

Groundwater resources assessment in the Mirandiba sedimentary Basin at NE Brazil

Thyego R. Silva^{a,*}, Mariucha M. Correia de Lima^a, Tiago N. Martins^b, Waldir D. Costa^c, Mateus S.C. Albuquerque^a, Manoel Júlio da T.G. Galvão^d

^a Water and Climate Agency of Pernambuco, Recife, Brazil

^b Department of Hydraulics and Environment, National Laboratory for Civil Engineering, Lisbon, Portugal

^c COSTA - Consultoria e Serviços Técnicos e Ambientais Ltda, Recife, Brazil

^d SGB/CPRM - Geological Survey of Brazil, Brazil

ARTICLE INFO

Editorial handling by: Elisa Sacchi

Keywords:

Sedimentary basin
Vertical electrical soundings
Hydrogeochemical processes
Meteoric water
Drinking suitability
Irrigation suitability

ABSTRACT

In semi-arid regions, groundwater is a vital water resource threatened by salinization and contamination. Geophysical and the physicochemical and isotopic compositions ($\delta^{18}\text{O}$ and $\delta^2\text{H}$) are investigated to determine the general geometrical characteristics of a closed basin and identify the origin and main evolutionary processes controlling the groundwater geochemistry and quality to provide reliable information for effective water management. The studied dominantly unconfined Mirandiba Basin lacks evaporitic (halite) deposits but contains comparatively higher chloride concentration, under the role of the semi-arid climate of NE Brazil. Geophysics unravels a shallow basin with a thickness lower than 400 m and a basement morphology suggesting a half-graben structure. Groundwater samples were classified into three groups: 1) cluster 1 samples correspond to more mineralized mixed cations-Cl to Na-Cl slightly acid waters, 2) cluster 2 samples correspond to less mineralized Na-Cl acid waters, and 3) cluster 3 samples correspond to neutral mixed cations-mixed anions waters. The isotopic signatures range from -4.95 to -3.16 ‰ and -29.74 to -17.50 ‰ for $\delta^{18}\text{O}$ and $\delta^2\text{H}$, respectively, indicating that groundwater is derived from rainwater with some samples suggesting evaporation. The integrated techniques have shown that the main factors controlling groundwater chemistry evolution are related to 1) wetting/evaporation that induced millennial cyclic salt (mainly halite) accumulation and later dissolution and leaching during recharge periods, 2) rock weathering, 3) reverse ion exchange, and 4) anthropogenic nitrate contamination. The physicochemical parameters of ~ 90 % of groundwater samples are within the WHO guidelines, and ~ 92 % within the good and excellent water quality category for drinking purposes. Similarly, irrigation ion-based indices showed overall suitability for irrigation. The approach followed in this study is useful for recognize the main processes (natural and anthropogenic) operating in groundwater, and was used to build a conceptual hydrogeologic model, for establishing effective management strategies in aquifers in arid to semi-arid areas.

1. Introduction

In the last century, groundwater became a primary water source, generally due to its high quality and quantity compared to surface water (Hoogesteger, 2022; Ravenscroft and Lytton, 2022). Numerous arid and semi-arid regions globally, such as Israel, the USA, Australia, China, India, Chile have received more attention through systematic projects and studies to address various socio-environmental impacts related to groundwater depletion and replenishment (e.g., Famiglietti, 2014;

Jasechko et al., 2024; Cartwright et al., 2004; Cartwright and Weaver, 2005; Gamboa et al., 2019; Taucare et al., 2020 and references therein) and contamination and salinization (e.g., Chaudhuri and Ale, 2014; Li et al., 2021; Grunfeld et al., 2024 and references therein) towards alleviating/mitigating the competing water pressures (Liu et al., 2024). In contrast, other regions still lack basic hydrological studies. This is the case of the semi-arid northeastern Brazil region, in which the Mirandiba Basin (dominantly unconfined) is located, and where data are still scattered or lacking, severely limiting effective water management.

* Corresponding author. Water and Climate Agency of Pernambuco, Av. Cruz Cabugá 1111, Santo Amaro, Recife, PE, 50040-000, Brazil.
E-mail address: rthyego@yahoo.com (T.R. Silva).

<https://doi.org/10.1016/j.apgeochem.2025.106572>

Received 21 November 2024; Received in revised form 17 September 2025; Accepted 22 September 2025

Available online 23 September 2025

0883-2927/© 2025 Elsevier Ltd. All rights are reserved, including those for text and data mining, AI training, and similar technologies.

Unlike other large continuous sedimentary basins with significant reserves under semi-arid climate (e.g., Africa, Australia, Chile: [Edmunds et al., 2003](#); [Cartwright et al., 2004](#); [Taucare et al., 2020](#)), in northeastern Brazil water scarcity is worsened by the occurrence of small disconnected shallow basins, which underlining the utmost importance of non-renewable limited groundwater for proper social-economic development. Furthermore, this region has been facing water scarcity and shortages for centuries (e.g., [Rebouças, 1997](#)), and only a few studies have been done to strategically secure water access. This situation has been aggravated in recent years due to increasing competition for water resources mainly for agriculture and human consumption in a context of rapid population growth and weather-related extreme events of flooding and droughts (e.g., [Hirata and Conicelli, 2012](#); [Marengo et al., 2021](#); [Silva and Lima, 2023](#)). Thus, systematic studies are paramount in northeastern Brazil integrating as many techniques as possible (e.g., geophysical, hydrological, and geochemical) to gain knowledge to promote a truly integrated water resources management (e.g., [Güler et al., 2012](#); [Tuinstra and van Wensem, 2014](#); [Benson et al., 2020](#); [Mirzavand et al., 2020a](#)).

Geophysical resistivity surveys have been effectively used to image the subsurface allowing indirect identification of groundwater contamination linked with natural or anthropogenic activities (e.g., [Ebraheem et al., 1997](#); [Choudhury et al., 2001](#); [Choudhury and Saha, 2004](#); [Kazakis et al., 2016](#); [Niculescu and Andrei, 2019](#); [Liu et al., 2024](#)) and decipher recharge areas (e.g., [Viguier et al., 2018](#); [Avilés et al., 2020](#); [Figueroa et al., 2021](#); [Fu et al., 2022](#)) contributing to the development of improved hydrogeological conceptual models (e.g., [Francés et al., 2015](#); [Viguier et al., 2018](#); [Avilés et al., 2020](#)). Furthermore, studying major dissolved ions as natural tracers and their spatial variability has provided geochemical information on groundwater characteristics and shed some light on physical and chemical processes that control water chemistry (e.g., [Appelo and Postma, 2005](#); [Calvi et al., 2024](#); [Moitinho et al., 2024](#)). Hydrochemical data has been subject to multivariate statistical analysis (MSA) in hydrochemistry studies to reduce the complexity of large-scale data sets, revealing relationships between the data components, so that important information (i.e., main controlling factors) may be retained, while residual noise is discarded (e.g., [Güler et al., 2002, 2012](#); [Cloutier et al., 2008](#); [Menció and Mas-Pla, 2008](#); [Jolliffe and Cadima, 2016](#); [Kazakis et al., 2017](#); [Argamasilla et al., 2017](#); [Silva et al., 2021](#); [Patel et al., 2024](#)). Besides, the use of environmental isotopes (^{18}O and ^2H) gives insights into the origin and movement of groundwater, offering an evaluation of physical processes affecting groundwater's pristine signature, such as mixing and evaporation (e.g., [Geyh, 2000](#); [Hoefs, 2009](#); [Barbosa et al., 2017](#)). Finally, groundwater concentration values assessment is crucial for identifying the water status for drinking and irrigation suitability. If chemical ion concentrations are above established acceptable limits, can cause human health problems when ingested (e.g., [WHO, 2011](#); [Adimalla, 2019](#)) or limit the water plant uptake which consequently hinders plant growth ([Mayer and Poljakoff-Mayber, 1982](#)). So, recognizing water quality avoids risks to human health, makes it possible to identify and prevent environmental contamination spread, and allows the design of proper monitoring programs. Application of quality indices integrated with a Geographic Information System (GIS)-based approach and interpolation methods have grown worldwide to improve the safety and secure drinking water and irrigation (e.g., [Jasrotia et al., 2019](#); [Adimalla et al., 2020](#); [Ghazaryan et al., 2020](#); [Tefera et al., 2021](#); [Karangoda and Nanayakkara, 2023](#); [Silva and Lima, 2023](#); among many others). Point sample analysis is used to estimate non-sampled areas generating spatial distribution maps of groundwater quality for various purposes, assisting in identifying the water quality zones and unraveling sensitive polluted zones (e.g., [Tabi et al., 2024](#)).

This work presents a comprehensive groundwater hydrogeochemistry assessment in the Mirandiba Basin, northeastern Brazil. The study employs a combined multidisciplinary approach of geophysical with geochemical, MSA, and GIS to obtain the following purposes:

- (1) investigate some geometrical aspects of the basin
- (2) decipher the hydrochemistry characteristics of the whole groundwater system;
- (3) identify the groundwater sources of contamination;
- (4) investigate the groundwater suitability for human consumption mainly investigating harmful occurrences (e.g., nitrate and salinization);
- (5) analyze the suitability of groundwater for irrigation;
- (6) provide spatialized maps to easily identify the groundwater areas (e.g., groundwater quality zones);
- (7) develop a hydrogeological conceptual model to summarize the natural and anthropogenic processes operating into groundwater;
- (8) suggests strategies toward integrated groundwater management.

This research contributes to the state-of-the-art resolving the current lack of hydrogeochemistry data of the region and will serve as a guide for designing future studies. Moreover, the interdisciplinary approach and results of this research may be applied in other basins to provide information toward efficient and sustainable groundwater management (e.g., delineating protecting areas, identifying vulnerable zones for remediation, regulating maximum flow rates, recognizing and improving yields, etc.).

2. Study area description

2.1. Geographic location, climate, and land use

The Mirandiba Sedimentary Basin, with an area of about 117 km², is located in the central portion of the state of Pernambuco ([Fig. 1a](#)), between the Longitude 37° 35'–38° 46' W and Latitude 08° 03'–08° 09' S, in the hot semi-arid region (BSH) of Northeast Brazil. In this region, there is only a dry and a rainy season, which is related to the migration from the Intertropical Convergence Zone (ITCZ). The historical average annual rainfall in the Mirandiba Basin is around 635 mm ([Supplementary Fig. 1: Galvão, 2013](#); data from 1962 to 2012); the highest values occur between January and April. It coincides with the southernmost position of the ITCZ during the summer, which brings a rainy season over NE Brazil ([Hastenrath, 2012](#)). The monthly average temperature data for the municipalities encompassing the Mirandiba Basin varies from 23.3 to 26.8 °C ([INMET, 2020](#)), with an average value of 25.3 °C ([Supplementary Fig. 1](#)). A standard Class A evaporation pan (U.S. National Weather Bureau, 1916 in [Dougherty, 1975](#)) showed values ranging from 160 to 280 mm/month reflecting high annual evaporation of ~2606 mm, which exceeds by far the annual precipitation ([Supplementary Fig. 1](#)). Circa 50 % of the basin is formed by shrubby vegetation (known as Caatinga) and the other half of the area is dedicated to agriculture and livestock activities ([Fig. 1b](#)).

