral content and water quality. Major ions (Ca^{2+}, Mg^{2+}, Na^+, K^+, HCO_3^-, Cl^-, SO_4^{2-}) are moderately sensitive water quality indicators. The originality of findings concerning the sensitivity of Groundwater Quality Index (GWQI) parameters and the conceptual model is highlighted through the relevance across varied geographical environments for groundwater assessments

In future research, it is necessary to monitor seasonal fluctuations in groundwater quality and discover contamination pathways to distinguish between natural and human sources. Future studies could provide a more comprehensive understanding of groundwater dynamics in volcanic regions, as well as practical approaches for managing water resources in a sustainable way while taking these challenges to consideration.

Acknowledgement

The authors would like to extend their gratitude to the Ministry of Research and Technology National Research and Innovation Agency, Saintek Scholarship Programme No. 945/H/2018 in 2018. Dr. Iwan Setiawan, Head of the Research Centre for Geological Resources at BRIN, for granting permission to use the laboratory facilities at E-Science Services at the National Research and Innovation Agencies (BRIN) Laboratory to analyze the water samples.

6. References

Ahmed, S., Mulhim, M., Qureshi, F., Kohli, S.K.; Hussain, A., Khan, M.M.A., Mansor, H.E. and James, E. (2021): Hydrogeochemical Characteristics, Temporal and Spatial Variation for the Evaluation of Groundwater Quality of Ganga Alluvial Plain for an Agricultural Region, India. Preprints. 2021090079. https://doi.org/10.20944/preprints202109.0079.v1

Ardhaneswari, M. and Wispriyono, B. (2022): Analisis Risiko Kesehatan Akibat Pajanan Senyawa Nitrat dan Nitrit Pada Air Tanah di Desa Cihambulu Subang. Jurnal Kesehatan Lingkungan Indonesia, 21(1), 65–72. https://doi.org/10.14710/jkli.21.1.65-72

Awliahasanah, R., Dheva, Nurlita, S., Ervina, Dyah, A., Dina, G., Delli, Y., Maulidia, Nyimas, S. and Desy, S. (2021): Analisis Risiko Kesehatan Lingkungan Kandungan Mangan Pada Air Sumur Warga Kota Depok. Jurnal Sanitasi Lingkungan, 1(2), 81–84

Alzwar, M., Akbar, N.and Bachri, S. (1992): Geological Map of the Garut and Pameungpeuk Quadrangle, Java.

Aouati, H., Demdoum, A., Kada, H. and Kouadra, R. (2023): The impact of climate change on groundwater quantity and quality in a semi-arid environment: a case study of Ain Azel plain (Northeast Algeria). Acta Geochimica, 42(6), 1065–1078. https://doi.org/10.1007/s11631-023-00633-7

Baldiris-Navarro, I., Acosta-Jimenez, J. C., González-Delgado, Á. D., Realpe-Jiménez, Á. and Fajardo-Cuadro, J. G. (2020): Multivariate statistical analysis applied to water quality of a tropical Coastal Lagoon, Cartagena, Colombian Caribbean. Indonesian Journal of Chemistry, 20(1), 141–149. https://doi.org/10.22146/ijc.43035

Barbosa Filho, J. and de Oliveira, I. B. (2021): Development of a groundwater quality index: GWQI, for the aquifers of the state of Bahia, Brazil using multivariable analyses. Scientific Reports, 11(1), 1–22. https://doi.org/10.1038/s41598-021-95912-9

Belkhiri, L., Tiri, A. and Mouni, L. (2020): Spatial distribution of the groundwater quality using kriging and Co-kriging interpolations. Groundwater for Sustainable Development. Volume 11,. https://doi.org/https://doi.org/10.1016/j.gsd.2020.100473

Bibi, M. H., Ahmed, F. and Ishiga, H. (2007): Assessment of metal concentrations in lake sediments of southwest Japan based on sediment quality guidelines. Environmental Geology, 52, 625-639.

