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Research Article

HYDROGEOCHEMICAL CHARACTERIZATION AND USABILITY ANALYSIS OF DEEP GROUNDWATER IN THE EASTERN PART OF HETAUDA-CHITWAN DUN BASIN, BAGMATI PROVINCE, NEPAL

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ABSTRACT

Groundwater is an essential commodity on which residents of the area are dependent for drinking and irrigation purposes. The study focuses on the evaluation of hydrogeochemistry and the suitability of groundwater for drinking and irrigation purposes in the eastern part of the Hetauda-Chitwan Dun Valley. Altogether, seventeen groundwater samples were collected from deep aquifers and analyzed for different physical and chemical constituents. The groundwater has been characterized as slightly acidic and soft. The dominant anions and cations are in the order of $HCO_3^- > Cl^- > SO_4^{2-} > NO_3^-$ and $Ca^{2+} > Na^+ > Mg^{2+} > K^+$ respectively. The groundwater facies in the study area are dominantly the Ca-HCO_3 type however some Ca-Mg-Cl facies were also identified. The groundwater chemistry in the area is predominantly governed by rock-water interaction where silicate weathering emerges as principal sources of ionic concentration. The analytical results compared with the National Drinking Water Quality Standard (NDWQS) show that all parameters lie within the permissible limit. The water samples fall under excellent to good classes in terms of drinking water quality index. Based on several indices like electrical conductivity (EC), salinity hazard (SH), sodium absorption ratio (SAR), and percent sodium (%Na) the groundwater is suitable for irrigation purposes. In contrast, magnesium ratio (MR) and soluble sodium percentage (SSP) show that 23.53% and 17.65% of the groundwater samples are unsuitable and doubtful for irrigation purposes, respectively. The outcome of the study can be better used for informed decision-making regarding water resource management and sustainable development in the evolving landscape of Hetauda Sub-metropolitan City.

Keywords: Groundwater facies, rock-water interaction, usability analysis

INTRODUCTION

Groundwater as a renewable source, is being used as an essential commodity for drinking, irrigation, and industrial purposes in many parts of the world. Globally, around 65% of the groundwater is used for drinking purposes, 20% for irrigation purposes, and 15% for industrial purposes (Raheja *et al.*, 2022). Groundwater has been used extensively and recognized as the vital and vulnerable natural resource that supports human health improvement and socioeconomic development (Zhang *et al.*, 2023). Unlike surface water, groundwater being concealed from the superficial interaction of the atmosphere, hydrosphere, and biosphere, the tendency of being polluted easily is comparatively low (Nagaraju *et al.*, 2016). In general, groundwater provides reliable, safe, and sustainable water for upcoming generations if the source is judiciously managed (Tegegne *et al.*, 2023). The advancement in exploration and exploitation techniques has globally exaggerated the pattern of groundwater usage. With the rapid population growth, urbanization, industrialization, and increase in agricultural activities groundwater regime has been globally overstressed. The impact has been pronounced both in terms of quantity and quality (Nandini & Suriya, 2020).

Water quality has nowadays been vital component that defines the usability of these vital natural resources. The quality of groundwater depends on natural processes such as rock-water interaction, climatic conditions, and geological context as well (Paternoster *et al.*, 2021). The other natural processes include mineral precipitation or dissolution, redox condition, ion-exchange, residence time, and mixing between different water types (Wang *et al.*, 2018). As discussed earlier, the quality of groundwater is the function of different geological and environmental phenomena, and their interaction and sometimes the anthropogenic interaction as well. Thus, it has been important to identify the source of chemical constituents in water. Meanwhile, the groundwater being concealed and devoid of direct observation, they have the tendency to get polluted being unnoticed until the contamination becomes so prominent that the water could be unusable. The use of contaminated water for irrigation can deteriorate the physical and chemical properties of soil ultimately leading to reduction in its productivity (Mukherjee & Singh, 2018). Meanwhile, the consumption of such water generates carcinogenic health risks to humans (Adimalla & Qian, 2019) Thus, monitoring groundwater chemistry and its chemical constituents can be considered critical for the sustainable use of the resources (Dassargues, 2018). Hence, it is necessary to evaluate groundwater quality to assess its suitability for irrigation and drinking purposes.

Several studies have been put forth on groundwater quality studies for several usages (Silwal *et al.*, 2022; Wang *et al.*, 2023). Pandey and Walraevens (2019) worked on SAR, %Na, magnesium hazard and compared laboratory test results with the World Health Organization (WHO, 2004) standard for evaluating groundwater quality in Rupandehi district, Nepal. Raju *et al.* (2016) studied the groundwater quality for drinking purposes and irrigation purposes by using the indices EC, %Na, and SAR along with Wilcox diagram in parts of Dun Valley aquifers in central Nepal. The literature review concluded that the assessment of groundwater quality is important and offers fundamental information on groundwater for the sustainable development of any region. The development of Hetauda Sub-metropolitan City as the provincial capital of Bagmati Province brings forth inevitable urbanization and industrialization. Amidst these transformations, agriculture remains a pivotal contributor to the local economy. However, reports on the deep tube wells installed for irrigation and drinking purposes in the region lack essential information on chemical parameters.