2.2. Geological and hydrogeological setting

The Mirandiba Basin is one of the intracontinental rift basins of northeastern Brazil ([Matos, 1999](#); [Gomes, 2001](#)). The evolution of this basin involved a thermal subsidence (synclisis) phase during the Paleozoic, followed by a rifting phase related to the fragmentation of the Gondwana Palecontinent during the Jurassic and Cretaceous ([Matos, 1999](#)). It was likely installed along Precambrian basement heterogeneities associated with the reactivation of pre-existing NE–SE sigmoidal-like shear zones. As shown in the geological map ([Gomes, 2001](#); [Galvão, 2013](#)) and in the lithostratigraphic column ([Diniz and Silva, 2014](#)) ([Fig. 1c](#) and [Supplementary Fig. 2](#)), the lithologic units in the study area extend from the Paleozoic to the Quaternary. The Silurian-Devonian series is represented by vertically interdigitated Tacaratu and Inajá formations, which consist of fluvial braided systems, associated with alluvial fans. It contains medium-to coarse sandstones, conglomerate sandstone levels, with subordinate pelitic intercalations, often kaolinitic. Ferruginous sandstones occur in the Inajá Formation, which does not outcrop in the basin. The Tacaratu Formation outcrops in an area of ~72.5 km². Then, the Jurassic series from the Aliança Formation were discordantly deposited, in a typical fluvial-shallow lacustrine depositional environment, shales, and clays, commonly

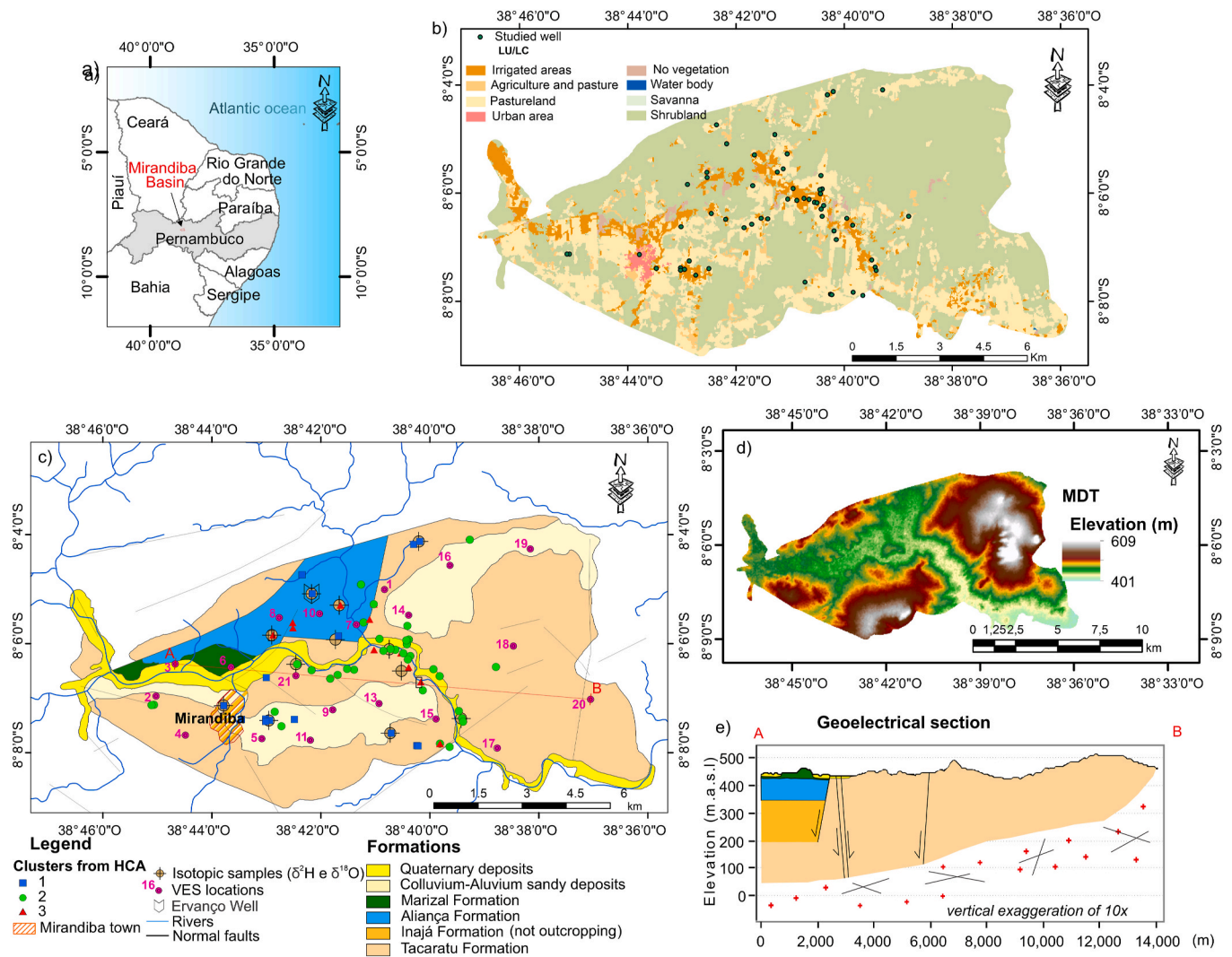


Fig. 1. (a) Location map of the Miranda Basin. (b) Land use/land cover (LU/LC) map patterns from the Miranda Basin. Data source: National Institute of Meteorology – INMET; Galvão (2013). (c) Geological-structural map showing the studied wells. Modified from Gomes (2001) and Galvão (2013). (d) Shuttle Radar Topography Mission (SRTM) map. (e) Geoelectrical cross-section through the basin encompassing VES3, 6, 21, and 20.

interbedded with limestones, fine sandstones, and rarely aragonite layers, which covers about 13.5 km². Then, the Aptian series related to the Marizal Formation (2 km²) composed of coarse sandstone, sometimes with polymictic conglomeratic levels, siltstone, shale, and diamictite deposits, in a proximal fluvial (alluvial fans) environment were deposited. Finally, the Neogene and Quaternary sedimentation is composed of colluvial-eluvial deposits and alluvial terraces, which respectively occur as sandy plateaus (~28.5 km²), and floodplains (~0.7 km²) along the Terra Nova stream and some of its tributaries.

The basin presents a smooth topography with elevations ranging from ~400 to 609 m above sea level (m.a.s.l.), with the highest elevations in the eastern and southwestern areas, and the lowest in its central parts (Fig. 1d). Depth to hydraulic head and ground surface (topographic level) in 90 wells taken in 2011 (most in November) were used to create a generalized average hydraulic head contour, which is used as a reference, in absolute elevation above mean sea level to examine flow direction and depression cones (modified from Galvão, 2013) – Supplementary Fig. 3. The hydraulic head configuration roughly follows the overlying ground surface topography and indicate a flow regime from marginal (north and south) areas towards the central areas of the basin, converging to the Terra Nova stream, an ephemeral stream that only receive water at sporadic periods and act as an influent river. Only a few depression cones are observed. The Tacaratu aquifer normally occurs

under unconfined conditions when not confined by the Aliança Formation. Only one pumping test, in a confined region, provided hydraulic conductivity and transmissivity of 7.5×10^{-6} m/s and 2.47×10^{-3} m²/s, respectively, while flow rates of wells tapping this aquifer were up to 150 m³/h (Costa Filho, 2013 in Galvão, 2013). The permanent groundwater reserves were roughly estimated to be ~2000 hm³ with a direct recharge volume of about 6.6 hm³yr⁻¹ (Galvão, 2013).

3. Materials and methods

3.1. Geophysical survey

Vertical electrical soundings (VES) were carried out using the continuous resistivity meter TDC 1000–12R2A (Tectrol, Brazil) with a Schlumberger electrode array (e.g., Zohdy et al., 1974; Parasnis, 1986; Telford et al., 1990) between October and November 2017. All VES were selected to cover the different geological units and the whole area observing the topographic and physical limitations for a minimal opening to reach the basement ($AB/2 = 600\text{--}1000$ m). The layer parameters such as apparent resistivity (ρ_a) and thickness (h) of different layers were obtained using the IPI2win software (Bobachev et al., 2003). The interpretation of the electric sounding involved the comparison of field profiles with characteristic curves. Most of the field values matched

curves from the IPI2Win v.3.0 software. The RMS error values of all VES ranged between 2.4 and 10.4 % indicating the reliability of the measured data.

3.2. Groundwater sampling and analysis

A total of 67 samples were collected between April 2010 (16) and November 2011 (51) by the Geological Survey of Brazil (CPRM). The sampling campaign was assembled to cover the geographical extension of the study area. A seasonal variation evaluation has not been feasible due to the limited data. All samples were collected directly at the wellhead using submersible pumps after purging. The maximum depth of wells is about 400 m. They were filtered and stored in new and washed with de-ionized water polyethylene bottles. After collection, the samples were stored at 4 °C and shipped to the laboratory for analysis. The analyses (Supplementary Table 1) were conducted in the ATECEL laboratory from the Campina Grande Federal University, Paraíba, Brazil, according to the standard procedures of APHA (2005). The electro-neutrality parameter ($100 \times [\Sigma z_{mc} - \Sigma z_{ma}] / [\Sigma z_{mc} + \Sigma z_{ma}]$; where z is the ionic valence, and mc and ma the molarity of cationic and anionic species, respectively; (Freeze and Cherry, 1979)) was less than ± 10 %, attesting the quality of the analyses.

