



Groundwater quality assessment in the La Mojana region of northern Colombia: implications for consumption, irrigation, and human health risks

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Abstract

Water quality is one of the most relevant issues related to water management, with water pollution and access to clean water for drinking and irrigation being common issues in developing countries. Groundwater is an available water source, especially where surface sources are scarce or unsuitable. In this sense, studies to improve knowledge of aquifers should be undertaken where information on groundwater resources is not available. In the current study, 50 groundwater samples were collected from rural and urban wells used by local communities for human consumption and to irrigate local crops. Several indices for drinking water and irrigation use have been used for the assessment of water quality. Conversely, the carcinogenic and noncarcinogenic human health risks due to exposure to heavy metals in the groundwater were estimated, as were the predominant hydrochemical characteristics. The groundwater water quality index (GWQI) shows values < 100 for all the samples; groundwater is recommended for drinking after disinfection. By contrast, the irrigation water quality index (IWQI) shows that 80% of groundwater samples pose a potential threat to irrigation, with restriction categories ranging from high to severe. The individual hazard quotients were < 1. However, the multielement and multipathway hazard index (HI) for children and adults were > 1, whereas As and Mn had a higher contribution to the HI. The Piper trilinear diagram shows that hydrochemical facies of Ca²⁺ and HCO₃⁻ are significantly dominant. By contrast, weathering of rocks and atmospheric precipitation is the dominant factors regulating the chemistry of groundwater in the aquifer system of La Mojana. Our findings indicate that there are significant potential noncarcinogenic health risks for local populations exposed to groundwater.

Keywords Aquifer management · Hydrogeochemical assessment · Environmental health · Drinking water risk

Introduction

On a global scale, groundwater quality has been significantly affected due to different anthropogenic sources such as urban sprawl, agricultural, livestock, and mining activities (Wagh et al. 2020; Torkashvand et al. 2021), as well as climate change, which represents a global challenge regarding water security due to water quality degradation (Nogueira et al. 2019; Islam et al. 2020). Groundwater is used as drinking

water and for other domestic needs by approximately 66% of the world's inhabitants, and approximately 50% of arable land is irrigated with groundwater (Gao et al. 2021; Bose et al. 2023). The assessment of groundwater quality is necessary for its use for different needs and is currently assessed in numerous aquifers worldwide (Margat and Gun 2013; Kashyap et al. 2018; Lu et al. 2018; Islam et al. 2019; Towfiqul Islam et al. 2020b).

In Colombia, due to low water demand and high availability of surface water, the groundwater is barely exploited (Lobo-Guerrero and Gilboa 1987). By contrast, the country has a potential aquifer area equivalent to 74.5% of the national territory, with estimated reserves in the order of 5848 km³ of water (IDEAM 2015a). In the Mojana region of Colombia, groundwater is the primary source of drinking water for populations. Although surface water is widespread in the region, it has been shown to struggle with

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contamination from different anthropogenic activities such as gold mining, agriculture, livestock, natural gas exploration, and domestic and industrial wastewater (Vergara Flórez et al. 2009; Pinedo-Hernández et al. 2015; Marrugo-Negrete et al. 2015; Enamorado et al. 2021).

Groundwater recharge, surface water quality, precipitation, and subsurface hydrochemical processes are factors affecting groundwater quality (Vasanthavigar et al. 2010). Notably, although water appears clear and odorless, it may contain dissolved contaminants that can degrade its quality and cause adverse effects on public health (Beyene et al. 2019). Several studies have been conducted focusing on groundwater contamination, its consequences on human health, and aspects related to the hydrochemistry of the processes that dominate in the aquifer (Zakir et al. 2020; Adimalla and Qian 2021; Ahmed et al. 2021; Bose et al. 2023; Bhavsar and Patel 2023).

Some toxic elements, such as arsenic (As), can frequently appear in the groundwater. The Nova Scotia groundwater is a well-documented case where this element has reached levels of approximately $5000 \mu\text{g L}^{-1}$. The origin is attributed to granitic bedrock obtained from pyrite and arsenopyrite, although in some cases, it is not well understood (Kennedy and Drage 2017). Other groundwater has been affected by the presence of not only As but also fluoride (F^-). The co-occurrence phenomenon in the Neogene-confined aquifer of the Guide Basin in China, with sediments as the main source of both pollutants, explains the increase in F^- concentrations in water by the precipitation of Ca^{2+} , which enhances the dissolution of F^- -containing minerals (Wang et al. 2018, 2024). Nitrate is a pollutant of concern in groundwater, especially for regions with intensive agriculture, such as India, where elevated nitrate concentrations in groundwater are associated with zones of maximum fertilizer application and 21 out of 36 states have nitrate levels above the allowable limit of 45 mg L^{-1} (Sarkar et al. 2021). Nitrate can easily reach groundwater in areas where manure has been applied for many years, with water concentrations near 1350 mg L^{-1} in shallow wells (Kyte et al. 2023). Exposure to F^- in drinking water causes dental fluorosis, and at higher concentrations, it leads to skeletal fluorosis (WHO 2004). By contrast, As and nitrate are carcinogens recognized by the IARC and classified in groups 1 and 2A, respectively (WHO and IARC 2010; WHO 2012).

Groundwater plays an important role in agricultural soil management; the higher the salinity of the water, the less suitable the resource for irrigation due to the potential increase in soil salinity, which is the most serious factor affecting plant growth (Imadi et al. 2016). Higher salt contents may result in low yields and sterile grains of rice; new varieties of salt-tolerant rice are required to address the issue (Paul and Rashid 2017). In the groundwater, the Ca^{2+} , Mg^{2+} , Na^+ , HCO_3^- , SO_4^{2-} , and Cl^- ions typically comprise

most of the dissolved solid's load; knowledge of the levels of these ions is necessary for the proper management of the exploitation of this water resource.

Water quality indices combine several variables into a single value, which is then associated with a category of risk that defines the use for drinking and irrigation. The irrigation water quality index (IWQI) of Meireles et al. (2010) is one of the most used; however, several other indices, such as Bascaron (1979), are widely accepted. Other authors proposed their own index based on methods that incorporate machine learning and AI (Manocha et al. 2023; El Morabet et al. 2023).

Comparable to the water quality indices, the human health risk assessment is used to evaluate the potential risk to human health and involves the exposure pathway, pollutant concentrations in the media, and exposure factors to calculate the exposure dose for comparison against a toxicological benchmark (WHO 2021). The exposure pathway of groundwater ingestion is a significant route of exposure to toxic substances, in some cases with a hazard quotient > 1 (Liu et al. 2023; Hou et al. 2023).

Despite the importance of aquifers to the population, no studies in the Mojana region have focused on groundwater resources. Thus, the objectives of this study were as follows: (1) to evaluate the quality of groundwater for drinking and irrigation purposes; (2) to study the health risks associated with potentially toxic elements in the study area; and (3) to identify the hydrochemical processes prevailing in the aquifer system.