Bouteraa, O., Mebarki, A., Bouaicha, F., Nouaceur, Z. and Laignel, B. (2019): Groundwater quality assessment using multivariate analysis, geostatistical modeling, and water quality index (WQI): a case of study in the Boumerzoug-El Khroub valley of Northeast Algeria. Acta Geochimica, 38(6), 796–814. https://doi.org/10.1007/s11631-019-00329-x

Bora, M. and Goswami, D. C. (2017): Water quality assessment in terms of water quality index (WQI): case study of the Kolong River, Assam, India. Applied Water Science, 7(6), 3125–3135. https://doi.org/10.1007/s13201-016-0451-y

Brown, R., McClelland, N., Deininger, R. and O'Connor, M. (1972): A water quality index–crashing the physiological barrier. Indic Environ Qual, 1, 173–182.

Chidiac, S., El Najjar, P., Ouaini, N., El Rayess, Y. and El Azzi, D. (2023): A comprehensive review of water quality indices (WQIs): history, models, attempts and perspectives. In Reviews in Environmental Science and Biotechnology (Vol. 22, Issue 2). Springer Netherlands. https://doi.org/10.1007/s11157-023-09650-7

Cooksey, R. W. (2020): Descriptive Statistics for Summarising Data. In Illustrating Statistical Procedures: Finding Meaning in Quantitative Data. https://doi.org/10.1007/978-981-15-2537-7_5

Dam, M.A.C. and Suparan, P. (1992): Geology of the Bandung Basin. Geological Research and Development Centre, Special Publication No 13.

Dedzo, G.M., Tsozué, D., Kpoumié, A. and Nzeukou, N.A. (2023): Identification of major sources controlling groundwater geochemistry in Mount Makabaï in the Far-North of Cameroon (the northernmost part of the Pan-African Belt). Acta Geochimica, 42(2), 266–289. https://doi.org/10.1007/s11631-022-00577-4

Derdour, A., Abdo, H. G., Almohamad, H., Alodah, A., Al Dughairi, A. A., Ghoneim, S. S. M. and Ali, E. (2023): Prediction of Groundwater Quality Index Using Classification Techniques in Arid Environments. Sustainability (Switzerland), 15(12), 1–20. https://doi.org/10.3390/su15129687

Domenico, P.A. and Schwartz, F.W. (1990): Physical and Chemical Hydrogeology. John Wiley & Sons. Canada.

El-Magd, S.A.A., Ahmed, H., Pham, Q.B., Linh, N.T.T., Anh, D.T., Elkhrachy, I. and Masoud, A.M. (2022): Possible Factors Driving Groundwater Quality and Its Vulnerability to Land Use, Floods, and Droughts Using Hydrochemical Analysis and GIS Approaches. Water (Switzerland), 14(24). https://doi.org/10.3390/w14244073

Eltarabily, M.G. and Moghazy, H.E.M. (2021): GIS-based evaluation and statistical determination of groundwater geochemistry for potential irrigation use in El Moghra, Egypt. Environmental Monitoring and Assessment, 193(5), 1–21. https://doi.org/10.1007/s10661-021-09058-2

Emmanuel, E., Sombo, T. and Ugwanyi, J. (2018): Assessment of Heavy Metals Concentration in Shore Sediments from the Bank of River Benue, North-Central Nigeria. Journal of Geoscience and Environment Protection, 06(04), 35–48. https://doi.org/10.4236/gep.2018.64003

Eslami, H., Esmaeili, A., Razaeian, M., Salari, M., Hosseini, A. N., Mobini, M. and Barani, A. (2022): Potentially toxic metal concentration, spatial distribution, and health risk assessment in drinking groundwater resources of southeast Iran. Geoscience Frontiers, 13(1), 101276. https://doi.org/10.1016/j.gsf.2021.101276

Francis, V., Krishnaraj, S., Kumar, S., Andiyappan, R. K. and Govindan, P. (2024): GIS-based groundwater potential zonation and assessment of groundwater quality and suitability for drinking and irrigation purposes in the Shanmughanadhi river basin, south India. Kuwait Journal of Science, 51(3), 100243. https://doi.org/10.1016/j.kjs.2024.100243

Fashae, A.O., Ayorinde, A. H., Olusola, O.A. and Obateru, O.R. (2019): Landuse and surface water quality in an emerging urban city. Applied Water Science, 9(2), 1–12. https://doi.org/10.1007/s13201-019-0903-2