For oxygen and hydrogen isotopic compositions, twelve samples were collected in July 2018 directly at the wellhead using submersible pumps after purging. The samples were stored in polyethylene bottles washed with the well water and filled to overflowing. Then, the samples were labeled, stored, and shipped by airplane from Pernambuco to the Beta Analytic Inc. laboratory, Miami, Florida. Both isotopes were analyzed with a Thermo Fisher Delta V Mass Spectrometer using continuous flow. 500 μ L of groundwater samples were introduced into a 12 ml vial and allocated in the auto-sampler in conjunction with a Thermo Fisher GasBench 2.0 according to the following sequence: three recognized standards (EVIAN [an in-house standard traceable to NIST IAEA USGS 50 LOUISE & GISP or SLAP] - $\delta^{18}\text{O}_{\text{VSMOW}} = -10.22$ ‰ and $\delta^2\text{H}_{\text{VSMOW}} = -72.88$ ‰; USGS47 [Lake Louise] - $\delta^{18}\text{O}_{\text{VSMOW}} = -19.8$ ‰ and $\delta^2\text{H}_{\text{VSMOW}} = -150.2$ ‰; and USGS50 [Lake Kyoga] - $\delta^{18}\text{O}_{\text{VSMOW}} = +4.95$ ‰ and $\delta^2\text{H}_{\text{VSMOW}} = +32.8$ ‰) followed by ten samples and two of the standards. The headspace of the samples was flushed with 2 % CO_2 in He and 2 % H_2 in He streams for 8 min to evacuate any remaining gas within the headspace and introduce CO_2 and H_2 , respectively, for $\delta^{18}\text{O}$ and $\delta^2\text{H}$ analyses. The reproducibility for $\delta^{18}\text{O}$ and $\delta^2\text{H}$ analyses was ± 0.06 ‰ and ± 1.5 ‰, respectively, while the precision was ± 0.13 ‰ for $\delta^{18}\text{O}$ and ± 0.61 ‰ for $\delta^2\text{H}$. The data were reported on the usual δ -scale in ‰ relative to the Vienna Standard Mean Ocean Water 2 (V-SMOW2) standard, according to the equation $\delta_{\text{sample}} (\text{‰}) = (R_{\text{sample}} / R_{\text{standard}}) \times 1000$, where R is the $^2\text{H}/^1\text{H}$ and $^{18}\text{O}/^{16}\text{O}$ atomic ratios.

3.3. Data analysis for MSA

Before proceeding MSA, the geochemical data were evaluated and a few water chemistry parameters with lower detection values (i.e., censored data) were identified. Many methods do exist to replace censored data (e.g., Sanford et al., 1993; Cloutier et al., 2008; Greenacre, 2021) as censored data hampers statistical analysis. In this study, the substitution of less-than the detection limit by 0.55 before the statistical reduction of data was employed (Sanford et al., 1993; Güler et al., 2002). After filling all censored values, the statistical software package SPSS 20 for Windows® (SPSS Corp., USA) was used for the manipulation and statistical data analysis. Data screening showed that all parameters are highly skewed positively, except for pH. Therefore, the data were log-transformed so that they correspond more closely to normally distributed data, except for pH. Finally, all the variables were standardized by calculating their standard scores ($z(i)$ -scores = $(x_i - \bar{x})/s$; where $z(i)$ = standard score of the sample i ; x_i = sample value i ; $\bar{x}$ = mean; s = standard deviation). Ten parameters (viz., pH, Ca^{2+} , Mg^{2+} , K^+ , Na^+ , Cl^- , SO_4^{2-} , HCO_3^- , NO_3^- , and Fe) values were used to perform

multivariate statistical techniques; hierarchical cluster analysis (HCA) and principal component analysis (PCA). The parameters with additive characteristics (e.g., EC, TDS, and TH) and with many samples showing lower detection values (e.g., manganese) were excluded from MSA. HCA was used to group samples into distinct populations. The Ward method, which employs an analysis of variance (ANOVA) approach to verify the distances between groups, was used as a linkage rule and the similarities among samples were measured by the Euclidian distance (e.g. Güler et al., 2002; Cloutier et al., 2008). Since HCA technique does not provide a statistical test of group differences, the Kruskal-Wallis and ANOVA tests associated with post-hoc evaluation were used to assess the occurrence of significant differences in the unstandardized (raw) samples from the identified groundwater groups with similar chemical characteristics. All tests were performed using a value of 0.05 as a critical level for all statistical tests, resulting in a 95 % confidence level. Additionally, PCA was employed to reduce the dimension of the original data set. The Kaiser–Meyer–Olkin (KMO) coefficient gave a value of 0.629 and Bartlett's sphericity test carried out on the correlation matrix showed a calculated $\chi^2 = 368.46$ ($P < 0.001$ and 45 degrees of freedom [df]) indicating that PCA is accurate in reducing the dimension of the hydrochemical data matrix. The Kaiser criterion was used to retain only Principal Components (PC) with eigenvalues higher than one, which provided a reduction for 3 PC in the study.

3.4. GIS and geostatistical analyses

QGIS (v. 3.26) and ArcGIS software (v. 10.6) were used to perform GIS analysis and geostatistical modeling. The Multilevel B-Spline model (threshold error = 0.0001) (Lee et al., 1997) was used for spatial interpolation. Compared to the most common interpolation method, the inverse distance weighted (IDW) method (e.g., Rakotondrabe et al., 2018; Ghazaryan et al., 2020; Tefera et al., 2021; Hernandez et al., 2021; Ahmad et al., 2021), the Multilevel B-Spline generates smooth surfaces with irregularly distributed samples and avoids the generation of the “bullseye” effect (Martins et al., 2022).

3.5. Saturation indices

Speciation-solubility calculations gave the mineral saturation indices [$\text{SI} = \log (\text{IAP}/K)$, where IAP is the ion activity and K equilibrium constant], which were performed using the AQUACHEM PHREEQC interface (Waterloo Hydrogeologic, Inc.; Parkhurst and Appelo, 1999). A positive value of SI for a particular mineral indicates oversaturation, and thus precipitation could occur; otherwise, a negative value means undersaturation and possible dissolution of a mineral.

3.6. Water quality analysis

3.6.1. Drinking purpose

Water quality indexes (WQI) were employed to assess the suitability of groundwater for drinking purposes. Weight factors of 1–5 were placed for each parameter based on their significance in the determination of water quality as well as an adverse effect on human health (e.g., Vasanthavigar et al., 2010; Giri et al., 2021). A weight of 5 was assigned to total dissolved solids (TDS), Cl^- and NO_3^- , 4 to pH and SO_4^{2-} , 3 to TH, 2 to Ca^{2+} , Mg^{2+} , Na^+ , K^+ , Fe and Mn, and 1 to HCO_3^- . The WQI was calculated using the following equation (Vasanthavigar et al., 2010):

$$Wi = wi / \sum_{i=1}^n wi$$

where, W_i = relative weight, w_i = weight of each water quality parameter, and n = number of parameters.

Then, a quality rating (Q_i) scale for each parameter was calculated by dividing its concentration in each groundwater sample by its respective drinking water quality standard, which was multiplied by 100:

$$Q_i = (C_i/S_i) \times 100$$

where, Q_i = quality rating, C_i = concentration (mg/L, except for dimensionless pH) of each water quality parameter in each water sample, and S_i = standard (mg/L, except for dimensionless pH) for each water quality parameter as per the World Health Organization standards (WHO, 1996, 2011).

Finally, for calculating the water quality index, the 'S-in' is first determined for each water quality parameter, which is then applied to determine the water quality index (WQI) as per the following formulas:

$$S\text{-in}_i = W_i \times q_i$$

$$WQI = \sum S\text{-in}_i$$

where, the $S\text{-in}_i$ = sub-index of the i th parameter, q_i = rating based on the concentration of the i th parameter, and n = parameter numbers.

Water quality can be classified into five categories based on the WQI values as follows: Excellent (WQI <50), Good (WQI 50–100), Poor (WQI 100–200), Very poor (WQI 200–300), and Unfit (WQI >300) for drinking purposes.

3.6.2. Irrigation purposes

Some well-known ratios such as Sodium Absorption Ratio (SAR), Soluble Sodium Percentage (SSP), Kelley Ratio (KR), Residual Sodium Carbonate (RSC), Permeability Index (PI), and Magnesium Hazard (MH) were used to evaluate the suitability of groundwater for irrigation use. The following expressions were used to retrieve the index values:

Sodium Absorption Ratio (SAR) = $Na^+/\sqrt{((Ca^{2+} + Mg^{2+})/2)}$; Richards (1954) and Todd (1980);

Residual Sodium Carbonate (RSC) = $(CO_3^{2-} + HCO_3^-) - (Ca^{2+} + Mg^{2+})$; Eaton (1950) and (Richards, 1954);

Soluble Sodium Percentage (SSP; Na%) = $100 \times (Na^+ + K^+)/ (Ca^{2+} + Mg^{2+} + Na^+ + K^+)$; Eaton (1950) and Wilcox (1955); Kelley's Ratio (KR) = $Na^+ / (Ca^{2+} + Mg^{2+})$; Kelley (1951);

Permeability Index (PI) = $100 \times (Na^+ + \sqrt{HCO_3^-}) / (Ca^{2+} + Mg^{2+} + Na^+ + K^+)$; Doneen (1964) and Sonkamble et al. (2012).

4. Results and discussion

4.1. Vertical electrical sounding

VES as one indirect (non-destructive) technique provides a means of spatially characterizing and imaging the subsurface (Telford et al., 1990; Loke et al., 2013). It can provide information on distinct lithologies and their variabilities being also sensitive to changes in soil moisture content (Merritt et al., 2016).

The VES-modeled resistivities showed large variations between 3 Ω m (VES3) and 49,214 Ω m (VES19). Master curves are four-layer and five-layer, mostly QH- and HA-types, or HKH- and HAH-types (Supplementary Table 2; e.g., Flathe, 1963; Zohdy et al., 1974; Zohdy, 1989; Prasanna et al., 2011). Soil presents a large variation with both low (5 and 47 Ω m; e.g., VES 6 and 17) and rather high values (795–18,505 Ω m with an average of 5981 Ω m; the other VES) (small AB/2 values), which is probably related to low moisture content (e.g., Merritt et al., 2016) common in the semi-arid regions. The thickness varied from 2.55 to 12.90 m with an average of 5.30 m. For the Neogene–Quaternary sediments, it is observed that the resistivity values are usually high varying from 28.50 to 11,944 Ω m, and suggests these formations are water barren. The thickness varied from 12.30 to 32.00 m with an average of 18.80 m. In the Aliança Formation, resistivity values were found to be low varying from ~5 to 23 Ω m (VES3, 6–8, 10), characterizing a typical aquitard layer mainly composed of shales, limestones, and clays likely containing trapped saltwater. The thickness showed little variation from 50.8 to 78.4 m with an average of 66.8 m. The resistivity value in the Marizal Formation was ~3.5 Ω m, likely due to the

presence of silty clay and/or clayey sand layers with a thickness of 5 m. In the Tacaratu Formation, resistivity values usually varied from 30.8 to 246 Ω m (thickness between 72 and 324 m, avg. ~205 m) suggesting that the geology/hydrogeology of the Mirandiba Basin presents some homogeneity, with a little lateral variation. For the Precambrian basement rocks, ρ values are usually high varying from 194 to 49,214 Ω m with an average of ~11,000 Ω m, interpreted as representing rather compact rocks with lower water content or even without water (e.g., Niculescu and Andrei, 2019).

A VES profile of about 14 km in length with a WNW–ESE direction cross-cutting the main formations was created encompassing VES3, 6, 21, and 20. Supplementary Fig. 4 presents the apparent resistivity cross-section, which evidences low values (<30 Ω m) in the WNW and higher ones toward the ESE side. It suggests that these sides are separated by a fault or fault zone, which placed two distinct lithologies (shales/limestones versus sandstones) at the VES6 or between VES6 and VES21 (Supplementary Fig. 4 and Fig. 1c–e). VES show that the Mirandiba Basin has the shape of a half-graben with the main fault or fault zone located on the northwestern edge (Supplementary Fig. 5), which is compatible with gravimetric data (e.g., Morais et al., 2021 and references therein).