Materials and methods

Study area

La Mojana region, located in northern Colombia, consists of an inland delta (Nardini and Franco Idarraga 2016) with an area of 9100 km^2 , mainly swamp systems. The Magdalena River, the largest in the Andean region, with a basin of $266,541 \text{ km}^2$, the Cauca River with $58,840 \text{ km}^2$, and the San Jorge River with $16,700 \text{ km}^2$, converge here (Aguilera-Díaz 2004). During the rainy season, these rivers frequently overflow and receive treated and untreated wastewater from the country's main urban, industrial, and metal mining areas. In the case of the Cauca River, an estimate shows that specific amount of pollution discharged in the upper Cauca River basin was $131.6 \text{ T BOD}_5/\text{day}$ and between 300 and 400 T/day of sediment (Galvis et al. 2018).

The La Mojana aquifer system is highly dependent on the climatic and hydric variability of the region, especially on the El Niño-Southern Oscillation phenomenon, since during the warm phase of El Niño, when the levels of the swamps are low, recharge is scarce. By contrast, during the

cold phase of La Niña, when the swamps reach their maximum depths, recharge is high, suggesting a high potential for altering the quality of groundwater as a result of surface water contamination processes, which, due to water flow in terms of the hydrological cycle, may be interfering considerably with the quality of the groundwater resource (Marrugo-Negrete et al. 2019).

This study was conducted in the municipalities of Majagual, San Marcos, San Benito Abad, Sucre, La Unión, Guaranda, and Caimito from the Sucre department in the La Mojana region (Fig. 1). These seven municipalities have an area of approximately 5123 km² and a population of 162,943 inhabitants who use the aquifer of the same name for drinking water supply or irrigation (Huguett et al. 1988; Corpomojana and Unicor 2017). This study area is part of the La Mojana aquifer system, which is the fourth largest aquifer system in the country, with 12,672 km² distributed in 34 municipalities (IDEAM 2015a). However, for this study, groundwater quality monitoring was prioritized in seven municipalities of the department of Sucre affected by environmental impacts of anthropogenic origin (IDEAM 2015b; Marrugo-Negrete et al. 2019). This aquifer system developed in a tectonic trench up to 6000 m deep, whose bedrock consists of low-grade metamorphic rocks of Cretaceous age

(Graterol 2006), has the entire stratigraphic record from the Oligocene to the present (Cediel et al. 2003; Cerón et al. 2007; Bermúdez Aguirre 2010; Arminio et al. 2011; Mora-Bohórquez et al. 2020), and has an average geothermal gradient estimated at 22.4 °C (Alfaro et al. 2009).

Water sampling and chemical analysis

The locations of the selected sampling stations are shown in Fig. 1. Groundwater samples were collected from tube wells used for drinking or irrigation. A total of 50 groundwater samples were collected during the month of February in the rainy season of 2022. Prior to sample collection, groundwater pumping was performed until stable pH and electrical conductivity (EC) were reached, and the exact location of each sampling point was recorded by GPS. High-density polypropylene, amber, or colorless glass bottles were used for sample collection following the prewashing, preservation, and sampling procedures described by Standard Methods for the Examination of Water and Wastewater (APHA et al. 2017). The bottles with the samples were labeled, preserved, refrigerated at a temperature of 4 °C, and quickly transported to the laboratory for further analysis.

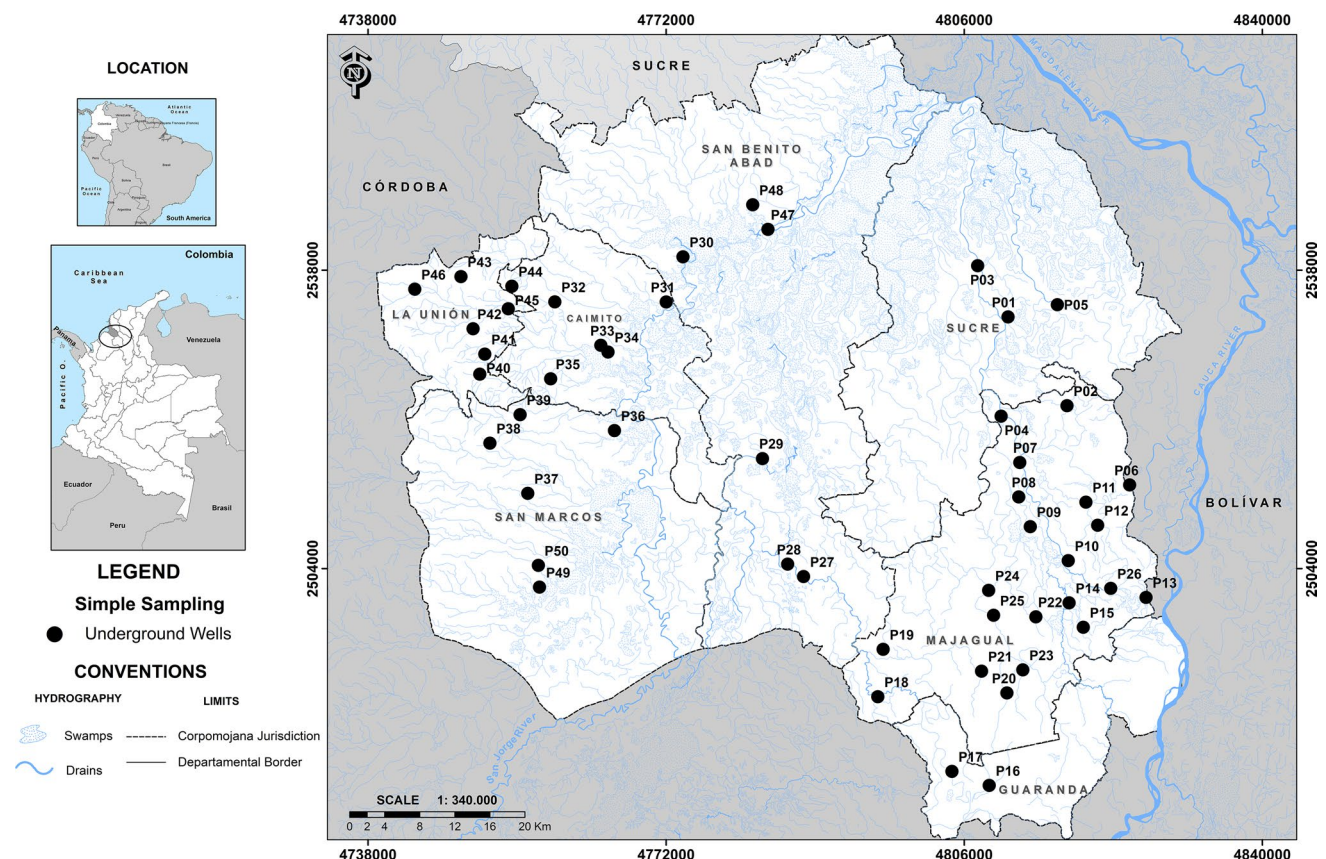


Fig. 1 Map of the study area showing the sampling location

The physicochemical characterization of samples was performed by analyzing the potential of hydrogen (pH), dissolved oxygen (DO), EC, turbidity, temperature, and total dissolved solids (TDS) in situ using a HANNA model HI9829 multiparameter probe.