Frei, R., Frei, K.M., Kristiansen, S.M., Jessen, S., Schullehner, J. and Hansen, B. (2020): The link between surface water and groundwater-based drinking water – strontium isotope spatial distribution patterns and their relationships to Danish sediments. Applied Geochemistry, 121. https://doi.org/10.1016/j.apgeochem.2020.104698

Gaikwad, S., Gaikwad, S., Meshram, D. and Wagh, V. (2020): Geochemical mobility of ions in groundwater from the tropical western coast of Maharashtra , India : implication to groundwater quality. In Environment, Development and Sustainability (Vol. 22, Issue 3). Springer Netherlands. https://doi.org/10.1007/s10668-019-00312-9

Gao, X., Li, X., Wang, W. and Li, C. (2020): Human activity and hydrogeochemical processes relating to groundwater quality degradation in the yuncheng basin, Northern China. International Journal of Environmental Research and Public Health, 17(3). https://doi.org/10.3390/ijerph17030867

Harja, A., Rezqi, F., Nanda, M.D. and Duvanovsky, D.A. (2021): Hydrogeophysical Study of Malabar as the Highest Mountain on the Bandung Basin Hydrological System. Jurnal Geologi dan Sumberdaya Mineral 22(4), 223–230.

Hartanto, P., Syah Alam, B.Y.C.S.S., Lubis, R.F. and Hendarmawan, H. (2021): The origin and quality of the groundwater of the rawadanau basin in Serang Banten, Indonesia. Rudarsko Geolosko Naftni Zbornik, 36(2), 11–24. https://doi.org/10.17794/rgn.2021.2.2

Hasan, M., Islam, M.A., Alam, M.J., Rahman, M. and Hasan, M.A. (2022): Hydrogeochemical characterization and quality assessment of groundwater resource in Savar – an industrialized zone of Bangladesh. Environmental Monitoring and Assessment, 194(8). https://doi.org/10.1007/s10661-022-10137-1

Hem, J. D. (1985): Study and interpretation of the chemical characteristics of natural water. US Geological Survey Water-Supply Paper, 2254.

Hendrayana, H., Harijoko, A., Riyanto, I.A., Nuha, A. and Ruslisan. (2023): Groundwater Chemistry Characterization in The South and Southeast Merapi Volcano, Indonesia. Indonesian Journal of Geography, 55(1), 10–29. https://doi.org/10.22146/ijg.76433

Hu, Y., Ray, J. R. and Jun, Y. S. (2013): Na^+, Ca^{2+}, and Mg^{2+} in brines affect supercritical CO_2–brine–biotite interactions: ion exchange, biotite dissolution, and illite precipitation. Environmental Science & Technology, 47(1), 191–197.

Indonesian Geospatial Information Agency. (2019): Landuse Data of West Java, Indonesia. https://doi.org/https://tanahair.indonesia.go.id/portal-web

Jupri, J. and Mulyadi, A. (2017): Suburban Zoning of Bandung Raya Area. Jurnal Geografi Gea, 17(2), 105. https://doi.org/10.17509/gea.v17i2.6888

Kawo, N. S., and Karuppannan, S. (2018): Groundwater quality assessment using water quality index and GIS technique in Modjo River Basin, central Ethiopia. Journal of African Earth Sciences, 147(June), 300–311. https://doi.org/10.1016/j.jafrearsci.2018.06.034

Kayemah, N., Al-Ruzouq, R., Shanableh, A. and Gokhan Yilmaz, A. (2021): Evaluation of Groundwater Quality Using Groundwater Quality Index (GWQI) in Sharjah, UAE. E3S Web of Conferences, 241. https://doi.org/10.1051/e3sconf/202124101005

Kate, S., Kumbhar, S. and Jamale, P. (2020): Water quality analysis of Urun-Islampur City, Maharashtra, India. Applied Water Science, 10(4), 1–8. https://doi.org/10.1007/s13201-020-1178-3

Khan, M., Almazah, M. M. A., EIlahi, A., Niaz, R., Al-Rezami, A. Y. and Zaman, B. (2023): Spatial interpolation of water quality index based on Ordinary kriging and Universal kriging. Geomatics, Natural14(1)., Hazards an. https://doi.org/https://doi.org/10.1080/19475705.2023.2190853

Kenkel, J. (2013): Analytical Chemistry for Technicians. In Analytical Chemistry for Technicians. https://doi.org/10.1201/b15309

Koesoemadinata, R.P. and Hartono, D. (1981): Stratigraphy and Sedimentation in the Bandung Region. Proceedings of Indonesian Assoc. Of Geologist Ann. Conf. X, Bandung, 318-336.