The coarseness of vertical electrical soundings results and water-level data associated with lack of direct measurements of hydraulic conductivity and permeability do not allow for a proper assessment if fault/fault zone hamper groundwater flow (i.e., act as a barrier: e.g., Ball et al., 2010) or enable preferential groundwater flow (i.e., act as a conduit) in high permeability areas (e.g., Figueroa et al., 2021; Fu et al., 2022). Nevertheless, the flat topography (~400–600 m.a.s.l) copes with the widespread distribution of permeable and porous outcropping formations of the basin likely favor diffuse recharge flows.

4.2. The origin and evolution of groundwater

4.2.1. Groundwater groups and facies

A hierarchical cluster analysis (HCA) was performed on the analyzed 67 samples. A dissimilarity distance of ~12 was chosen and three clusters defined (Fig. 2), and the average composition from the clusters is shown in Table 1. These number of clusters are the same found using the empirical procedure from Pacheco Castro et al. (2018). The Piper diagram further validates the obtained three clusters/groups by their distinct chemical facies (Fig. 3). Cluster 1 represents samples that are mixed cations–Cl to Na–Cl with slightly acid pH values (avg. 6.8; std deviation 1.2) and higher TDS (avg. ~678 ppm; std deviation 446) distributed in the basin. Cluster 2 includes less mineralized groundwaters (avg. 201 ppm; std deviation 103) with the lowest pH values (avg. 5.9; Std. dev. 0.9) and typically Na–Cl facies. Finally, cluster 3 also presents low mineralization groundwaters (avg. TDS of ~192 ppm; std deviation 59), with a neutral to basic pH (avg. 7.5; Std. dev. 0.6) and mixed cations–mixed anions facies.

The statistical tests conducted over the unstandardized data provided the following observations:

- The ANOVA test for pH (normal distribution) from the different subgroups defined by HCA showed a statistically significant difference ($F(2.64) = 16.883$; $p < 0.001$).
- Post-hoc Tukey and Bonferroni tests evidenced statistically significant differences ($p < 0.001$) between clusters 1 and 2, and 2 and 3 but did not show a difference between 1 and 3.
- The Kruskal-Wallis test for the TDS ($\chi^2(2) = 31.234$; Asym. $p < 0.001$) as well as for the other parameters (non-normal) were determined to be statistically significant ($p < 0.001$), except to Fe that was the only not statistically significant.
- Post-hoc Mann-Whitney U test was used comparing pairs of clusters suggesting that most clusters 1–2, 2–3, and 1–3 are statistically significant at Asym. $p < 0.05$ (see the figure from the "Drinking suitability" section).

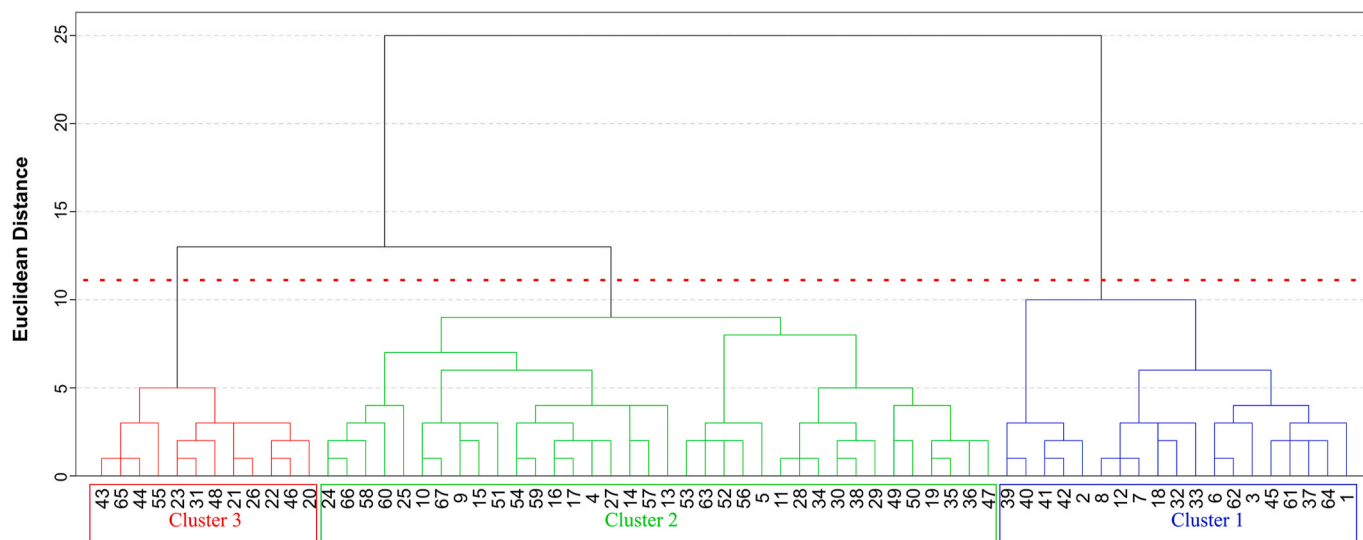


Fig. 2. Dendrogram showing the hierarchical clustering of the analyzed groundwater samples.

Table 1

Mean water chemistry of each cluster determined from HCA.

Groups/ Clusters	N° of Samples	pH	EC (μS/ cm)	TDS (mg/L)	Total hardness (mg/L)	Ca ²⁺ (mg. L ⁻¹)	Mg ²⁺ (mg. L ⁻¹)	Na ⁺ (mg. L ⁻¹)	K ⁺ (mg. L ⁻¹)	Cl ⁻ (mg. L ⁻¹)	SO ₄ ²⁻ (mg. L ⁻¹)	HCO ₃ ⁻ (mg. L ⁻¹)	NO ₃ ⁻ (mg. L ⁻¹)	Fe (mg. L ⁻¹)
1	19	6.84	989.11	634.42	320.41	35.09	50.29	100.14	22.87	270.20	61.19	89.03	0.15	0.28
2	36	5.92	314.69	201.40	91.70	9.85	15.61	32.25	14.10	88.82	12.22	26.64	0.66	0.36
3	12	7.60	273.58	180.00	137.03	13.60	21.11	19.04	9.71	62.81	34.56	66.13	0.13	0.31

Bold values – highest values.

Geographically, the defined clusters evidenced distinct spatial distribution for cluster 1 relative to clusters 2 and 3. On the contrary, clusters 2 and 3 present a good correspondence with proximity of sampled wells located in the central part of the basin along the quaternary sediments following the ephemeral streams. Nevertheless, clusters 2 and 3 evidence qualitative distinctions concerning nitrate-potassium deterioration (see PCA discussion in the next section).

4.2.2. Multivariate statistical analyses

The results of HCA and PCA applied to the 10 parameters as variables (pH, Ca²⁺, Mg²⁺, K⁺, Na⁺, Cl⁻, SO₄²⁻, HCO₃⁻, NO₃⁻, and Fe) defined three similar associations. The parameters HCA defined three associations in the phenon line with a bond distance of ~14 (Supplementary Fig. 6): (1) association of Na⁺ and Cl⁻ probably indicates that the dissolution of halite, an essential groundwater geochemical process promoted by secular to millennial precipitation/evaporation in a semi-arid climate (e. g., Adams et al., 2001; Wood, 2019) and also perhaps by halite dissolution from matrix cement during flow path; (2) association of pH, Ca²⁺, HCO₃⁻, and SO₄²⁻ suggests an alkaline environment, which may indicate weathering of carbonate and sulfate minerals; (3) association of K⁺ and NO₃⁻, and Fe probably associated with the anthropogenic activities and dissolution of iron oxides, respectively. Similarly, the analysis of the main components explained 68.18 % of the variance with the first three factors. The main component (PC1) explains 40.10 % of the total variance (Table 2; Fig. 4) showing an association of many parameters that present strong positive charges on Na⁺, Cl⁻, Ca²⁺ and Mg²⁺, and moderate on HCO₃⁻. All these parameters gathered in one factor can reflect the effect of natural factors such as the dissolution of halite, carbonates and silicates, sulfates, and ion exchange, which mainly occur in the samples from the Cluster 1. PC2 explains 17.19 % of the variance showing negative charges on pH, HCO₃⁻ and SO₄²⁻ and positive charges on K⁺ and NO₃⁻, which separate relatively well samples from the Cluster

2 (slightly impoverished in HCO₃⁻ and enriched in K⁺ and NO₃⁻) compared to Cluster 3. Finally, PC3 explains 10.90 % of the variance by showing a strong positive charge on Fe. PC1 can be considered as the “geogenic” component related to the main geochemical processes that regulate groundwater salinity since ions with high charges in PC1 were also the main contributors to groundwater mineralization. PC2 can be considered as the “alkaline environment” and “anthropogenic” component related to human influence. Fertilizer use, land clearance, and animal and human disposal are candidates, but the first one is favored given the related positive loads on K⁺ and NO₃⁻ that are typical plant nutrient constituents. PC3 can be related to the dissolution of iron oxides, evidenced by strong positive loadings on the Fe parameter.

4.2.3. Major and minor chemistry

The molar ratios between major constituents of groundwater were used to evaluate the ion sources. The binary plots using Mg²⁺/Na⁺, HCO₃⁻/Na⁺, and Cl⁻/Na⁺ versus Mg²⁺/Na⁺, respectively, with the evaporite, carbonate and silicate fields evidence a trend between evaporite and carbonates (Fig. 5a and b) or with the Cl⁻/Na⁺ ratios plotting near the evaporite endmembers showing a clear influence of it (Fig. 5c) in the groundwater loads. The plot of Na⁺ versus Cl⁻ shows that groundwater plot near the equiline 1:1 for low mineralized samples and below it with increasing concentration indicating mineral (halite) dissolution and reverse ion exchange (Fig. 5d). In scatter plots of (Ca²⁺ + Mg²⁺) vs. (HCO₃⁻ + SO₄²⁻), all clusters fall above the equiline indicating an excess of Ca²⁺ + Mg²⁺ suggesting a potential for the release of these elements by carbonates weathering and suggesting reverse ion exchange (Fig. 5e). The chloro-alkaline indices were plotted (Fig. 5f) to investigate the role of ion exchange, and the general positive results suggest exchange between Na in the groundwater with Ca and Mg in the aquifer material (e.g., Zaidi et al., 2015). A graph of (Ca²⁺ + Mg²⁺) – (HCO₃⁻ + SO₄²⁻) vs. (Na⁺ + K⁺) – Cl⁻ reveals that the studied