In light of these considerations, there arises a need to characterize the groundwater and further investigate the suitability of groundwater from deep tube wells for both irrigation and drinking purposes. The different physical and chemical parameters of the groundwater was analysed using the Piper diagram, Gibbs diagram, Chloroalkaline Indices, and Gaillardet model to explore the hydrochemistry of groundwater of deep tube wells. Furthermore, the groundwater quality for drinking purposes was assessed by comparing the water quality parameters with the guidelines laid down by NDWQS (NDWQS, 2005) and by calculating the Water Quality Index (WQI). On the other hand, the suitability of groundwater for irrigation purposes was evaluated from the indices such as Electrical Conductivity (EC) or Salinity Hazard (SH), Sodium Absorption Ratio (SAR), %Na, (Soluble Sodium Percentage) SSP, and Magnesium Ratio (MR).

The study aims to bridge the information gap and determine whether the groundwater in the study area meets the necessary criteria for safe and effective use in agriculture and as a potable water source. This research is crucial for informed decision-making regarding water resource management and sustainable development in the evolving landscape of Hetauda Sub-metropolitan City.

Study area

The study area represents parts of the Hetauda sub-metropolitan City of Makwanpur district, Bagmati Province, Nepal. It lies between 27.3° – 27.5° N longitudes and 84.8°– 85.2° E latitudes covering an area of about 112 km^2 (Fig. 1). Rapti and Karra are two major rivers that play major and significant roles in depositing a huge amount of sediments in the study area. The study area represents a tiny fragment of the Hetauda-Chitwan Dun Basin marked by the Dun Gravel Deposit of the Quaternary Period (Tamrakar, 2004). The east-west extending valley is surrounded by the Sub-Himalaya (Churia Range). It is intricated by north dipping Central Churia Thrust (CCT) in the south along NW-SE (Tamrakar *et al.,* 2008).

MATERIALS AND METHODS

In April 2022, groundwater samples were collected from 17 deep tube wells with depths ranging from 80 m to 157 m (Fig. 1). Sampling protocols included rinsing bottles with the same water, and samples were obtained after pumping water to minimize pipeline stagnation. In-situ measurements of pH, EC, and Total Dissolved Solids (TDS) were conducted using a portable multimeter (PCSTestr 35). Standard procedures (APHA, 2005) were strictly followed for sample collection, storage, and analysis. The concentration of sodium (Na^{2+}) and potassium (K^+) were determined by flame photometry (APHA, 2005), whereas, the total hardness, calcium hardness, alkalinity (HCO_3^-), and chloride (Cl^-) were determined by titration method (APHA 2005). Similarly, the concentration of iron (Fe^{3+}), sulphate (SO_4^{2-}), and nitrate (NO_3^-) were measured using spectrophotometric method (APHA, 2005). Meanwhile, the concentrations of Ca^{2+} and Mg^{2+} were calculated using the calculation from total hardness and calcium hardness (APHA, 2005). Various diagrams and models, including Piper plot (Piper, 1944), Gibbs diagrams (Gibbs, 1970), Chloroalkaline Indices (Schoeller, 1965), and Gaillardet model (Gaillardet *et al.*, 1999) were used for the hydrogeochemical characterization of groundwater within the area. Piper diagram was prepared using Grapher 13 by Golden software LLC., while Gibbs diagram and other Indices were calculated using Microsoft Excel 2016.

The groundwater quality parameters (physical and chemical) were compared with the maximum permissible limit as per NDWQS (NDWQS, 2005) to check the quality of groundwater for drinking. Similarly, using the Weighted Arithmetic Water Quality Index (WAWQI), WQI (Brown *et al.*, 1972) was calculated and classified for the suitability analysis for drinking purpose (Equation 1). For this, the groundwater quality parameters (physical and chemical) were compared with the maximum permissible limit as per NDWQS (NDWQS, 2005).

$$\text{WAWQI} = \frac{\sum Q_i W_i}{\sum W_i} \quad \text{---------Equation 1}$$

Where, *Qi* (Equation 2) and *Wi* (Equation 3) are calculated separately.

$$Qi = 100[(Vi - Vo)/(Si - Vo)] \quad \text{-------Equation 2}$$

Where, *Vi*= estimated concentration of the ith parameter *Vo*= ideal value of the parameter in pure water (0) (except pH=7.0). *Si* is the recommended standard value of the ith parameter

$$Wi = K/Si \quad \text{----------Equation 3}$$

Where, *K*= proportionality constant and is calculated as shown in equation 4.

$$K = \frac{1}{\Sigma(\frac{1}{Si})} \text{ .... Equation 4}$$

Based on the calculated value of WQI, the water is further classified as excellent (0-25), good (26-50), poor (51-75), very poor (76-100) and Not suitable (>100).