Kopić, J., Loborec, J. and Nakić, Z. (2016): Hydrogeological and hydrogeochemical characteristics of a wider area of the regional well field eastern Slavonia – Sikirevci. Rudarsko Geolosko Naftni Zbornik, 31(3), 47–66. https://doi.org/10.17794/rgn.2016.3.4

Kumar, P. R., Gowd, S. S. and Krupavathi, C. (2024): Groundwater quality evaluation using water quality index and geospatial techniques in parts of Anantapur District, Andhra Pradesh, South India. HydroResearch, 7, 86–98. https://doi.org/10.1016/j.hydres.2024.01.001

Li, D., Xu, Y., Zhang, X., Yang, Z., Wang, S., He, Q. and Jia, Z. (2022): Water quality, natural chemical weathering and ecological risk assessment of the contaminated area of vanadium ore in Yinhua River, China: Evidence from major ions and trace elements. Acta Geochimica, 41(1), 84–99. https://doi.org/10.1007/s11631-021-00509-8

Ma, X., Wang, L., Yang, H., Li, N. and Gong, C. (2020): Spatiotemporal analysis of water quality using multivariate statistical techniques and the water quality identification index for the qinhuai river basin, east china. Water (Switzerland), 12(10). https://doi.org/10.3390/w12102764

Maria, R., Satrio, Iskandarsyah, T.Y.W.M., Suganda, B.R., Delinom, R.M., Marganingrum, D., Purwoko, W., Sukmayadi, D. and Hendarmawan, H. (2021): Groundwater recharge area based on hydrochemical and environmental isotopes analysis in the south bandung volcanic area. Indonesian Journal of Chemistry, 21(3), 609–625. https://doi.org/10.22146/ijc.58633

Mishra, A., Rai, A., Mishra, P. K. and Rai, S.C. (2023): Evaluation of hydro-chemistry in a phreatic aquifer in the Vindhyan Region, India, using entropy weighted approach and geochemical modelling. Acta Geochimica, 42(4), 648–672. https://doi.org/10.1007/s11631-023-00610-0

Masood, A., Aslam, M., Pham, Q. B., Khan, W. and Masood, S. (2022):Integrating water quality index, GIS and multivariate statistical techniques towards a better understanding of drinking water quality. Environmental Science and Pollution Research, 29(18), 26860–26876. https://doi.org/10.1007/s11356-021-17594-0

Moussaoui, Z., Gentilucci, M., Wederni, K., Hidouri, N., Hamedi, M., Dhaoui, Z. and Hamed, Y. (2023): Hydrogeochemical and Stable Isotope Data of the Groundwater of a Multi-Aquifer System in the Maknessy Basin (Mediterranean Area, Central Tunisia). Hydrology, 10(2). https://doi.org/10.3390/hydrology10020032

Mohamed, N. A., Wachemo, A. C., Karuppannan, S. and Duraisamy, K. (2022): Spatio-temporal variation of groundwater hydrochemistry and suitability for drinking and irrigation in Arba Minch Town, Ethiopia: An integrated approach using water quality index, multivariate statistics, and GIS. Urban Climate, 46(June), 101338. https://doi.org/10.1016/j.uclim.2022.101338

oliver, A. M. (2023): Descriptive statistics: Organizing, summarizing, describing, and presenting data. Research Gate, November, 17. https://doi.org/10.13140/RG.2.2.31782.91203

Navarro, B.I., Jimenez, A.J.C., Delgado, G.Á.D., Jiménez, R.Á. and Cuadro, F.J.G. (2020): Multivariate statistical analysis applied to water quality of a tropical Coastal Lagoon, Cartagena, Colombian Caribbean. Indonesian Journal of Chemistry, 20(1), 141–149. https://doi.org/10.22146/ijc.43035