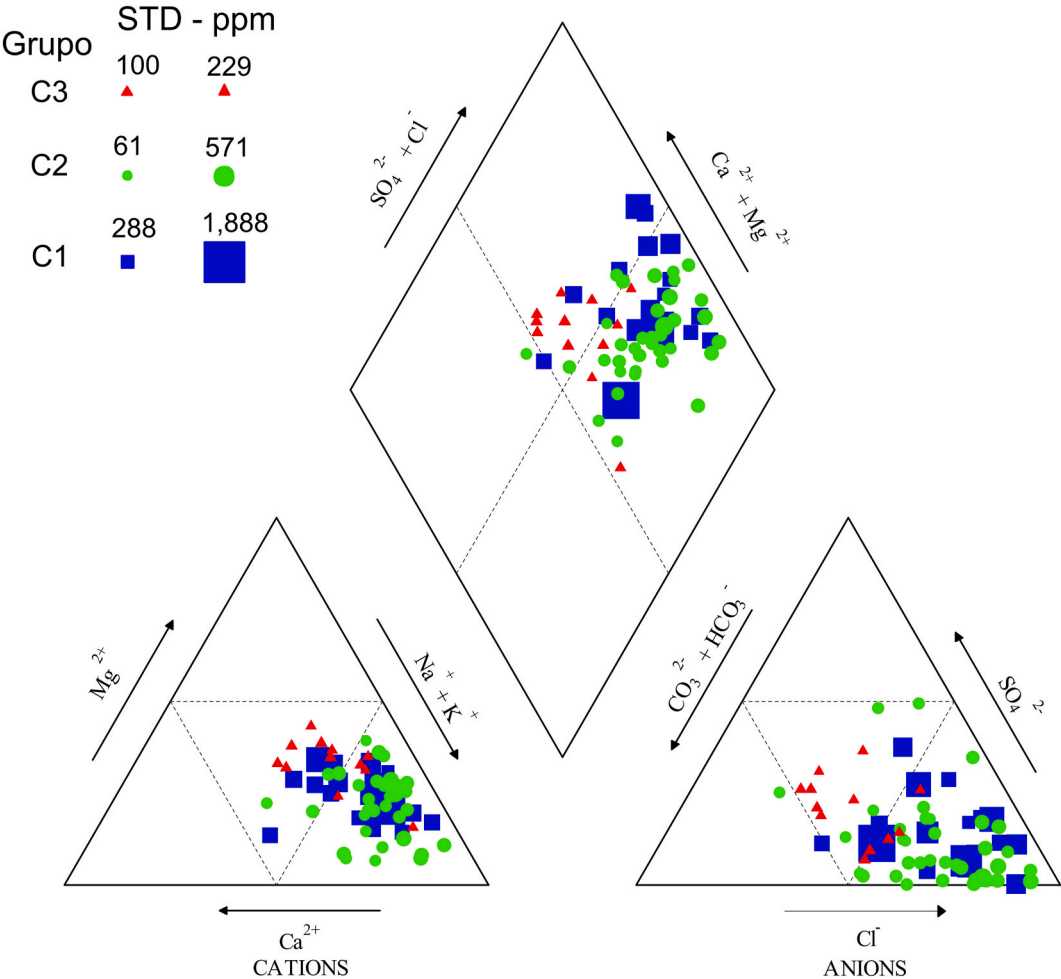


Fig. 3. Piper diagram of groundwater labeled by defined HCA groups.

Table 2
Factor matrix for the principal components.

Parameters	Principal components		
	PC1	PC2	PC3
pH	0.414	-0.495	0.414
Ca ²⁺	0.824	-0.032	0.010
Mg ²⁺	0.886	0.098	0.021
Na ⁺	0.790	0.393	-0.196
K ⁺	0.343	0.649	0.161
Cl ⁻	0.881	0.399	-0.099
SO ₄ ²⁻	0.466	-0.435	-0.334
HCO ₃ ⁻	0.671	-0.460	0.223
NO ₃ ⁻	-0.435	0.538	0.020
Fet	0.023	0.196	0.828
Eigenvalue	4.009	1.719	1.090
Cumulative eigenvalue	4.009	5.728	6.818
% of variance	40.093	17.189	10.903
Cumulative % of variance	40.093	57.282	68.185

Bold values – highest values.

groundwater clusters 2 and 3 fit in a line with a slope close to -1, which reinforces that Ca²⁺ (Mg²⁺) and Na⁺ may have interacted as a result of the reverse ion exchange process (Fig. 5g: e.g., Argamasilla et al., 2017; Torres-Martínez et al., 2021; Mirzavand et al., 2020b; Mirzavand and Walter, 2024). To investigate the role of human activities, a plot of NO₃⁻/Cl⁻ versus Cl⁻ was used (Fig. 5h) evidencing Cl⁻ concentration between 1 and 10 mmol/l with low NO₃⁻/Cl⁻ ratios, which suggests that NO₃⁻/Cl⁻ was derived from manure or mixing between the latter and

agriculture fertilizer input (e.g., Torres-Martínez et al., 2020).

4.2.4. Isotope geochemistry

The isotopic compositions (δ²H and δ¹⁸O) of 12 analyzed groundwater samples from the Tacaratu aquifer are listed in Supplementary Table 3 and plotted in Fig. 6, along with the Global Meteoric Water Line (GMWL; Craig, 1961), and samples from the Tacaratu aquifer in the Araripe Basin (~100 km NW from the Mirandiba Basin; Vidal Silva et al., 2007), which has its sedimentation directly correlated with the Mirandiba Basin. The Recife precipitation collected between January 2013 and December 2014 (δ²H = 7.38*δ¹⁸O + 11.1; Cary et al., 2015), the closest dataset for rainwater available in the literature (~450 km E from the Mirandiba Basin) were also plotted for comparison. The Mirandiba groundwater samples have δ¹⁸O values varying from -4.95 to -3.16 ‰ and δ²H from -29.74 to -17.50 ‰, which is analogous to the groundwater composition of the Araripe Basin (δ¹⁸O = -4.8 to -2.7 ‰, δ²H = -32.10 to -14.5 ‰). Altogether, the groundwater samples from the basins are significantly depleted (avg. δ¹⁸O = -4.08 ‰, avg. δ²H = -22.96 ‰) when compared to present-day rainwater (avg. δ¹⁸O = -1.14 ‰, avg. δ²H = +2.67 ‰). Such a difference could be related to groundwater recharge under past wetter and/or cooler conditions than modern times (e.g., Edmunds et al., 2003; Zhu et al., 2007; Jasechko et al., 2014; Hakimi et al., 2021; Silva et al., 2021), but more data are required to conclude it. Furthermore, rain removal from a moist air mass during continental incursion can make residual vapor continuously more depleted in the heavy isotopes (e.g., Hoefs, 2009). However, hydrological and paleobotanical information corroborates with the proposition of wetter conditions in NE Brazil suggesting that

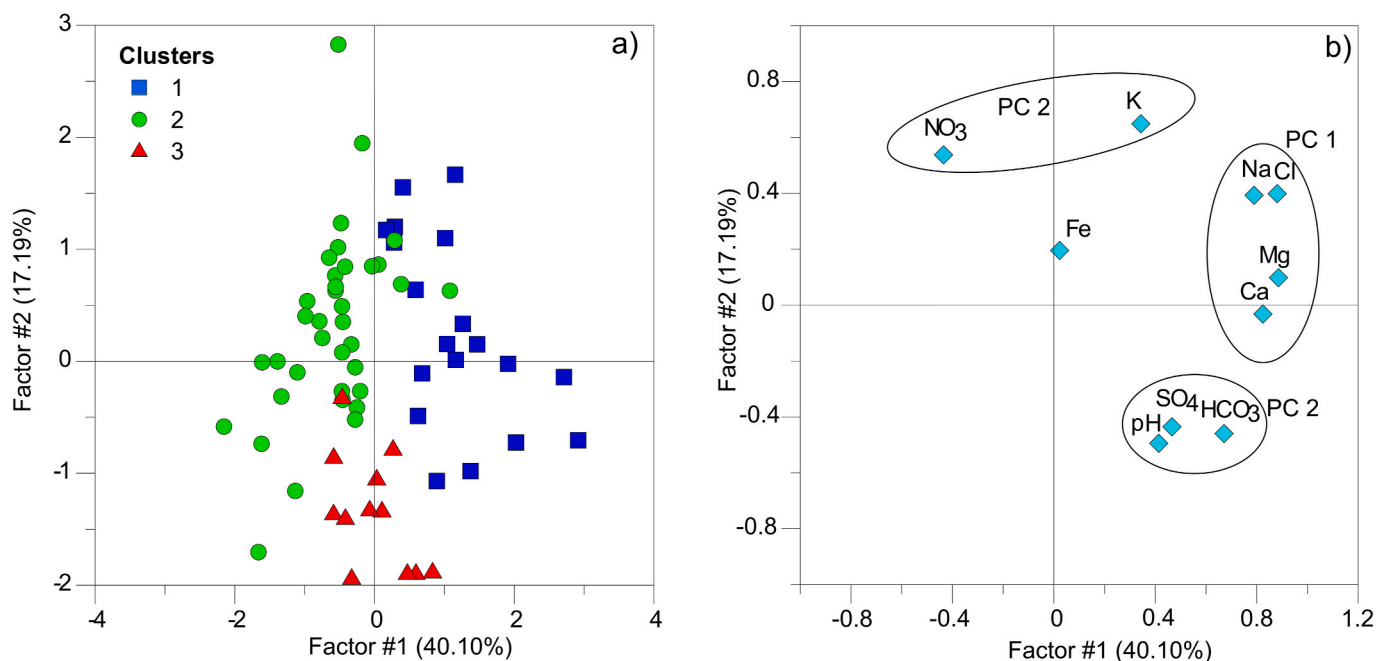


Fig. 4. Results of PCA showing the first two PCs of individual (a) samples and (b) variables.

hydro-ecological connection between the Amazonian Forest and the coastal Atlantic Forest of NE Brazil existed (e.g., Cheng et al., 2013; Bertrand et al., 2017), where nowadays occur a semi-arid shrubby vegetation. The $\delta^{18}\text{O}$ and $\delta^2\text{H}$ in groundwaters in the Mirandiba Basin are linearly correlated, akin to that for the GMWL, with an equation of $\delta^2\text{H} = 5.84 \cdot \delta^{18}\text{O} + 0.85$ ($r^2 = 0.82$), clearly stating that groundwaters have a meteoric origin (e.g., Mirzavand et al., 2020a; Mirzavand and Walter, 2024). A slightly lower angular coefficient, compared to the GMWL, evidences that evaporation took place during surficial runoff or infiltration in the vadose zone. Four samples are under confined conditions, with three of them falling in the GMWL or slightly above it, whereas one sample (#P-056) evidences the highest degree of evaporation of all analyzed samples. The evaporation regression line that passes through sample #P-056 intercepts the GMWL ($\delta^{18}\text{O} = -4.1$ ‰, $\delta^2\text{H} = -23$ ‰) at a similar composition of the other confined samples. A plot of $\delta^{18}\text{O}$ versus Cl^- was used to assess the processes controlling mineralization and suggests that evaporation and dissolution or fertilizer/sewage inputs impacted groundwater quality (e.g., Bahir et al., 2019; Torres-Martínez et al., 2021).