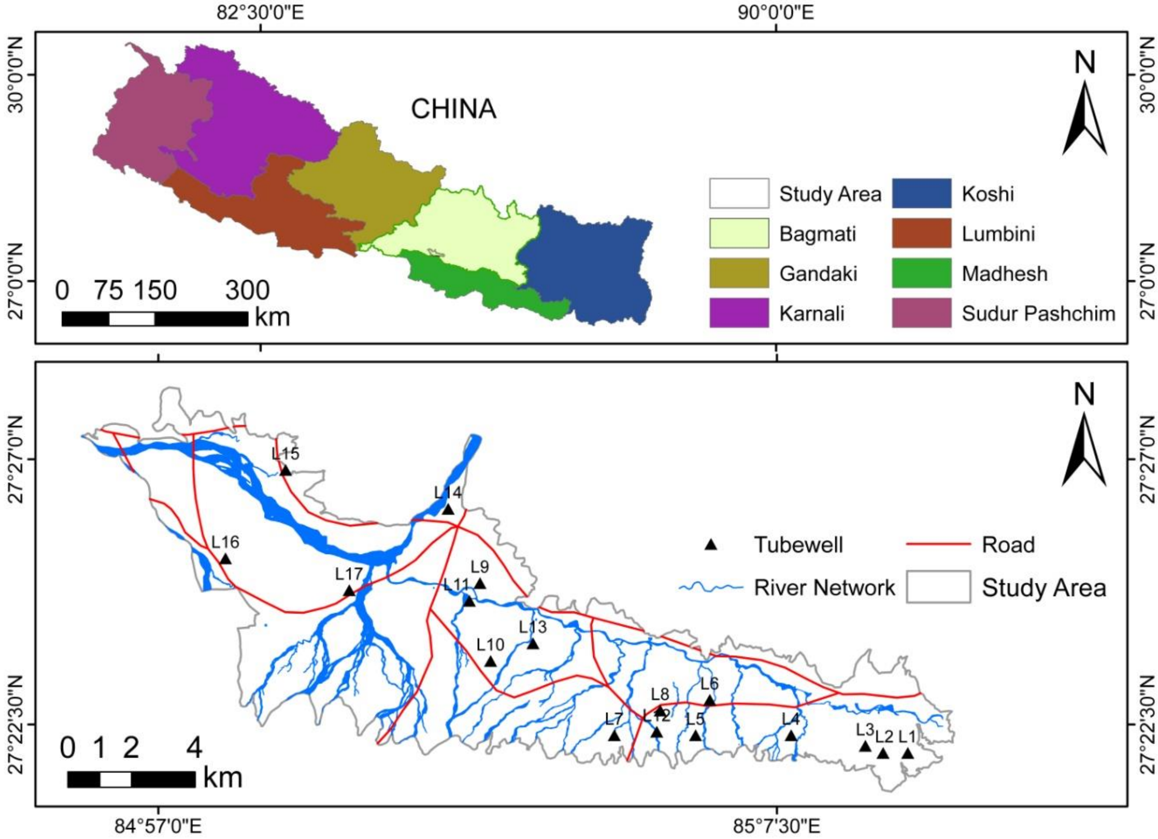

Figure 1. Location map of the study area showing tube wells used for sampling water

The suitability of groundwater for irrigation purposes was evaluated by several measures like EC (Richards, 1954), SH (Richards, 1954), %Na (Equation 5) (Wilcox, 1955), SAR (Equation 6) (Richards, 1954), SSP (Equation 7) (Todd, 1960), U.S. Salinity Laboratory (USSL's) classification (USSL, 1954), Wilcox diagram (Wilcox, 1948) and MR (Equation 8) (Raghunath, 1987).

$$\%Na = \frac{(Na+K)*100}{Na+K+Ca+Mg} \text{ .... Equation 5}$$

$$SAR = \frac{\text{Na}}{\sqrt{(Ca+Mg)/2}} \text{ .... Equation 6}$$

$$SSP = \frac{100*Na}{Ca+Mg+K} \text{ .... Equation 7}$$

$$MR = \frac{100*Mg}{Ca+Mg} \text{ .... Equation 8}$$

Where, the cations are expressed in mEq/L.

RESULTS AND DISCUSSION

Physical parameters

The physical parameters of the seventeen deep tube wells (Fig. 1) were analyzed statistically. The results are presented in box and whisker plots (Fig. 2). The values of pH lie within the range of 6.03-7.21 with an average value of 6.40 suggesting the groundwater in the study area is slightly acidic. Similarly, the values of EC and TDS lie within the range of 36.3-534 µS/cm and 24.8-323 mg/L respectively. The average concentration of EC is 111.36 µS/cm while, that of TDS is 71.03 mg/L. It indicates that the groundwater of the deep tube wells in the study area falls under the fresh (Freeze & Cherry, 1979) and low saline (Handa, 1969) categories. The average concentration of these parameters lies within the standards prescribed by NDWQS (2005).