Nguyen, G. H., and Huynh, N. T. H. (2023a): Characterization of Groundwater Quality and Human Health Risk Assessment. Civil Engineering Journal (Iran), 9(3), 618–628. https://doi.org/10.28991/CEJ-2023-09-03-09

Nguyen, G. H., and Huynh, N. T. H. (2023b): Seasonal Variations in Groundwater Quality under Different Impacts Using Statistical Approaches. Civil Engineering Journal (Iran), 9(3), 497–511. https://doi.org/10.28991/CEJ-2023-09-03-01

Nyarko, O.F., Asgre, S.J., Asare, S.V., Duah, A.A., Karikari, A.Y., Malina, K.J. and Malina, G. (2022): Hydrogeochemical Studies to Assess the Suitability of Groundwater for Drinking and Irrigation Purposes: The Upper East Region of Ghana Case Study. Agriculture (Switzerland), 12(12). https://doi.org/10.3390/agriculture12121973

Okereafor, U., Makhatha, M., Mekuto, L., Uche-Okereafor, N., Sebola, T. and Mavumengwana, V. (2020): Toxic metal implications on agricultural soils, plants, animals, aquatic life and human health. International Journal of Environmental Research and Public Health, 17(7), 1–24. https://doi.org/10.3390/ijerph17072204

Oliver, M. A. and Webstrer, R. (1990): Kriging: a method of interpolation for geographical information systems. International Journal of Geographical Information Systems, 4(3), 313–332. https://doi.org/https://doi.org/10.1080/02693799008941549

Orús, R., Hernández-Pajares, M., Juan, J. M. and Sanz., J. (2005): Improvement of global ionospheric VTEC maps by using kriging interpolation technique. Journal of Atmospheric and Solar-Terrestrial Physics, Volume 67, 1598-1609. https://doi.org/Https://doi.org/10.1016/j.jastp.2005.07.017

Pande, C. B., Moharir, K. N., Singh, S. K. and Dzwairo, B. (2020): Groundwater evaluation for drinking purposes using statistical index: study of Akola and Buldhana districts of Maharashtra, India. Environment, Development and Sustainability, 22(8), 7453–7471. https://doi.org/10.1007/s10668-019-00531-0

Pant, R.R., Bishwakarma, K., Kandel, K., Poudel, S., Nepal, J., Neupane, B. B. and Singh, V.B. (2023): Seasonal variations and health risk assessment of trace elements in the

Badigad River, lesser Himalayas, Nepal. Acta Geochimica, 42(4), 689–703. https://doi.org/10.1007/s11631-023-00611-z

Pratama, R.Y., Sulaksana, N., Sukiyah, E., Iskandarsyah, T.Y.W.M., Novico, F., Zulfahmi, Z., Sudjono, E. H. and Ranawijaya, D. (2023): Short-Term Coastal Landscape Evolution in Cirebon Bay Using Coastline Environment Analysis. Journal of Environmental Engineering and Landscape Management, 31(3), 186–195. https://doi.org/10.3846/jeelm.2023.19468

Putri, L. P., Russell, D. J., O'Sullivan, B. G., Meliala, A. and Kippen, R. (2022): A critical review of definitions of rural areas in Indonesia and implications for health workforce policy and research. Health Research Policy and Systems, 20(1), 1–16. https://doi.org/10.1186/s12961-022-00847-w

Rahman, M. A., Islam, M. R., Kumar, S. and Al-Reza, S. M. (2021): Drinking water quality, exposure and health risk assessment for the school-going children at school time in the southwest coastal of bangladesh. Journal of Water Sanitation and Hygiene for Development, 11(4), 612–628. https://doi.org/10.2166/washdev.2021.016

Rakotondrabe, F., Ngoupayou, N.J.R., Mfonka, Z., Rasolomanana, E.H., Abolo, N.A.J. and Ako, A.A. (2018): Water quality assessment in the Bétaré-Oya gold mining area (East-Cameroon): Multivariate Statistical Analysis approach. Science of the Total Environment, 610–611, 831–844. https://doi.org/10.1016/j.scitotenv.2017.08.080

Razi, M.H., Wilopo, W., and Putra, D.P.E. (2024): Hydrogeochemical evolution and water–rock interaction processes in the multilayer volcanic aquifer of Yogyakarta-Sleman Groundwater Basin, Indonesia. Environmental Earth Sciences, 83(6), 1–17. https://doi.org/10.1007/s12665-024-11477-6