Chlorides (Cl^-) were measured using the argentometric method SM 4500 Cl^- B. Nitrates were measured using the spectrophotometric method SM 4500 NO_3^- -B. Bicarbonates (HCO_3^-), carbonates, and total alkalinity were measured using the titration method SM 2320 B. Total coliforms (TC) and fecal coliforms (*Escherichia coli*) were measured using the enzyme substrate test SM 9223 B. Metals (Ca, Mg, Na, K, Zn, Pb, Cd, Cu, Co, Mn, and Cr) were measured using the Inductively Coupled Plasma Optical Emission Spectrometry EPA Method 6010D using a Thermo Scientific iCAP PRO X Duo ICP-OES, Hg by cold vapor atomic absorption spectroscopy by EPA Method 7473 using a Lumex RA 915 with Zeeman correction and As by Continuous Hydride Generation Atomic Absorption Spectrometric Method 3114 C using a Thermo Scientific ICE 3500 Series and VP100 Continuous Flow Vapor System (US EPA 2007, 2018; APHA et al. 2017).

Water quality and human health risk

Water quality for drinking and irrigation purposes was evaluated by calculating different indices: GWQI (Towfiqul Islam et al. 2020b), IWQI (Meireles et al. 2010), Sodium Absorption Ratio (SAR) (Richards 1954), Residual Sodium Carbonate (RSC) (Eaton 1950), Soluble Sodium Percentage (SSP) (Todd and Mays 2005), Sodium Percentage (Na%) (Wilcox 1955), Kelley's Ratio (KR) (Kelley 1963), Permeability Index (PI) (Donen 1964), Total Hardness (TH), and Magnesium Hazard Ratio (MHR) (Raghunath 1987).

The carcinogenic (due to As) and noncarcinogenic (due to As, Fe, Mn, and Zn) human health risks were estimated through the Risk Assessment Guidance for Superfund (US EPA 1989). Two exposure routes, the ingestion of groundwater and dermal contact with groundwater, were considered (US EPA 2004), and the scenario of reasonable maximum exposure to obtain the higher risk was used as criteria. The equations for the calculation of exposure dose, hazard quotient (HQ), HI, and cancer risk (CR), and variables of exposure factors are shown in the Supplementary Material (Table S1), based on the study of Towfiqul Islam et al. (2020a) and the Handbook of Exposure Factors (US EPA 2011).

Hazard analysis of potentially hazardous activities

The methodological guidelines proposed by Foster and Hirata (1991) on contaminant loads potentially hazardous to groundwater were followed to identify the potentially

hazardous activities in the La Mojana aquifer system. A soil categorization according to potentially hazardous activities was achieved on the basis of the existence of an interaction between the subsoil and the anthropic activities that are carried out on the surface soil. As a result of this interaction, there is both the possibility of generating a risk of contamination and not, depending on the physical, chemical, and biological properties of the soil, the geomorphology, the topography, and the contaminant transport processes.

The land use and land cover data between 2018 and 2020 suggested by the Institute of Hydrology, Meteorology, and Environmental Studies were analyzed. The absence of wastewater treatment systems, inadequate disposal of solid waste in urban and rural areas, point-source discharges from slaughterhouses, and flooding of graveyards during rainy seasons were identified as potential sources of contaminant loads. The nonpoint sources of discharge included contamination at wellheads during periods of high water, gold mining activities, and overflows of the Cauca River, which receives wastewater from big cities, industries, farmers, and mining facilities.

The cartographic data were recategorized in a Geographic Information System following the spatial distribution of land use in the study area and considering the category hazard assigned by Foster and Hirata (1991).

Hydrogeochemical assessment

The Piper three-linear diagram (Piper 1944) was used to understand the sources of the constituent salts dissolved in the water, and then a comparison was made between two sampling campaigns conducted during a low water season in 2017 (namely, dry season, data from Corpomojana and Unicor (2018)) and another high water season (namely, the wet season, data from this study), with flooding persisting for more than 18 months at the time of sample collection in 2022.

Gibbs diagrams can be used to indicate the mechanisms of formation of major ion hydrochemistry based on evaporative crystallization, weathering of rocks, and atmospheric precipitation that correspond to groundwater chemical composition processes (Gibbs 1970).

The weathering potential of silicates and carbonates in groundwater was evaluated by the Gaillardet diagram (Gaillardet et al. 1999). Conversely, the plot of ratios ($\text{SO}_4^{2-} + \text{HCO}_3^-$) versus ($\text{Ca}^{2+} + \text{Mg}^{2+}$) and $[(\text{Mg}^{2+} + \text{Ca}^{2+}) - (\text{SO}_4^{2-} - \text{HCO}_3^-)]$ versus $[(\text{Na}^+ + \text{K}^+) - \text{Cl}^-]$ was used to determine whether cation exchange produces a significant impact on chemical characteristics (Li et al. 2015, 2018; Liu et al. 2021; Yuan et al. 2023).

Results and discussion

Physicochemical parameters

The descriptive statistics of the physicochemical and microbiological properties detected in the groundwater and the maximum admissible levels are presented in Table 1. The values of pH, EC, DO, TDS, and depth ranged from 5.53 to 8.37 (mean: 7.44), 34 to 616 $\mu\text{S cm}^{-1}$ (mean: 279.7 $\mu\text{S cm}^{-1}$), 0.5 to 6.3 mg L^{-1} (mean: 2.27 mg L^{-1}), 17 to 308 mg L^{-1} (mean: 141.3 mg L^{-1}), and 5 to 185 m (mean: 92.5 m), respectively. According to the pH values, only two samples are not within the permissible limits (6.5–9.0) established by the regulations for drinking water or risk, which indicates good quality in 96% of the groundwater samples of the aquifer. EC and TDS classify the groundwater as freshwater (EC < 1500; TDS < 1000) (Freeze and Cherry 1979; Brindha and Kavitha 2015; Idowu et al. 2017), reflect low degrees of mineralization related to water–rock interaction, and indicate little water transit within the aquifer (AlSuhaimi et al. 2019); they comply with Colombian legislation (MAVDT and MPS 2007) and WHO guidelines (WHO 2017), except for that established by the EU (EU 2020), where conductivity exceeds the recommended values in 58% of the samples. The DO content reveals the recent recharge of the aquifer by presenting results between 1.03 and 6.3 mg L^{-1} for 88% of the samples (Chen and Liu 2003). This may be associated with water recharge processes through fault zones during periods of flash flooding that can generate oxygenation conditions due to the mixing of water in the system and alter the EC. Main cations and anions presented the decreasing order $\text{Na}^+ > \text{Ca}^{2+} > \text{Mg}^{2+} > \text{K}^+$ and $\text{HCO}_3^- > \text{Cl}^- > (\text{NO}_3^- \text{ and } \text{SO}_4^{2-}; < \text{LD})$. In terms of cations and anions, only the average HCO_3^- exceeds the limits recommended by the UCCC (< 91) for irrigation water. In addition, 74% of the groundwater samples do not meet this criterion. Na^+ is the dominant cation with an average value of 30.7 mg L^{-1} (range: 0.22–59.5 mg L^{-1}). By contrast, HCO_3^- corresponds to that of the anions, with an average value of 170.3 mg L^{-1} (range: 11–360 mg L^{-1}). Na^+ and HCO_3^- exhibit positive correlations with TDS ($r_{\text{Na}^+} = 0.764$; $r_{\text{HCO}_3^-} = 0.958$), Ca^{2+} ($r_{\text{Na}^+} = 0.362$; $r_{\text{HCO}_3^-} = 0.867$), and Mg^{2+} ($r_{\text{Na}^+} = 0.314$; $r_{\text{HCO}_3^-} = 0.836$), revealing an alkalinizing effect in groundwater (pH > 7; 86% of samples) and suggesting that water–rock interaction is a possible key contributor to the mineralogy of the groundwater samples studied (Li et al. 2018).