Chemical parameters

The concentration ranges of major ions were analyzed statistically and were plotted in box and whisker plots (Fig. 3). The abundance of anions followed the order of $HCO_3^- > Cl^- > SO_4^{2-} > NO_3^-$ based on the average concentration while, that of cations followed the pattern of $Ca^{2+} > Na^+ > Mg^{2+} > K^+$. It signifies the prevalence of alkaline-earth metals (Ca+Mg) over alkalis (Na+K) and weak acids (CO_3 +HCO_3) over strong acids (Cl+ SO_4) in the samples (Fig. 4a). It signifies the hydrogeochemistry being controlled by carbonate and silicate minerals and the impact of sulfate minerals, halite minerals, and anthropogenic activities is low. Dissolution of carbonate minerals results Ca^{2+} and Mg^{2+} (Wang *et al.*, 2020). The weathering of halite and silicate minerals of feldspar originates Na^+ (Mostafa *et al.*, 2017) and the chemical breakdown of silicates (clay minerals) induces K^+ in the groundwater (Saha *et al.*, 2019). However, higher resistance of K^+ to chemical weathering, ion exchange and dissolution might have resulted in a lower concentration of K^+ as compared to Na^+ in the study area (Mallick *et al.*, 2018). The low concentrations of SO_4^{2-} and NO_3^- in the samples suggest the lack of gypsum and anhydrite and no sign of fertilizers, sewage effluents, and municipal/agricultural waste (Mallick *et al.*, 2018). The average concentrations of the ions lie below the standards prescribed by NDWQS (2005).

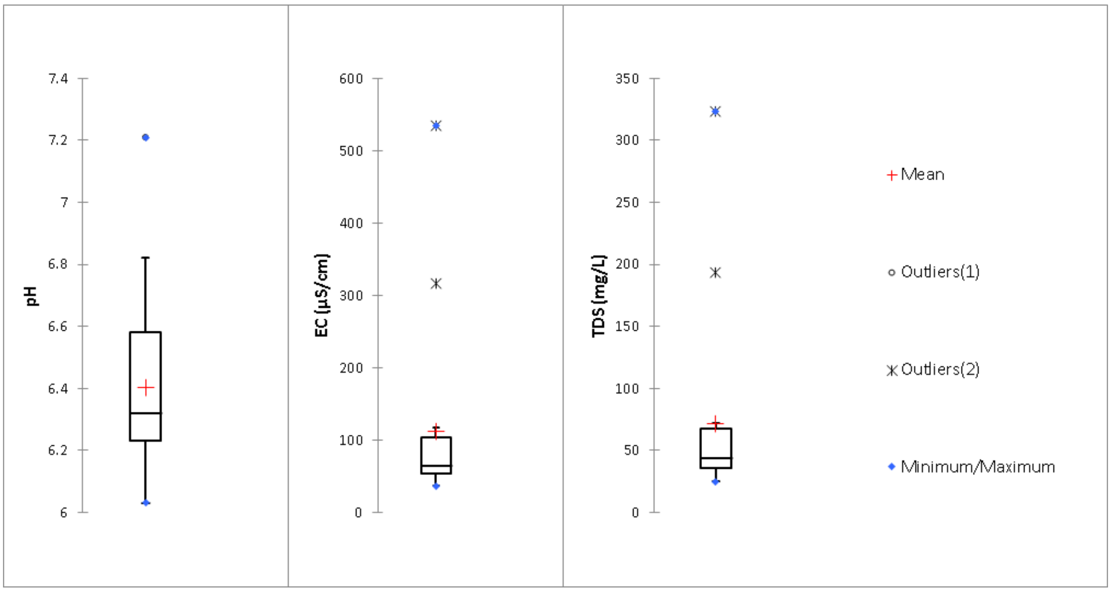

Figure 2. Box and whisker plot showing the statistical distribution of in-situ physical parameters