4.2.5. Mineral saturation (geochemical stability)

The results show that groundwater from all clusters is highly undersaturated concerning halite (-9.0 to -5.2 ; mean -7.0 , std. deviation 0.7) and gypsum (-4.8 to -1.7 ; mean -3.0 , std. deviation 0.7), suggesting that these minerals are likely to dissolve in groundwater (Fig. 7a and b). Halite and gypsum show a slight undersaturation trend in clusters 3 and 2 relative to cluster 1. These clusters show slightly parabolic proportional relationships in the plots of TDS against the saturation indexes for the referred minerals (e.g., Dassi, 2011). These relationships may suggest the presence of halite and gypsum in the geological matrix (e.g., Hakimi et al., 2021). However, detailed matrix mineralogy information is lacking for the studied basin. Some authors (e.g., Tellam, 1995; Güler and Thyne, 2004) have found that high concentrations, over many thousand milligrams per liter, are required to approach equilibrium regarding halite and gypsum. Given the nearly constant SI values for these evaporites, it is more likely that these salts are leached from the soils, after concentration by evaporation during sporadic but cyclic wetting and drying under a semi-arid climate, during plausible winter-time groundwater recharge (e.g., Adams et al., 2001; Jasechko et al.,

2014). For calcite and dolomite, there is no clear trend for any cluster (Fig. 7c and d). Undersaturation is evidenced in groundwater samples from clusters 2 and 3 (a few near to equilibrium) concerning calcite and dolomite, ranging from -5.0 to -0.7 and -10 to -1.3 , and -2.4 to -0.2 and -4.2 to -0.2 , respectively, which indicates that their dissolution may occur in the aquifers. On the other hand, for cluster 1, $\sim 35\%$ of groundwater samples were in equilibrium or oversaturated with calcite and dolomite, -1.8 to 0.9 and -3.4 to 2 , suggesting that precipitation is likely to take place, contributing to the existing water chemistry composition.

4.3. Drinking suitability

The descriptive statistics from the analyzed physical-chemical parameters are portrayed in Table 3. All parameters obtained were compared with those from the World Health Organization (WHO, 2011) and Brazilian (BMH) standards (Brazil, 2011), which are rather similar, whereas the WHO limit for the pH is slightly more restrictive. pH values range from 4.2 to 9.4 (avg. 6.5 , std. deviation 1.1) with twenty-two samples out of the BMH limits, which are mostly acidic from the cluster 2 (sixteen samples) and 1 (five samples). EC, TDS, and TH varied from 96 to 2950 $\mu\text{S}/\text{cm}$ (avg. 499 , std. deviation 475), 61 – 1888 mg/L (avg. 320 , std. deviation 314), and 32 – 773 mg/L (avg. 165 , std. deviation 142) with respectively, three, three, and two samples from cluster 1 surpassing the WHO threshold (Table 3 and Fig. 8).

Ca^{2+} and Mg^{2+} varied from 2 to 80 mg/L (avg. 18 , std. deviation 16) and 2.5 – 117 mg/L (avg. 26 , std. deviation 23), respectively, therefore within WHO limits (Table 3 and Fig. 8). Na^+ and K^+ ranged from 2 to 338 mg/L (avg. 49 , std. deviation 61) and 4 – 69 mg/L (avg. 16 , std. deviation 11) evidencing two and four samples, respectively, above WHO allowable limits (Table 3 and Fig. 8). SO_4^{2-} varied from below the detected limit to 196 mg/L within the WHO threshold (Table 3 and Fig. 8). Similarly, NO_3^- ranged from 0.01 to 3.7 mg/L (avg. 0.42 , std. deviation 0.63), which is within the short-term exposure of 50 mg/L devised by WHO (2011). However, around half of the samples surpass the long-term exposure addendum of the WHO guideline value of 0.2 mg/L for nitrate (WHO, 2008), which is a concern since groundwater is the main source for drinking supply (Table 3 and Fig. 8). Cl^- and HCO_3^- varied from 14 to 701 mg/L and 4 – 483 mg/L with eight and one

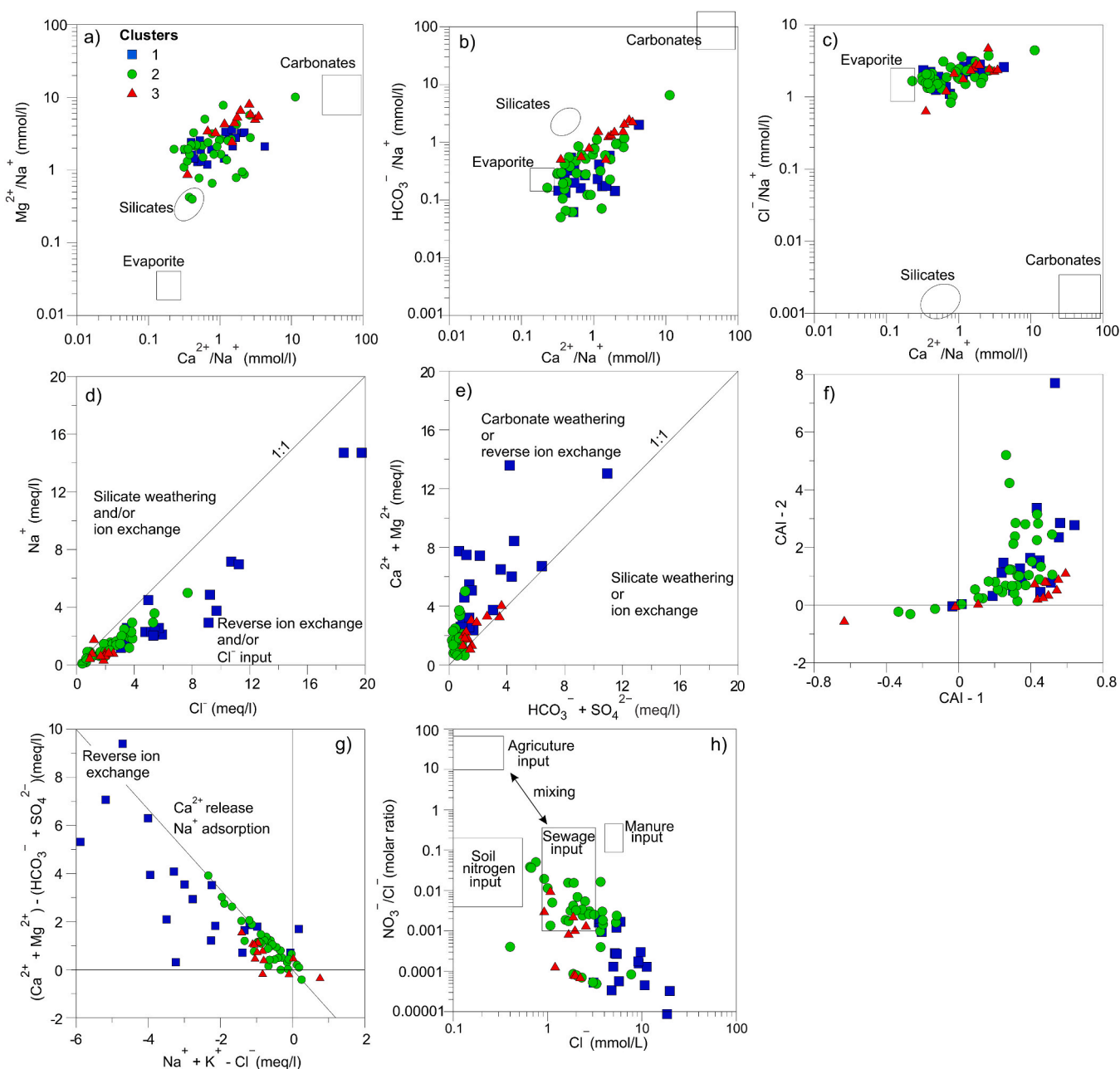


Fig. 5. (a) $\text{Mg}^{2+}/\text{Na}^+$ versus $\text{Ca}^{2+}/\text{Na}^+$. (b) $\text{HCO}_3^-/\text{Na}^+$ versus $\text{Ca}^{2+}/\text{Na}^+$. (c) Cl^-/Na^+ versus $\text{Ca}^{2+}/\text{Na}^+$. Data for silicate, carbonate, and evaporite endmembers are from Gaillardet et al. (1999). (d) Na^+ versus Cl^- . (e) $\text{Ca}^{2+} + \text{Mg}^{2+}$ versus $\text{HCO}_3^- + \text{SO}_4^{2-}$. (f) CAI-1 versus CAI-2. (g) $(\text{Ca}^{2+} + \text{Mg}^{2+}) - (\text{HCO}_3^- + \text{SO}_4^{2-})$ versus $(\text{Na}^+ + \text{K}^+) - \text{Cl}^-$. (h) $\text{NO}_3^-/\text{Cl}^-$ versus Cl^- . Fields for soil nitrogen, agriculture, sewage, and manure are from Torres-Martínez et al. (2021).

groundwater samples, respectively, beyond WHO limits (Fig. 8). Fe varied between 0.15 and 0.97 mg/L showing more than half of the samples slightly above the WHO recommended threshold (avg. 0.33, std deviation 0.16; Table 3 and Fig. 8). At levels exceeding 0.3 mg/L, iron in water causes stains plumbing fixtures and laundry, and does not cause any serious health effect (e.g., WHO, 2011; Rakotondrabe et al., 2018). The interpolated distribution maps for the analyzed parameters are presented in Supplementary Fig. 7–8.

The parameters results were used to retrieve drinking water quality indexes (DWQI). It assumes that those parameters that are more harmful to health have a higher weight (i.e., contribute more) than those that present lower adverse effects. The calculated value for each sample represents a meaningful number that sheds light on the groundwater quality status. It has been used to indicate recommendations for groundwater quality protection (e.g., build future monitoring systems

and remediation action plans, e.g., Li et al., 2015; Silva and Lima, 2023). All computed DWQI are below 102, mainly within the excellent (forty-four samples) and good (twenty-one samples) categories for drinking purposes. These values reflect the general good quality of groundwater, usually within WHO and Brazilian recommended limits. The interpolated geographical distribution of the calculated index values revealed groundwater variability, evidencing that only a small portion in the central-northern area is within the poor water category (Fig. 9).