The average concentrations of Fe, Mn, Zn, and As were 0.5 mg L^{-1} (range: 0.011–4.18 mg L^{-1}), 0.17 mg L^{-1} (range: 0.003–0.78 mg L^{-1}), 0.038 mg L^{-1} (range: 0.0024–0.18 mg L^{-1}), and 0.0045 mg L^{-1} (range:

0.00037–0.00377 mg L^{-1}), respectively. Compared with the Colombian regulations and the permissible limit of WHO for drinking water, all the samples of Mn and Zn, are within the permissible limits. By contrast, 4% and 8% of the samples exceeded the WHO permissible limit for drinking water for Fe (3.0 mg L^{-1}) and As (0.01 mg L^{-1}), respectively. The potentially toxic elements such as Cd, Pb, Ni, Co, Cr, Cu, and Hg, were below the detection limit in 100% of the samples, although a certain part of the study area remains flooded after the Cauca River breakage in 2021 at the site known as “Cara de gato,” there was no transport of these elements from the surface water to the aquifer. Nitrates were not detected in any of the groundwater samples, regardless of the heavy use of chemical fertilizers in agricultural activities conducted in the study area.

According to the microbiological results, TC and *E. coli* were present in 86% and 40% of the water samples, with a maximum value of 4,360 NMP/100 mL (mean: 641.3) and 505 NMP/100 mL (mean: 74.2), respectively. WHO and Colombian regulations clearly establish that 100 mL of water samples should not contain coliforms; their presence indicates that there is a contamination pathway between a source of bacteria (e.g., surface water, animal waste, and contaminated rainwater) and the water supply.

The physicochemical properties, anions, cations, and potentially toxic elements in the groundwater samples are within the range or even lower than the studies of different groundwaters worldwide listed in Table 1. Compared with the previous study in the area conducted in the dry season (Corpomojana and Unicor 2018), all the variables had lower values, except for HCO_3^- and Na^+ . These higher values could be related to water–rock interaction, aquifer recharge, and flooding or precipitation. A similar tendency was reported by Gao et al. (2021) in aquifers of the northern Shandong Peninsula, China.

Water quality

Associated with the comparison of results with the regulations for evaluating water quality, different indices were calculated to determine the feasibility for potable use or irrigation (Fig. 2). Notably, groundwater in the study area is used for drinking or irrigation purposes, so it is important to ensure that water quality is not compromised, as it can greatly affect human health and soil fertility for crop yields. In this sense, GWQI is a valuable and unique index to identify water quality and its suitability for drinking water by representing the composite influence of different parameters. The GWQI results ranged from 19.6 to 95.6% (mean: 44.1), suggesting that the water quality at all sampling sites was good to excellent for drinking. However, elimination treatment for *E. coli* bacteria should be considered since the records of the water quality risk index for human

Table 1 Physical and chemical properties of groundwater, limit values, and relevant literature data for comparison

	Depth	pH	EC	TDS	DO	TC	<i>E. coli</i>	HCO ₃ ⁻	Cl ⁻	Na	K	Ca	Mg	Mn	Zn	Fe	As	
<i>This study</i>																		
Mean (n=50)	92.5	7.44	279.7	141.3	2.3	641	74.2	170.3	11.98	30.7	2	20.3	10.6	0.17	0.038	0.5	0.0045	
SD	35.1	0.59	149.2	77.2	1.4	787	118.3	95.5	5.15	16.7	1.25	14.1	8.2	0.2	0.04	0.84	0.0087	
Min	5	5.53	34	17	0.5	0	0	11	3.37	0.22	0.46	0.75	0.51	0.003	0.0024	0.011	0.00037	
Max	185	8.37	616	308	6.3	4,360	505	360	25.2	59.5	6.2	51.9	34.4	0.78	0.18	4.18	0.0377	
<i>Drinking water guidelines</i>																		
Colombia legislation (MAVDT and MPS 2007)		6.5–9.0	1000		0	0	0	250										0.01
WHO (WHO and IPCS 1996; WHO 2011, 2017)		6.5–8.5	1400	1000	0	0	0	500	250	50	12	75	125	4	5	3		0.01
EU (2020)		6.5–9.6	250		0	0	0	250	200									0.01
<i>Irrigation water guidelines</i>																		
FAO (1985)		6.0–8.5						600	1,100	900		400	60					
UCCC (1974)		6.5–8.5						91	133	68–204								
<i>Other studies</i>																		
Krishan et al. (2023)		7.66	6,619	4,435				322	1,960			465	390					
Siraj et al. (2023)		7.48	870	435				356	107.4			33	43		0.23			
Wali et al. (2022)		5.9–8.4	64–1,240	32–207				0.7–40	0.7–5.4	0.1–17.9	22–40	0.3–61.8	2.0–19.0		0.5	0.1–7.5	6.5–8.5	
Rakib et al. (2022)		8.33	180					1.6	10.2	0.8	0.8	2.1	1	2.2 × 10 ⁻³	1.4 × 10 ⁻³	8.7 × 10 ⁻³	5.3 × 10 ⁻⁴	
Towfiqul Islam et al. (2020b)	15–145	7.34						221.4	2,005.7	701.6		88.5	105.5	0.47	6.24	6.24	3 × 10 ⁻⁵	
Islam et al. (2019)														0.684		7.72	0.0088	
Kashyap et al. (2018)														0.025		0.272	0.0027	
Lu et al. (2018)																		1.09
Corpomojana and Unicorn (2018)		7.63	373.7	204				138.9	24.5	18.2	2.9	41.3	11.3					

Metals, anions, TDS and OD (mg L⁻¹), EC (μS cm⁻¹), TC, and *E. coli* (NMP/100 mL), depth (m)