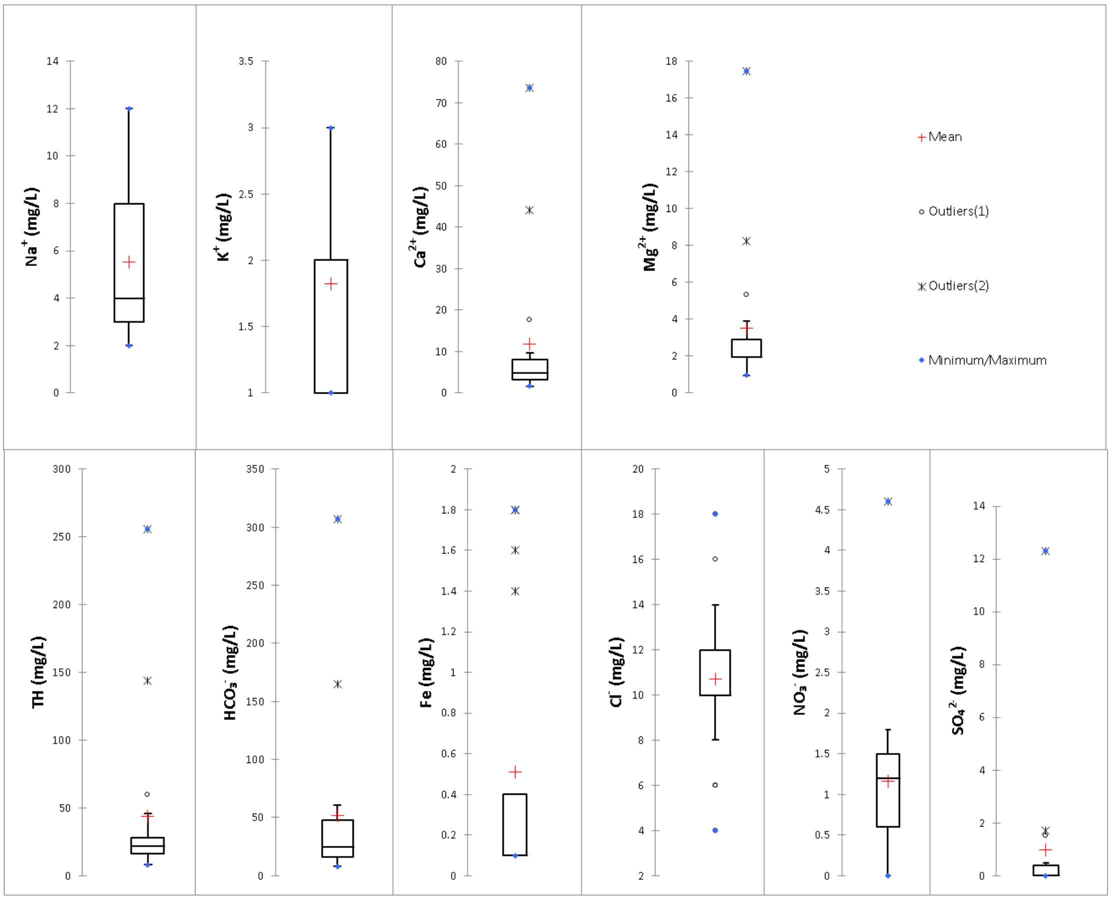

Figure 3. Box and whisker plot showing the statistical distribution of chemical parameters of deep aquifers

The average Fe concentration was 0.51 mg/L which is above the general standard and within the acceptable values set by NDWQS (2005) under the condition of unavailability of alternative sources (Fig. 3). Altogether, 5 samples were found to have a concentration higher than 0.3 mg/l, however, lies with the acceptable limits (3 mg/l) where the alternative sources are not available (NDWQS, 2005). Generally, the concentration of Fe is higher in deep groundwater because of an insufficient amount of oxygen to oxidize it into a ferric state. Because of less amount of oxygen in deep groundwater, Fe resides in a soluble ferrous state and doesn't oxidize easily (Pant, 2011).

Hydrogeochemical Characterization

The hydrogeochemical facies, a function of lithology, flow patterns, and solution kinetics of an aquifer (Raju *et al.*, 2009), explains the chemical composition of groundwater bodies of an aquifer (Mahaqi *et al.*, 2018). Based on the ionic content, the facies of the groundwater were classified and compared with a Piper diagram (Piper, 1944). Here the alkaline earth-metals (Ca^{2+} and Mg^{2+}) overpowered the alkalis (Na^+ and K^+) and weak acids (HCO_3^-) exceeds over strong acids (Cl^- and SO_4^{2-}), which indicates two hydrogeochemical facies, Ca-HCO_3 and mixed Ca-Mg-Cl type in the deep aquifer (Fig. 4a). The mixed fields (class 3 in piper diagram) indicate an anthropogenic influence (Piper, 1944), water-rock interaction (Wang *et al.*, 2023) and ion exchange process (Egbueri *et al.*, 2019). Similarly, the remaining fields (class 1) suggest recharge from freshwater (Xiao *et al.*, 2017).