Resubun, M., Wahyunie, E. and Tarigan, S. (2019): Analysis Potency of Water Avaibility and Water Demand in Cisangkuy Watershed. Musamus AE Featuring Journal, 2(1), 1-10. https://doi.org/10.35724/maef-j.v2i1.2516

Rusydi, A. F., Setiawan, T., Maria, R., Firmansyah, F., Damayanti, R., Mulyono, A., Rahayudin, Y., Bakti, H., Perdananugraha, G. M. and Rivera, C.J. J. (2023): Groundwater nitrogen concentration changes in an urbanized area of Indonesia over ten years period. IOP Conference Series: Earth and Environmental Science, 1201(1), 012035. https://doi.org/10.1088/1755-1315/1201/1/012035

Rushdi, M. I., Basak, R., Das, P., Ahamed, T. and Bhattacharjee, S. (2023): Assessing the health risks associated with elevated manganese and iron in groundwater in Sreemangal and Moulvibazar Sadar, Bangladesh. Journal of Hazardous Materials Advances, 10(February), 100287. https://doi.org/10.1016/j.hazadv.2023.100287

Sabino, H., Silva, G. C., Costa, V. E. and Menezes, J. (2023): Conceptual model of a semi-arid coastal aquifer using hydrogeochemical seasonal variation and isotopic fingerprints in Tamoios, Rio de Janeiro, Brazil. Environmental Monitoring and Assessment, 195(3), 1–17. https://doi.org/10.1007/s10661-023-10913-7

Sajib, A. M., Diganta, M. T. M., Rahman, A., Dabrowski, T., Olbert, A. I. and Uddin, M. G. (2023): Developing a novel tool for assessing the groundwater incorporating water quality index and machine learning approach. Groundwater for Sustainable Development, 23(October), 101049. https://doi.org/10.1016/j.gsd.2023.101049

Selmane, T., Dougha, M., Hasbaia, M., Ferhati, A. and Redjem, A. (2022): Hydrogeochemical processes and multivariate analysis for groundwater quality in the arid Maadher region of Hodna, northern Algeria. Acta Geochimica, 41(5), 893–909. https://doi.org/10.1007/s11631-022-00553-y

Şener, Ş., Şener, E. and Davraz, A. (2017). Evaluation of water quality using water quality index (WQI) method and GIS in Aksu River (SW-Turkey). Science of the Total Environment, 584, 131–144.

Shafiq, W., Ullah, H., Zaheer, M., Mehmood, M., Farooq, U., Khan, M.J., Mashwani, S.A. and Ullah, S. (2021): Aquifer characterization and physiochemical analysis of district dera ghazi khan punjab, pakistan. Rudarsko Geolosko Naftni Zbornik, 36(3), 47–57. https://doi.org/10.17794/rgn.2021.3.4

Singh, P.A.K., Deka, J. P. and Kumar, M. (2020): Natural recharge transcends anthropogenic forcing that influences arsenic vulnerability of the quaternary alluviums of the Mid-Gangetic Plain. Npj Clean Water, 3(1), 1–12. https://doi.org/10.1038/s41545-020-0075-5

Sukri, A. S., Saripuddin, M., Karama, R., Nasrul, Talanipa, R., Kadir, A., and Aswad, N. H. (2023): Utilization Management to Ensure Clean Water Sources in Coastal Areas. Journal of Human, Earth, and Future, 4(1), 23–35. https://doi.org/10.28991/HEF-2023-04-01-03

Tabi, R. N., Gibrilla, A., Boakye, P., Agyemang, F. O., Foaah, A. A. and Oduro-Kwarteng, S. (2024): Appraisal of groundwater quality and hydrochemistry in three regions of Ghana: Implications for drinking purposes. Groundwater for Sustainable Development, 26(May), 101193. https://doi.org/10.1016/j.gsd.2024.101193