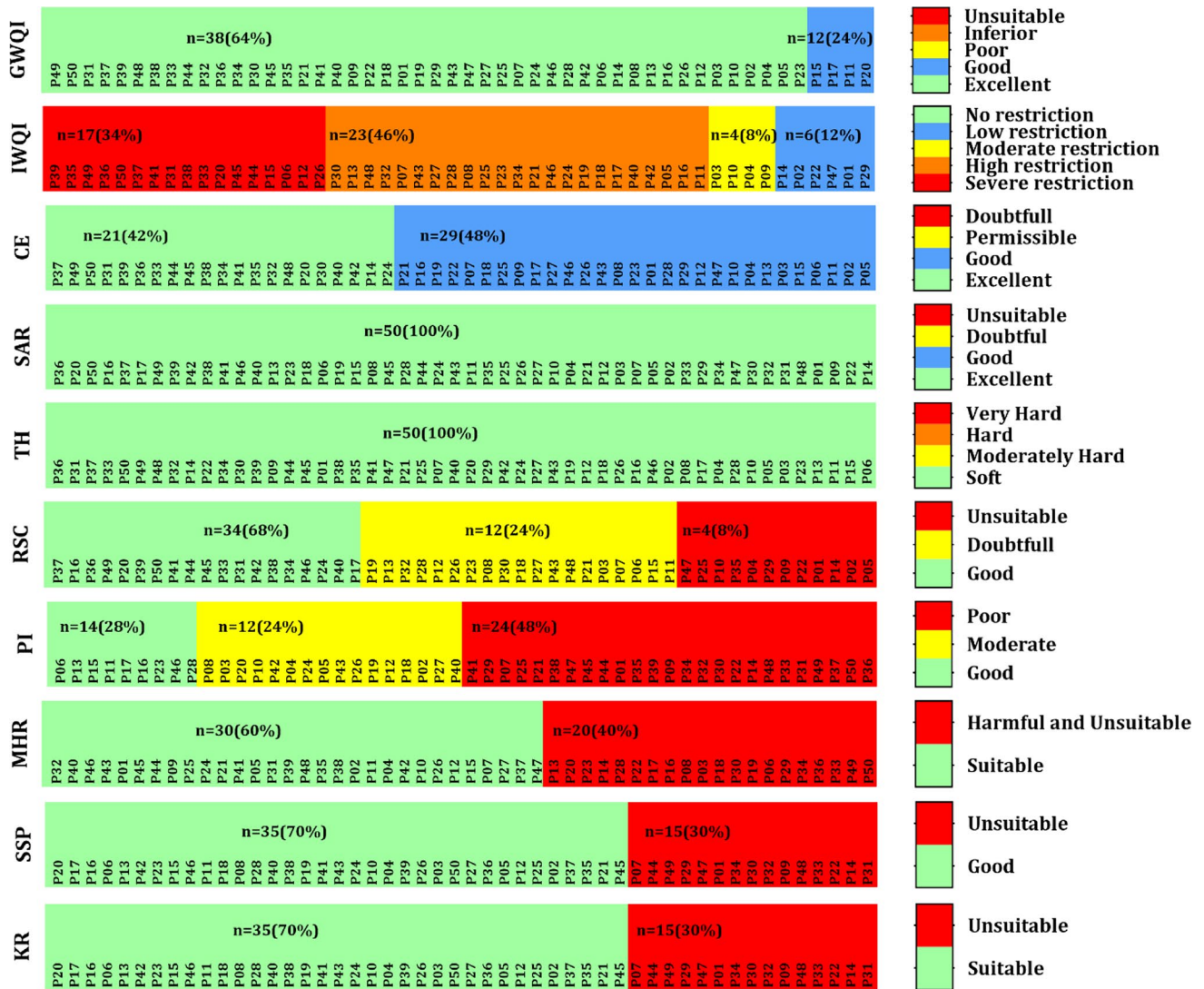


Fig. 2 Classification of groundwater in the La Mojana aquifer system according to GWQI, IWQI, EC, SAR, RSC, KR, SSP, PI, MHR, Na%, and TH indices for drinking and irrigation uses

consumption published by the Colombian Ministry of Health and Social Protection for some municipalities in the study area showed high to medium sanitary risks (MVCT et al. 2020; MSPS et al. 2023).

Regarding irrigation quality, the EC values of groundwater in the study area are considerably low, ranging from 34 to 616 $\mu\text{S cm}^{-1}$ (mean: 279.7 $\mu\text{S cm}^{-1}$) (Table 1). Using the classification scheme of Richards (1954), 42% of the samples were in the excellent category, whereas 58% were in the good category. This implies that, with respect to EC, 100% of the samples are suitable for irrigation. SAR values ranged from 0.04 to 5.52 with a mean of 1.68 (Fig. 2); therefore, the water quality of the study region is excellent for 100% of the samples. Therefore, it is unlikely that prolonged irrigation with groundwater could impede soil infiltration, which would eventually lead to alkaline soils (Mukherjee

et al. 2022). The Na% ranged from 12.7 to 87.1%, with a mean of 47.2%. Only 6% (3 samples) were found to have excellent water quality, and 36% were classified as good and permissible (18 samples per classification). However, 10% (5 samples) were considered doubtful, and 12% (6 samples) were considered unsuitable in the study region. Therefore, it is certain that 78% of the groundwater samples are generally suitable for irrigation purposes with respect to their Na% values. However, 22% of the samples are dominated by sodium content, so an increase in the concentration of sodium in the irrigation water could generate a cation exchange (Na vs. Ca/Mg), reducing the drainage capacity of the soil (Singh et al. 2021; Sunkari et al. 2022). SSP values ranged from 8.94 to 86.7%, with an average of 45.5%. Of the samples, 70% were classified as good for irrigation, whereas 30% were classified as unsuitable, suggesting the potential

effects of Na^+ and K^+ on soil permeability. The RSC values ranged from -0.16 to 2.66 , with an average of 1.05 . According to the results, 24% of the samples are classified as doubtful and 8% as unsuitable, whereas 68% are safe for irrigation, suggesting the low potential of irrigation water to induce soil alkalinity (Zhou et al. 2020). KR ranged from 0.10 to 6.61 , with a mean of 1.36 , where 70% of the samples are suitable for irrigation (sodium deficit), whereas 30% are unsuitable for irrigation ($\text{KR} > 1$; higher Na content than the sum of Ca and Mg).

Considering TH, 100% of the samples are classified as soft ($\text{TH} < 75$), so the distribution of water through water supply systems (pipes) does not present incrustations. The MHR ranged from 16.3 to 76.2 , with a mean of 46.4 . Of the samples, 40% showed $\text{MHR} > 50$, suggesting potential threats to soil quality. Finally, PI values ranged from 60.4 to 303.1 , with a mean of 112.7 . Of the samples, 28% and 24% were classified in the good and moderate categories, respectively, whereas the remaining 48% were classified in the two lowest quality categories (poor and bad), suggesting that a prolonged use of this groundwater has a negative impact of the soil permeability, since its groundwater characteristics have the potential to modify the Na, Ca, Mg, and HCO_3^- contents in the soil; Consequently, the plant growth

and crop yield may be severely affected, mainly by alkali metals (Na^+ and K^+) and their dissolved chemical complexes (carbonates) (Kurunc et al. 2020; Phogat et al. 2020; Ahmed et al. 2021).