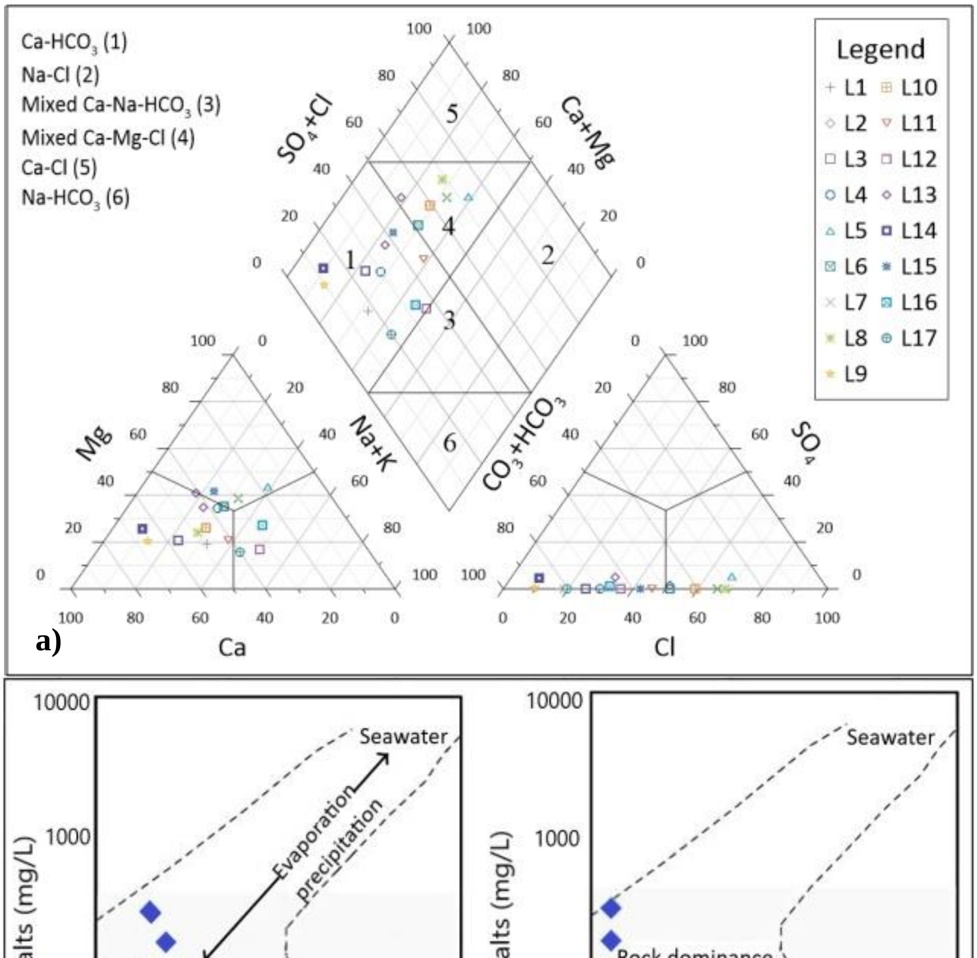

Figure 4. Piper trilinear diagram (a); and Gibbs diagram (b) for the groundwater samples

Several natural processes, evaporation or crystallization, precipitation, and rock-water interaction (Nematollahi *et al.*, 2016), which governs the hydrogeochemistry can be identified from the Gibbs diagram (Gibbs, 1970). The diagram indicates that rock dominance and precipitation dominance are the mechanisms that controls the occurrence of cations and anions in the deep aquifer of the study area (Fig. 4b). The rock dominance indicates the presence of rock-water interaction, whereas the precipitation dominance indicates the dissolved ions are derived basically from the rainwater, rather than originated from interaction with soils and rocks (Gibbs, 1970). The evaluation through Gibbs plots, as depicted in Fig. 4b, provides valuable insights into the hydrochemical origins of groundwater within the study area. This analysis emphasizes the close interplay between water and geological formations, signifying the intricate relationships shaping the groundwater composition.