4.4. Irrigation suitability

Sodium Absorption Ratio (SAR), Soluble Sodium Percentage (SSP), Kelley Ratio (KR), Residual Sodium Carbonate (RSC), and Permeability Index (PI) as well as salinity [EC/TDS] were used to evaluate the suitability of groundwater for irrigation use. Water composition (i.e., the

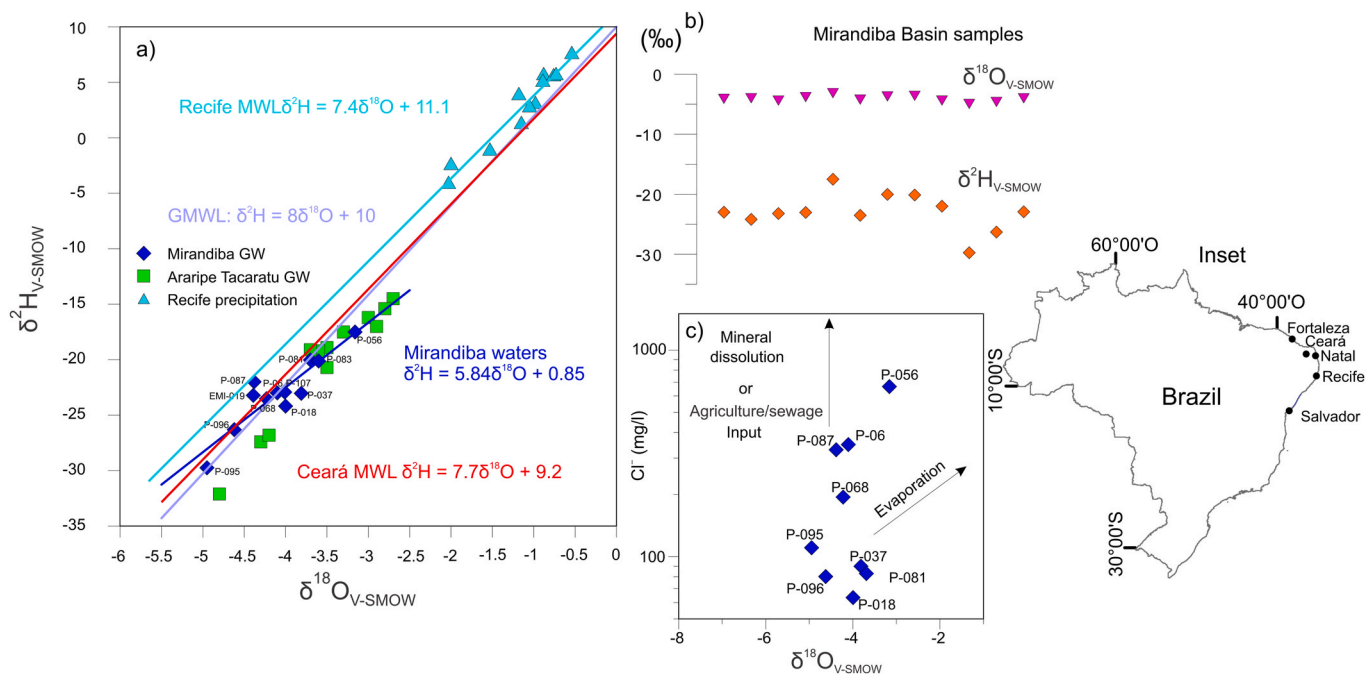


Fig. 6. (a–b) Plots showing $\delta^{18}\text{O}$ and $\delta^2\text{H}$ isotopic values. (c) $\delta^{18}\text{O}$ versus Cl^- concentration.

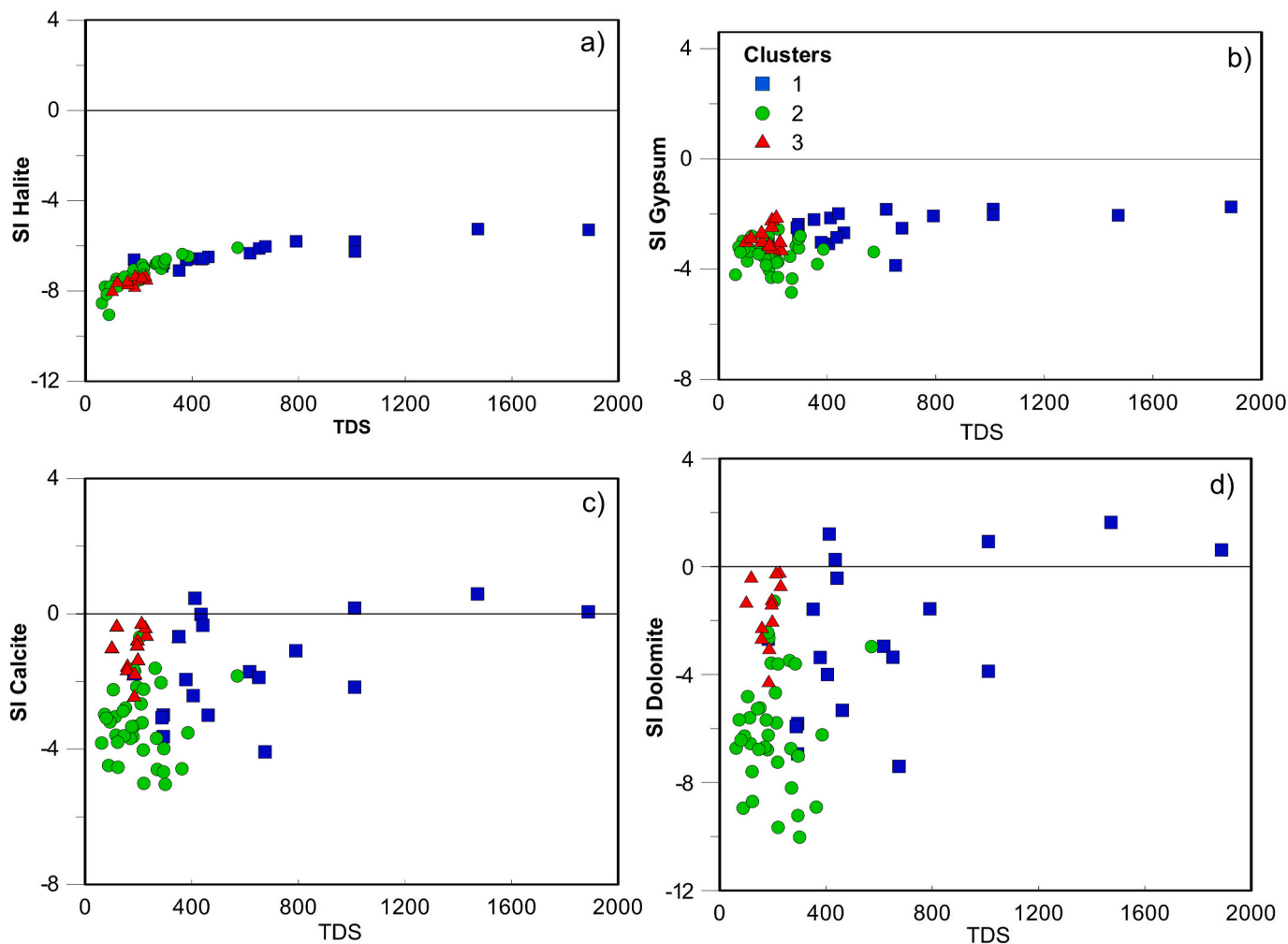


Fig. 7. TDS versus saturation indices of groundwater for (a) Halite, (b) Gypsum, (c) Calcite, and (d) Dolomite.

Table 3

Descriptive statistics for the whole analyzed groundwater samples and individualized by defined clusters.

Variables		pH	EC	TDS	TH	Ca ²⁺	Mg ²⁺	Na ⁺	K ⁺	Cl ⁻	SO ₄ ²⁻	HCO ₃ ⁻	NO ₃ ⁻	Fe
Unit		–	uS/cm	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
Total (n = 67)														
Mean		6.5	498.58	320.3	164.6	17.68	26.42	49.1	15.8	135.59	30.1	51.4	0.42	0.33
Median		6.5	340	213.12	115.62	10.4	18.48	33.35	13.65	90.4	16.8	31.72	0.18	0.31
Mode		5.5a	96a	182.40a	40.62a	5.20a	5.52a	20.7	12.48	66.29a	1.92	33.55	0.01	0.23
Std. Deviation		1.1	478.8	313.9	142.6	16.1	23.5	60.7	10.8	129.6	36.6	66.3	0.63	0.16
Skewness		0.1	3.2	3.1	2.2	1.9	2.1	3.6	2.7	2.6	2.5	4.6	3	1.98
Minimum		4.17	96	61.44	31.87	2	2.48	2.07	3.9	14.18	0.1	4.27	0.01	0.15
Maximum		9.4	2950	1888	773.25	79.6	116.88	338.1	68.64	700.85	196.32	483.12	3.72	0.97
Percentiles	25	5.62	246	158.72	84.37	7	12.72	17.94	9.36	66.29	7.2	22.57	0.03	0.23
	75	7.3	590	362.88	196.5	23.2	31.08	52.44	17.55	176.19	40.32	53.68	0.49	0.39
WHO (1996, 2011)		6–8.5	1500	1000	500	200	150	200	30	250	250	300	50	0.3
BMH		6–9.5	–	1000	500	–	–	200	–	250	250	–	42.6	0.3
Number of samples above recommendation		22	3	3	2	0	0	2	4	8	0	1	0	39

Cluster 1 (n = 19)														
Mean		6.8	989.11	634.42	320.41	35.10	50.29	100.14	22.86	270.20	61.19	89.03	0.15	0.28
Median		6.8	689	440.96	303.7	34	41.4	58.88	19.5	192.14	49.92	39.65	0.09	0.31
Mode		6.5	450 ^a	293.12a	130	7.4a	15.1a	52.4	13.65a	124.1	10.56	18.3	0.09	0.31
Std. Deviation		1.11	657.59	440.73	178.21	19.75	30.50	92.13	13.83	169.41	52.17	110.27	0.17	0.08
Skewness		0.37	2.02	1.72	1.07	0.66	0.97	2.04	2.13	1.59	1.36	2.77	1.52	–0.16
Minimum		4.8	450	182.4	128.8	7.4	15.1	27.1	10.9	108.8	0.96	16.5	0.01	0.2
Maximum		9.4	2950	1888	773.3	79.6	116.9	338.1	68.6	700.9	196.3	483.1	0.62	0.4
Percentiles	25	6.2	590	351.36	140.62	22.8	25.2	48.3	12.87	169.1	27.36	20.74	0.03	0.23
	75	7.4	1145	790.4	390.6	49.4	64.2	111.78	30.03	343.86	77.28	141.52	0.22	0.31

Cluster 2 (n = 36)														
Mean		5.91	314.69	201.4	91.7	9.85	15.61	32.25	14.1	88.82	12.22	26.64	0.66	0.36
Median		6.05	287	183.68	88.75	8.2	13.62	24.96	13.65	77.46	7.44	27.45	0.44	0.31
Mode		5.5	96 ^a	61.44a	40.62a	5.2a	5.5a	20.7	12.48a	66.29a	1.92	33.55	0.01	0.23
Std. Deviation		0.9	160.55	102.75	48.51	5.86	10.23	23.28	8.69	54.17	11.73	12.88	0.78	0.21
Skewness		–0.03	1.44	1.44	1.74	1.99	1.49	1.65	3.07	1.31	1.34	0.28	2.23	1.51
Minimum		4.17	96	61.44	31.87	2	2.5	2.07	3.9	14.18	0.1	4.27	0.01	0.15
Maximum		7.75	892	570.88	274.37	32.2	49.6	114.8	54.99	272.96	45.6	58.56	3.72	0.97
Percentiles	25	5.35	190.5	121.92	56.88	6.2	8.64	15.7	8.97	55.84	2.88	15.4	0.11	0.23
	75	6.58	416	266.24	113.43	11.9	19.08	43.41	16.38	125.46	17.52	33.55	0.83	0.47