According to SAR, TH, RSC, SSP, and KR indices, most of the groundwater wells were suitable for irrigation purposes; however, when considering the IWQI developed by Meireles et al. (2010), 46% and 34% of wells showed high restrictions (IWQI: 40–55) and severe restrictions (IWQI: 0–40), suggesting that it should be used in soils with high permeability, without compacted layers, and moderate to high tolerance plants since IWQI considers the cumulative effects of the influencing parameters (Makki et al. 2021).

Potential threats of human activities

Figure 3 shows the potential groundwater hazard map for La Mojana. Substantially high hazards were found in urban areas and for the tributary streams to the marshes of the municipality of San Benito de Abad, where pollution has been linked to the discharge of domestic and nondomestic wastewater from the municipalities of Sincelejo, Corozal, and Sincé. The high hazard corresponds to the water bodies of the Swamp system and the San Jorge and Caño

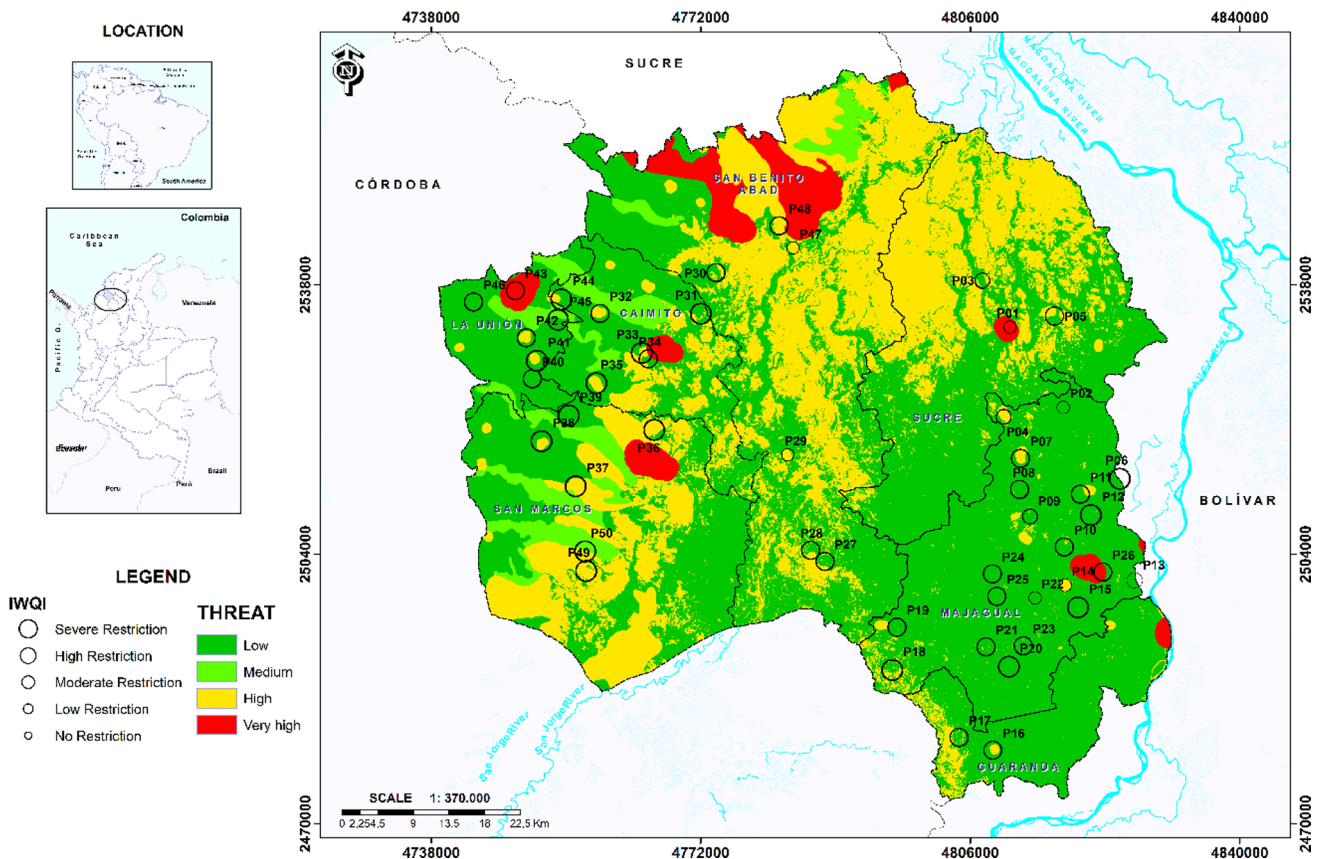


Fig. 3 Map of the spatial distribution of the IWQI and potentially hazardous activities in the La Mojana region

Mojana riverbeds, where sedimentation processes and the accumulation of potentially polluted alluvial sediments can be observed. Conversely, extensive areas of agriculture and livestock farming are also found in these regions. The area categorized as medium hazard includes the alluvial deposits of the streams and creeks, where the pollution load is mainly due to the discharge of domestic and nondomestic wastewater from the municipalities of Sahagún, Chinú, and Pueblo Nuevo. The areas with low hazards correspond to locations where human activities have not yet been identified.

Based on the spatial distribution of areas with potential hazards, the relationship to the IWQI findings has been analyzed. Figure 3 shows the regions of Caimito, La Unión, San Benito Abad, and San Marcos, where the IWQI has primarily high and severe restrictions; meanwhile, in the Majagual area, where low hazards occur predominantly, most of the monitored wells showed low to moderate restrictions.

There is an overall correlation between the potential hazards established by mapping and analysis of land use and land cover in La Mojana and the IWQI restriction categories, with some exceptions, as in the case of the municipality of Sucre. Therefore, it is evident that, while groundwater contamination processes are governed by the transport dynamics of environmental systems per se, there is a marked incidence of contamination associated with the proximity of possible sources. Therefore, wells located in areas with a high hazard, according to the land use, should be prioritized for protective actions (Bawa and Dwivedi 2019; Huerfano-Moreno et al. 2023).

Human health risk assessment

HQ, HI, and CR used for noncarcinogenic and carcinogenic health risks due to ingestion and dermal contacts with specific elements for adults and children are shown in Table 2. The HI values for both age groups exceeded the safety limit (HI > 1), with an HI value greater for children than adults. As the element with the highest HQ value for the ingestion pathway, while Mn was the highest for the dermal contact pathway, the contributions of Fe and Zn were relatively less relevant for the noncarcinogenic health risks.

Previous health risk assessments in the study area have focused on exposure to mercury from fish consumption and have shown that the estimated weekly intake for children and women of childbearing age was above the provisional tolerable weekly intake (Marrugo-Negrete et al. 2020). In the Mojana area, the other exposure pathway assessed was rice consumption, but the mercury HQ values were always < 1 (Enamorado-Montes et al. 2021).