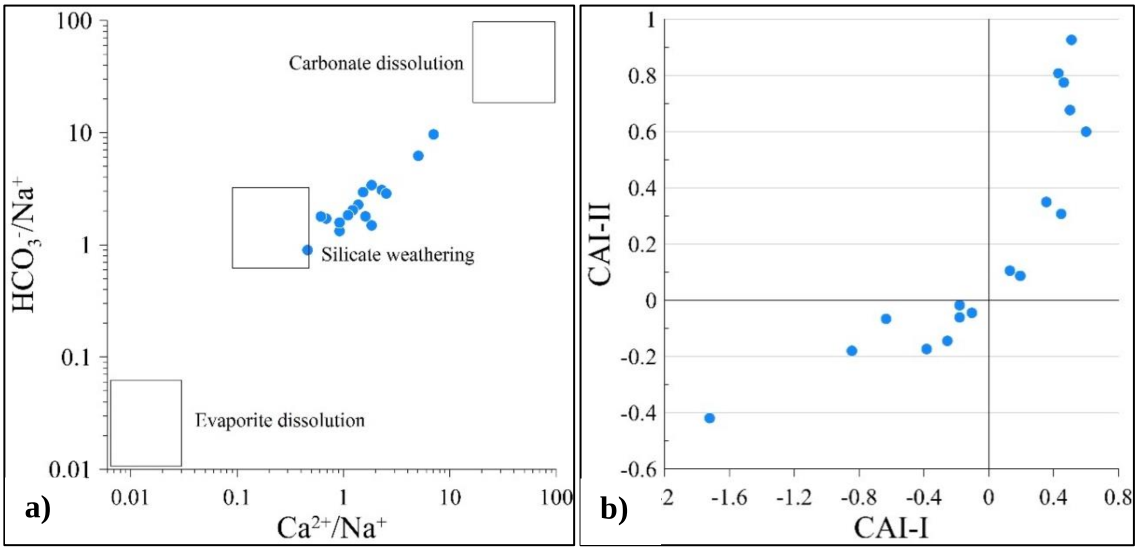

Figure 5 Gaillardet diagram based on Ca^{2+}/Na^+ vs HCO_3^-/Na^+ (a); and scatter plot of CAI-II vs CAI-I (b)

To further understand the specific mechanisms steering this water-rock interaction, the utilization of the Gaillardet model becomes imperative. As advocated by Wu *et al.* (2021), this model offers a more distinct and comprehensive explanation of the underlying processes. By applying the Gaillardet model, the study aims to unravel the intricate dynamics governing the chemical evolution of groundwater, thereby enhancing our understanding of the complex interconnections between geological formations and water quality in the study area. The Gaillardet model (Fig. 5a) confirms that the groundwater in the study area predominantly aligns within the action range associated mostly with silicate rocks and minor with the carbonate rocks, while displaying a notable distance from the evaporate action range. Considering the geological compositions in and around the basin, a preliminary conclusion can be drawn that the chemical attributes of groundwater in the basin are primarily influenced by the dissolution and filtration processes of silicate rocks and carbonate rocks.

Forward and reverse ion exchanges between Ca^{2+} and Na^+ control the hydrogeochemistry in the basin. A positive Chloro-alkaline index, indicative of reverse ion exchange, is the result of an ionic exchange between K^+ and Na^+ in water with Ca^{2+} and Mg^{2+} in rock/soil (Zaidi *et al.*, 2015). While a negative index of a sample is the result of an ionic exchange between K^+ and Na^+ in rock/soil with Ca^{2+} and Mg^{2+} in water (Egbueri *et al.*, 2019). In the present study, nine samples (L2, L5-L8, L10, L11, L13, and L15) and other eight samples showed reverse and forward ionic exchange reactions respectively (Fig. 5b). The synthesis of the information from the Gibbs plot, Gaillardet diagram, and Chloro-alkaline indices collectively indicates that the water chemistry in the area is predominantly governed by rock-water interaction. Specifically, silicate weathering emerges as the principal source of ionic constituents. The minor influence of carbonate dissolution is also noticeable, and this can be correlated with the weathering of the Lesser Himalayan carbonate rocks and their derivatives in the sediments. This insight underscores the geological processes shaping the chemical composition of the water, emphasizing the significance of silicate weathering as a major contributor.

Suitability of groundwater quality for drinking and irrigation purposes

The calculated values of several indices for the groundwater samples are shown in Table 1. The analytical results compared with NDWQS (2005) show that all parameters lie below the standard, making it suitable for drinking purposes. The quality index of drinking purpose suggests the water to be excellent to good based on the parameter analyzed. Based on the calculated value four samples indicate the water to be of good quality (26-50) and thirteen water samples lie in excellent class (0-25). However other parameters including the microbiological and other heavy metals and trace elements are to be assessed to insure better inferences.

The groundwater is suitable for irrigation in terms of EC, SH, SAR, and %Na as the samples of the deep tube wells in the study area contain low amount of dissolved solids which is further supported by USSL's classification (Fig. 6a) and Wilcox diagram (Fig. 6b). The EC and SH of the samples fall under the class of excellent to good (<750 µS/cm) while, the SAR, under the class of excellent (<10). Likewise, the samples fall under the permissible to excellent category of %Na since their values lie below 60%. Exceptionally, 17.65% and 23.53% of the samples are doubtful (60-80%) and unsuitable (>50) for irrigation in terms of SSP and MR, respectively (Table 1). The values of SSP and MR lie in the range of 10.053 - 79.739% and 23.622 - 71.464, respectively.