Ticinesi, A., Nouvenne, A. and Meschi, T. (2022): The Optimal Dietary Calcium Intake for Preventing Incident and Recurrent Symptomatic Kidney Stone Disease. Mayo Clinic Proceedings, 97(8), 1416–1418. https://doi.org/10.1016/j.mayocp.2022.06.024

zacevic, F. and Islam, M. S. (2020): Potential toxic elements in sediment of some rivers at Giresun, Northeast Turkey: A preliminary assessment for ecotoxicological status and health risk. Ecological Indicators, 113(February). https://doi.org/10.1016/j.ecolind.2020.106237

Varol, S. and Davraz, A. (2015): Evaluation of the groundwater quality with WQI (Water Quality Index) and multivariate analysis: a case study of the Tefenni plain (Burdur/Turkey). Environmental Earth Sciences, 73(4), 1725–1744. https://doi.org/10.1007/s12665-014-3531-z

Wheeler, S., Henry, T., Murray, J., McDermott, F. and Morrison, L. (2021): Utilising CoDA methods for the spatiotemporal geochemical characterisation of groundwater; a case study from Lisheen Mine, south central Ireland. Applied Geochemistry, 127(February). https://doi.org/10.1016/j.apgeochem.2021.104912

Williamson, D. F., Parker, R. A., and Kendrick, J. S. (1989): The box plot: A simple visual method to interpret data. Annals of Internal Medicine, 110(11), 916–921. https://doi.org/10.7326/0003-4819-110-11-916

WHO. (2004): Manganese in Drinking-water. Background document for development of WHO Guidelines for Drinking-water Quality. 2.

WHO. (2022): Guidelines for drinking-water quality (Issue fourth edition incorporating the first and second addenda). https://doi.org/10.1016/j.envpol.2017.03.012

Wu, J., Zhang, Y. and Zhou, H. (2020): Groundwater chemistry and groundwater quality index incorporating health risk weighting in Dingbian County, Ordos basin of northwest China. Chemie Der Erde, 80(4), 125607. https://doi.org/10.1016/j.chemer.2020.125607

Wu, X., Probst, A., Barret, M., Payre-Suc, V., Camboulive, T. and Granouillac, F. (2021): Spatial variation of denitrification and key controlling factors in streams and ponds sediments from a critical zone (southwestern France). Applied Geochemistry, 131. https://doi.org/10.1016/j.apgeochem.2021.105009

Yang, H., Rose, N. L. and Battarbee, R. W. (2002): Distribution of some trace metals in Lochnagar, a Scottish mountain lake ecosystem and its catchment. Science of the Total Environment, 285((1-3)), 197-208.

Yousuf, M., Baloch, J., Zhang, W., Abdullah, B., Shoumik, A., Nigar, A., Elhassan, A.A.M., Elshekh, A.E.A., Bashir, M.O., Fathi, A., Salih, M., Mohamed, A. and Iqbal, J. (2022): Hydrogeochemical Mechanism Associated with Land Use Land Cover Indices Using Geospatial , Remote Sensing Techniques , and Health Risks Model. Sustainability. 2022; 14(24):16768. https://doi.org/10.3390/su142416768

Zak, D., Hupfer, M., Cabezas, A., Jurasinski, G., Audet, J., Kleeberg, A., McInnes, R., Kristiansen, S. M., Petersen, R. J., Liu, H. and Goldhammer, T. (2021): Sulphate in freshwater ecosystems: A review of sources, biogeochemical cycles, ecotoxicological effects and bioremediation. Earth-Science Reviews, 212. https://doi.org/10.1016/j.earscirev.2020.103446

Zecevic, M. (2019): Assessment of the risk of potable water supply in the area of amphibious military operation. Rudarsko Geolosko Naftni Zbornik, 34(2), 67–76. https://doi.org/10.17794/rgn.2019.2.8

Zhang, H., Gao, Z., Shi, M., Fang, S., Xu, H., Cui, Y. and Liu, J. (2019): Study of the effects of land use on hydrochemistry and soil microbial diversity. Water (Switzerland), 11(3). https://doi.org/10.3390/w11030466

Zrelli, Gueddari. and Bouhlila, R. (2018): Spatial and temporal variations of water quality of mateur aquifer (Northeastern Tunisia): Suitability for irrigation and drinking purposes. Journal of Chemistry, 2018. https://doi.org/10.1155/2018/2408632