Dermal contact with groundwater is the primary route of Mn exposure in the Mojana region. Mn becomes potentially toxic with prolonged exposure and can cause neurological damage that is sometimes irreversible (Atsdr 2012; Avila et al. 2013). Conversely, ingestion of groundwater is the primary route of exposure to As in this area, and this route of exposure has been specifically associated with lung cancer, even at very low concentrations (Rinklebe et al. 2019; WHO 2022).

In the current study, $CR_{\text{ingestion}} > CR_{\text{dermal}}$, the values for the dermal exposure pathway were within the safe limit for both population groups; however, the values for the ingestion exposure pathway exceeded the acceptable range of cancer risk, which is between 1×10^{-6} and 1×10^{-4} ; the $CR_{\text{ingestion}}$ was higher for children than for adults. Long-term ingestion of groundwater from wells in the La Mojana aquifer system may pose a potential cancer risk to the population due to the occurrence of As. The issue may be more severe for this zone due to flash floods or long periods of time that can modify the physicochemical quality of groundwater by taking advantage of contaminants moving through the fissures that have not yet closed due to the dry season (Vargas Quintero 2010).

Hydrochemical type evolution

According to the Piper diagrams in Fig. 4a, during the dry season, there is a dominance of calcic bicarbonate waters and even some chloride waters that show periods of residence within the aquifer measured in thousands to millions of years (black circle in Fig. 4a). On the contrary, the influence of strong floods during the wet season placed the waters in the calcic and sodic bicarbonate facies without a specific

Table 2 Hazard quotient (HQ), hazard index (HI), and carcinogenic risk (CR) from oral and dermal exposure to heavy metals from the groundwater

	HQ _{Ingestion}		HQ _{dermal}		HI			
	Adult	Child	Adult	Child	Adult	Child		
As	0.5288	0.495	As	0.0026	0.0053	As	0.53	0.50
Zn	0.0009	0.0008	Zn	0.0003	0.0005	Zn	0.00	0.00
Fe	0.0004	0.0003	Fe	0.0385	0.0792	Fe	0.04	0.08
Mn	0.0142	0.0133	Mn	0.411	0.8445	Mn	0.43	0.86
ΣHQ	0.5443	0.5094	ΣHQ	0.4524	0.9295	ΣHI	1.00	1.44
Carcinogenic risks (CR) for As								
CR _{Ingestion}	2.00E-04	9.48E-02	CR _{dermal}	2.55E-06	5.24E-06			

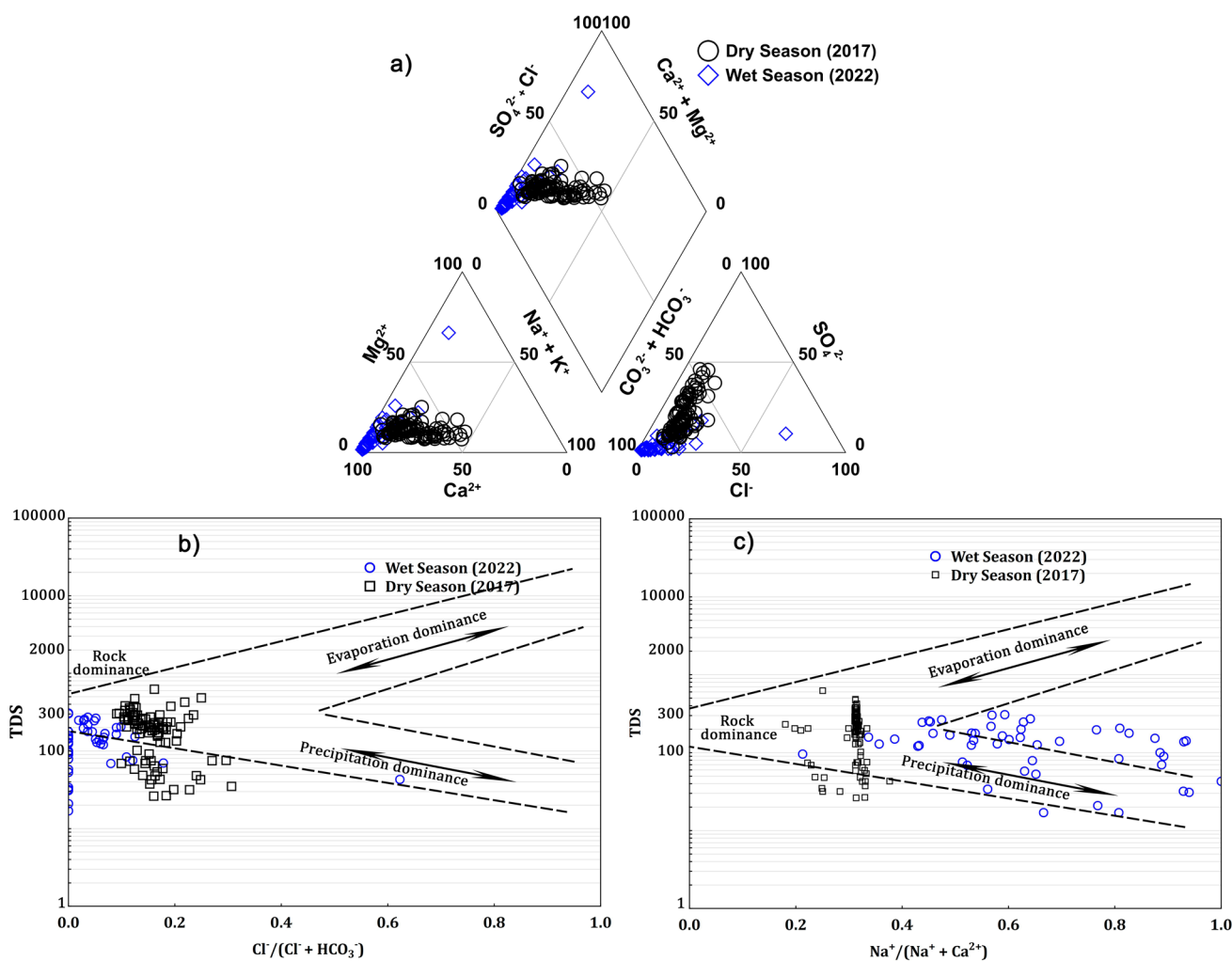


Fig. 4 Piper diagram (a), Gibbs plot anion (b), and cation (c) ratio

dominant type, an indication of considerably recent recharge (blue diamonds in Fig. 4a).

Figure 4b and c show the Gibbs diagram for the groundwater samples analyzed. Consistent with the findings from the Piper diagrams, the results provided by the Gibbs methodology show that, at low water periods, represented by the black rectangles in Fig. 4b, the water–rock domain, i.e., cation exchange and weathering, predominates. Although the water–rock domain continues under flooded conditions, as indicated by the blue circles in Fig. 4c, there is a strong influence of the precipitation domain regardless of the depth of the sampled wells, suggesting that a dominant source of recharge in the study area is atmospheric precipitation as it experiences heavy rainfall with flooding effects over long periods of time, which can improve hydrodynamic conditions and increase the degree of mixing.