Table 1. Calculated value of drinking and irrigation water quality indices of the samples

Sample	EC (SH) (µS/cm)	SAR	% Na (%)	SSP (%)	MR	WQI
L1	103.5	0.493	35.816	42.749	28.539	16.088
L2	57.2	0.195	21.981	20.462	50.044	37.425
L3	116.7	0.449	24.969	27.827	26.689	19.085
L4	107.2	0.513	28.901	36.841	47.816	39.721
L5	56.7	0.465	44.587	52.572	71.464	47.221
L6	57.4	0.327	36.259	35.223	49.992	16.201
L7	91.7	0.349	39.398	39.477	57.135	15.619
L8	54.2	0.251	36.580	29.930	33.326	17.092
L9	316	0.363	13.797	14.984	23.622	8.985
L10	64.8	0.371	33.870	35.454	36.315	14.457
L11	71.3	0.513	44.995	49.837	33.403	42.402
L12	36.3	0.821	54.146	79.739	33.403	17.822
L13	46.8	0.278	29.244	26.596	45.498	23.818
L14	534	0.326	10.477	10.053	28.134	17.740
L15	47.9	0.279	26.224	28.084	54.538	8.648
L16	39.4	0.462	49.431	70.445	49.992	12.791
L17	92	0.822	45.156	74.363	28.539	9.258

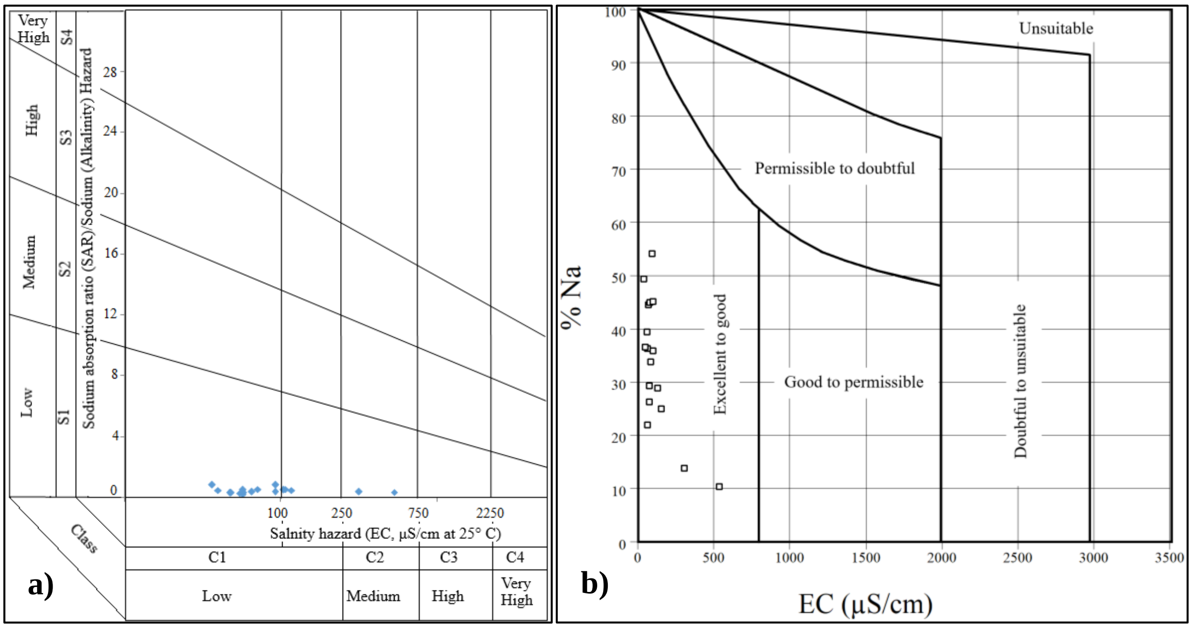

Figure 6. Classification of groundwater based on SH and SAR (a); and EC and %Na (b)

CONCLUSIONS

The groundwater, characterized by low saline is acidic, soft, and fresh in nature. The dominant anions and cations are in the order of $HCO_3^- > Cl^- > SO_4^{2-} > NO_3^-$ and $Ca^{2+} > Na^+ > Mg^{2+} > K^+$, respectively. The groundwater facies in the study area are $Ca\text{-}HCO_3$ and mixed Ca-Mg-Cl type. Silicate weathering and carbonate dissolution can be attributed to the sources of dissolved ions in the groundwater. The analytical results compared with NDWQS showed that all parameters lie below the standard, making it suitable for drinking purpose. In terms of drinking water quality index, the samples fall under excellent to good classes. Based on several indices like EC, SH, SAR, and %Na the groundwater can be utilized for irrigation purpose. In contrast, MR and SSP showed that 23.53% and 17.65% of the groundwater samples are unsuitable and doubtful for irrigation purpose respectively.

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AUTHOR CONTRIBUTIONS

NR, CBS, MK, and NS conceptualized the project. NR and AA carried out the fieldwork and laboratory work and analysis under the supervision of CBS, MK, and NS. NR and AA analyzed the results obtained from in-situ and laboratory tests. NR and CBS contributed to writing the original draft, editing and preparing the manuscript with coordination with AA, MK and NS.

CONFLICT OF INTERESTS

The authors do not have any conflict of interest pertinent to this work.

DATA AVAILABILITY STATEMENTS

The data that support the findings of this study are available from the corresponding author, upon reasonable request.

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