SAŽETAK

Upotreba indeksa kvalitete podzemne vode, multivarijantne statistike i hidrogeokemije za procjenu značajki podzemne vode u vulkanskome području Malabar, Indonezija

Na području slijeva južnoga Bandunga zabilježen je znatan rast stanovništva u posljednjih deset godina, posebno u regijama koje graniče sa Zapadnom Javom. Posljedično, došlo je do povećanja potražnje za podzemnom vodom, ključnim resursom koji se koristi za brojne namjene. S druge strane, ljudske aktivnosti znatno su utjecale na promjenu kvalitete podzemne vode u vulkanskome području Malabar koji se nalazi u okviru slijeva Bandung. U slijevu Bandung vulkansko područje Malabar važno je mjesto za obnavljanje zaliha podzemne vode koja se koristi u svrhu vodoopskrbe u urbanim dijelovima. U okviru ovoga istraživanja prikupljeno je 27 uzoraka vode tijekom sušne i kišne sezone. Cilj ovoga istraživanja bio je analizirati sezonsku varijabilnost parametara korištenjem različitih metoda. Korištene metode uključuju multivarijantnu statistiku, prostorno modeliranje i indeks kvalitete podzemne vode. Prostorno-vremenska varijabilnost pokazala je da je učinak razrjeđivanja putem oborina tijekom kišne sezone pridonio znatnim sezonskim varijacijama. Hidrogeokemijski facijes određen je kao Ca-Cl, CaMg-Cl, CaMg-HCO_3 i NaK-HCO_3. Analiza indeksa kvalitete podzemne vode (GWQI) pokazala je da fizičko-kemijski čimbenici utječu na klasifikaciju kvalitete vode od neprikladne do izvrsne. Sukladno konceptualnomu modelu uzvodno područje ima izvrstan indeks kvalitete podzemne vode, dok je u nizvodnome području on ima smanjen zbog antropogenoga utjecaja i procesa otapanja. Rezultati upućuju na to da NH_4^+-N, Fe^{2+} i Mn^{2+} imaju znatan utjecaj na indeks kvalitete podzemne vode. Doprinos ovoga istraživanja vidljiv je i u analizi osjetljivosti svakoga parametra na taj indeks, dok se konceptualni model razlikuje od prethodnih istraživanja. Ovakav konceptualni model može se primijeniti u različitim geografskim okruženjima u svrhu određivanja kvalitete podzemne vode te njezine distribucije s obzirom na sezonske promjene i na promjene u načinu korištenja zemljišta.

Ključne riječi:
podzemna voda, hidrogeokemijske karakteristike, indeks kvalitete podzemne vode, multivarijantna statistika, konceptualni model

Author's contribution

Rizka Maria (1) (Dr, senior researcher, hydrogeology) performed the field work, provided the geological and hydrogeochemical data, and water quality index analyses. **Anna Fadliah Rusydi (2)** (Dr, junior researcher, hydrogeology), provided the hydrochemical data. **Dyah Marganingrum (3)** (Dr, Principal Expert Researcher) provided the chemistry analysis. **Retno Damayanti (4)** (Dr, Principal Expert Researcher, mining engineering) provided the geochemistry data. **Heri Nurohman (5)** (M.T., assistant researcher, geological engineering) presented all the images and assisted with the modelling analysis. **Hilda Lestiana (6)** (M.T., junior researcher, geomatic engineering) provided the geographic modelling analysis. **Riostantieka Mayandari Shoedarto (7)** (PhD, junior researcher, geomatic engineering) provided the introduction and the geological analysis. **Asep Mulyono (8)** (Dr, senior researcher, soil engineering) provided the statistical data and analysis. **Yudi Rahayudin (9)** (PhD, junior researcher, geological engineering) provided the geological conditions of the research area. **Taat Setiawan (10)** (Dr, senior researcher, geological engineering) provided the spatial temporal hydrogeochemistry. **Teuku Yan Walliana Muda Iskandarsyah (11)** Dr, associate professor, applied geology) provided the hydrogeological and environmental analysis. **Bombom Rachmat Suganda (12)** (Dr, associate professor, geological engineering) provided the geological environmental data analyses. **Hendarmawan Hendarmawan (13)** (Prof, Professor of hydrogeology) was responsible for analysing the geological analyses and overall manuscript structure.