We found that HCO_3^- contributes 88% of the total anion for the campaign conducted in 2022 and 67% for 2017. The largest number of samples was concentrated in

the silicate region indicated in Fig. 5a. However, for the sampling campaign during the wet season, some points are characterized by the weathering of evaporitic rocks. This indicates that rock weathering is an important factor affecting the hydrochemical characteristics.

The main source of the chemical composition of groundwater for the different sampling campaigns was the predominance of silicate weathering, suggesting that most of the samples are distributed over the trend line $x = y$, according to Fig. 5b (Li et al. 2018). As shown in Fig. 5c for the wet season, it is observed that the data are distributed on the negative slope line with respect to the dry season and do not follow a pattern, suggesting that there is a time-dependent cation exchange in the groundwater and that the effects of previous recharge and flooding in the area play a fundamental role not only in the dilution processes but also in the hydrochemistry. In the study area, the cation exchange has caused an increase in Na^+ and K^+ contents in the groundwater during the flooding season,

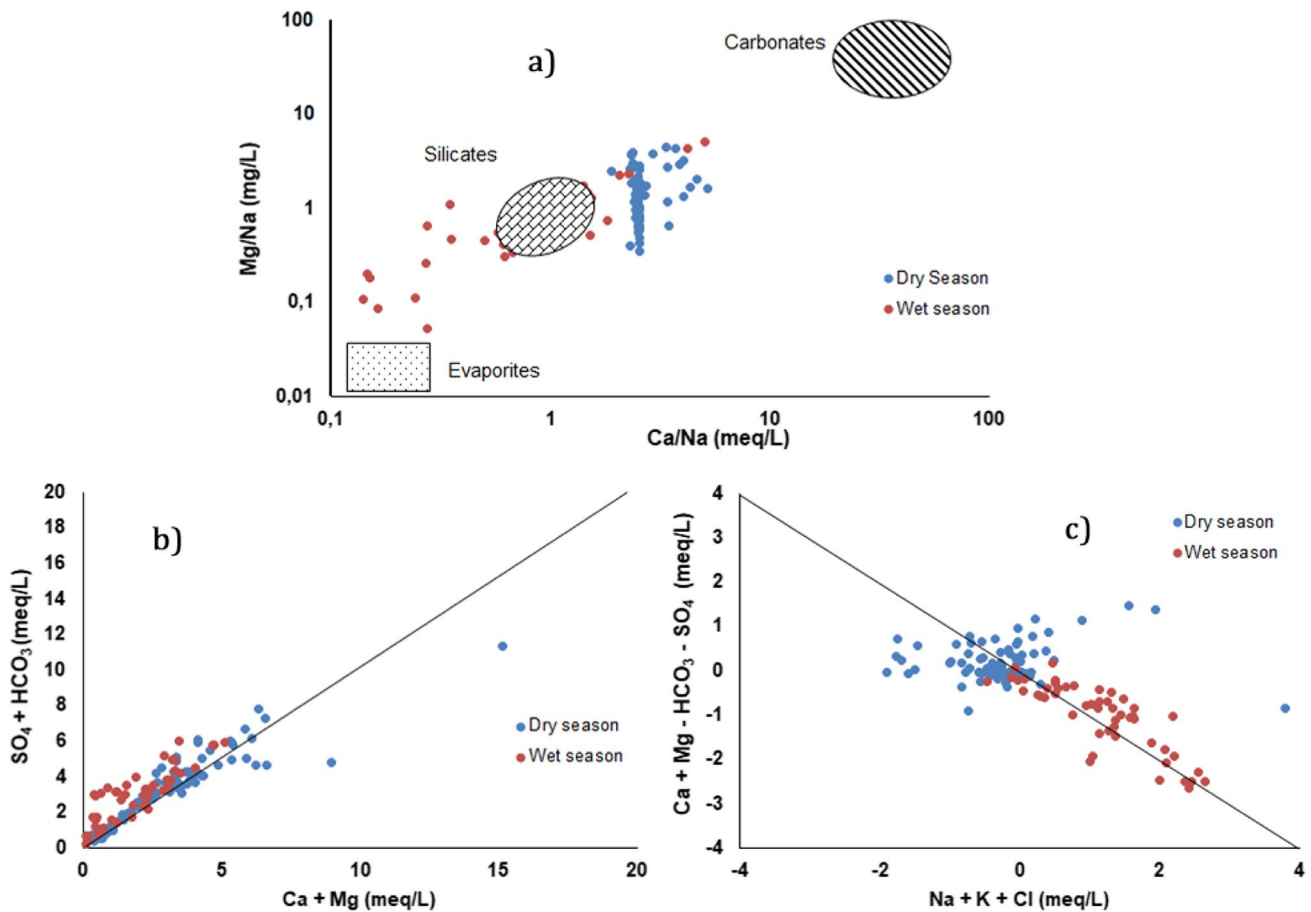


Fig. 5 Gaillardet diagram (a), bivariate plot ratios $(SO_4^{2-} + HCO_3^-)$ versus $(Ca^{2+} + Mg^{2+})$ (b), and $((Mg^{2+} + Ca^{2+}) - (SO_4^{2-} - HCO_3^-))$ versus $((Na^+ + K^+) - Cl^-)$ (c)

whereas Ca^{2+} and Mg^{2+} decreased with respect to the dry season campaign.

Conclusion

The use of shallow water wells in the La Mojana region of Colombia is compromised not only for drinking but also for irrigation purposes. The principal variables contributing to the water quality deviation are the presence of TC and *E. coli* and the additive effects of TDS, Na^+ , EC, Cl^- , and SAR. The levels of As in the groundwater represent a potential human health risk for both noncarcinogenic and carcinogenic effects on children and adults. No prolonged consumption of water is recommended due to HI and $CR_{ingestion}$ values.

The first assessment of the groundwater geochemistry of the La Mojana aquifer system denotes HCO_3^- and Ca^{2+} dominance. The silicate weathering is strongly affected by the sampling campaign, and flood events frequently occur in the study area. Further data and monitoring are required

as the next step to elucidate geochemical behavior. The results of this study can serve as a reference for environmental data and the selection of vulnerable areas of high agricultural socioeconomic importance and factors affecting overall water quality requiring management action.

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Author contributions All authors contributed to the study’s conception and design. JJP-H and JH-A performed the material preparation, data collection, and analysis; GE-M, MR-P, and JO-P contributed to the analysis data, improving the presentation of the result; and RP-U edited the paper and research method. In the first draft of the manuscript, critical comments in planning and editing were conducted by JM-N and JP-H, and all authors commented on previous versions of the manuscript.

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Data availability The data used in this study are available on request from the corresponding author.

Declarations

Conflict of interest The authors declare that they have no competing interests.

Ethical approval Not applicable to this study.

Consent to participate Not applicable to this study.

Consent for publication Not applicable to this study.

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