Cluster 3 (n = 12)														
Mean		7.60	273.58	180	137.03	13.6	21.11	19.04	9.71	62.81	34.56	66.13	0.13	0.31
Median		7.65	298	190.72	121.88	11.1	20.16	18.29	9.75	68.24	342.40	58.87	0.05	0.31
Mode		6.5a	156 ^a	99.8a	68a	5.8	9.96a	19.78a	10.14a	69.84	9.60a	21.96a	0.01	0.23
Std. Deviation		0.61	66.93	39.90	50.02	8.17	7.33	8.06	2.48	17.03	20.26	35.16	0.19	0.09
Skewness		0.18	–0.52	–0.88	0.24	1.16	–0.21	2.15	0.64	–0.55	0.82	0.64	2.17	0.02
Minimum		6.5	156	99.84	68	5.8	9.96	8.78	5.46	32.61	9.6	21.96	0.01	0.15
Maximum		8.8	358	229.12	208	31.2	31.08	41.86	14.82	90.40	72.96	128.10	0.66	0.42
Percentiles	25	7.19	208.5	157.76	94.09	6.75	14.76	15.69	8.16	46.71	16.92	39.19	0.01	0.23
	75	8.05	325.5	208.32	189.78	19.35	28.47	20.47	10.92	69.84	42.28	94.40	0.21	0.42

a. Multiple modes exist. The smallest value is shown. TH - Total Hardness; BMH - Brazilian Ministry of Health. n - Number of samples.

chemical constituents) and soil have a great influence on agricultural yield production because they interact and could negatively impact permeability and consequently plant growth.

US salinity diagram (Fig. 10a; Richards, 1954) shows that groundwater from clusters 2 and 3 falls in the C1S1 and C2S1 whereas those from cluster 1 plot mostly in the C2S1 and C3S1 with only two samples within C4S2. Electrical conductivity from most samples indicates low salinity hazard (<750 µS/cm; ~85 % samples) suggesting little modification from the osmotic pressure in the root zone (e.g., Mayer and Poljakoff-Mayber, 1982), while a few samples are only recommended to salt-tolerant crops, particularly in soils with unrestricted drainage. For SAR (sodium (Alkali) hazard), all samples present values below 6 (avg. 1.6, stand. dev. 1.1) indicating suitability for irrigation regarding this index. These results agree with soluble sodium percentage (SSP or %Na) and Kelley's ratio values of 22–73 % (avg. 44 %, stand. dev. 12) and 0.09

to 2.51 (avg. 0.72, stand. dev. 0.46; 83.5 % samples within good category ≤1), respectively. In a plot of %Na versus EC (Fig. 10b), clusters 2 and 3 fall in the excellent to good category, while only two samples from cluster 1 plot in the doubtful to unsuitable field. The calculated RSC values spanned from –10.7 to –0.18, below +1.25, clearly within the good category and indicating no hazardous effect of excess alkalinity on groundwater. Concerning the permeability index (Fig. 10c), which evaluates long-term groundwater suitability, the analyzed samples plot within class I and II (PI = 33 to 90), except for three samples that are class III, indicating that most groundwater is good for irrigation. Contour maps for calculated indices evidence good groundwater quality through the basin, with a small area in the northeastern of the basin evidencing a few pockets exceeding recommended values for EC, PI, and SAR (Fig. 11a–f).

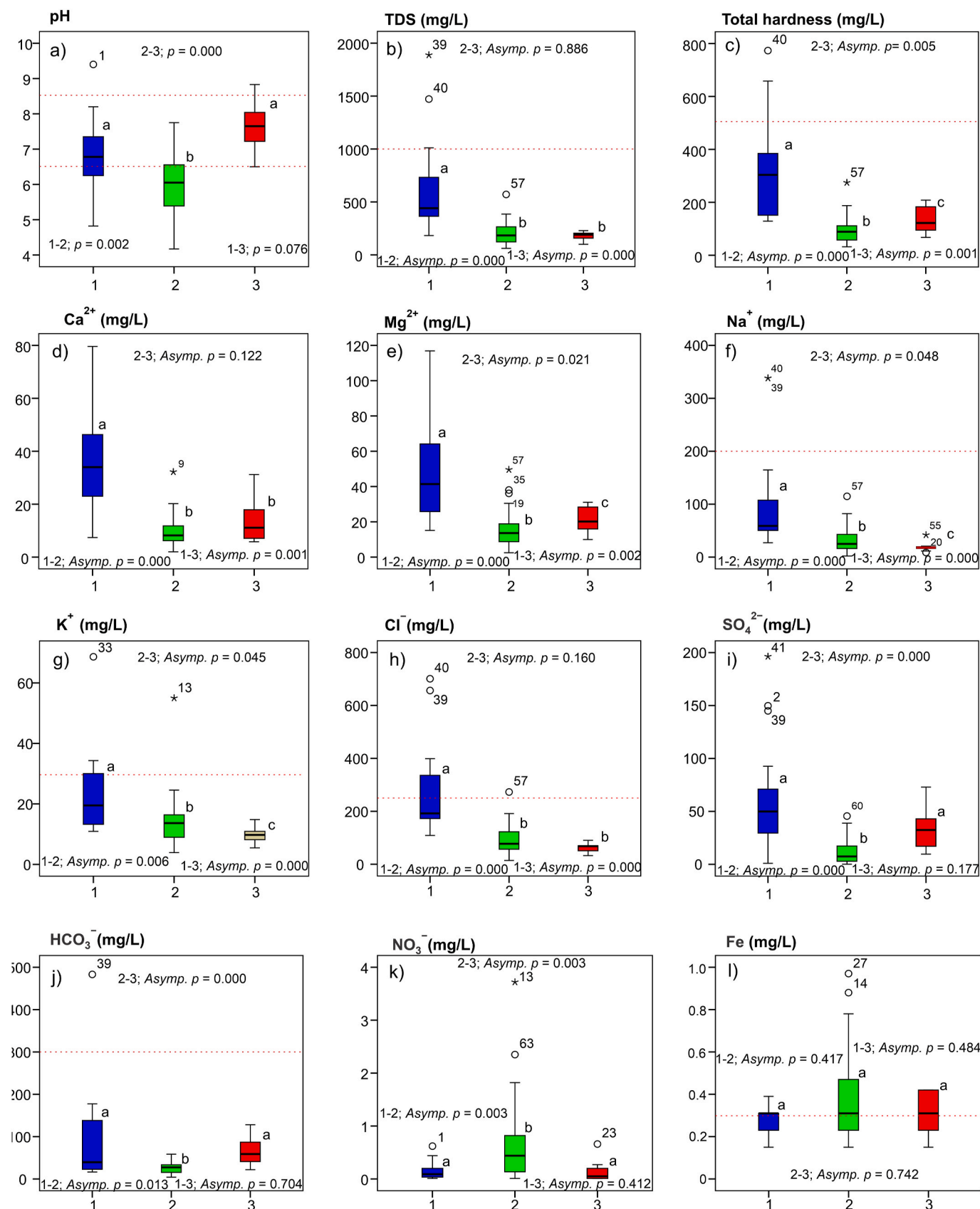


Fig. 8. Box plots of pH, TDS, total hardness, Ca²⁺, Mg²⁺, Na⁺, K⁺, Cl⁻, SO₄²⁻, HCO₃⁻, NO₃⁻, and Fe labeled by clusters. The color boxes represent the lower and upper quartiles with the median in middle. The circle indicates 1.5 x interquartile range (IQR) (outliers), and whiskers indicate 3 x IQR. Different letters within each panel represent significantly different data distributions (Asymp. $p < 0.05$) according to a Mann-Whitney U test. Lower and upper red lines when available are the WHO/BHM recommended threshold.

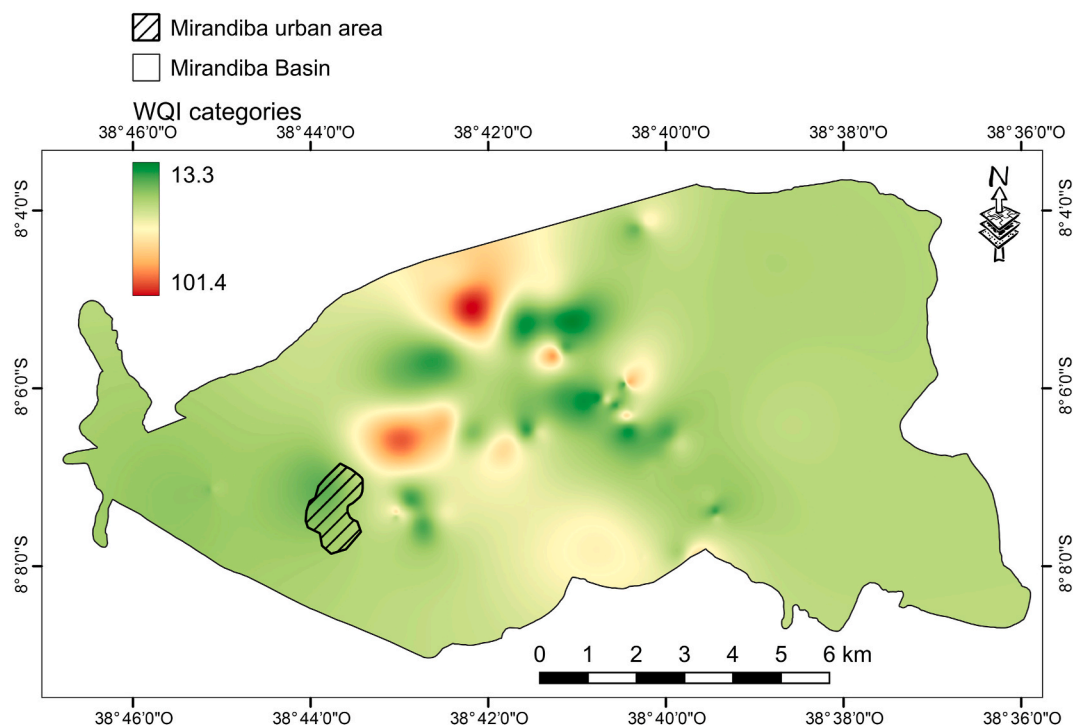


Fig. 9. Water quality index map.

4.5. Conceptual hydrogeologic model

The geophysical, hydrogeochemical, and stable isotopic data were used to develop a conceptual model (Fig. 12) of the operation processes in the Tacaratu aquifer of the Mirandiba Basin. Geophysics (VES) showed a shallow basin with a slightly greater depth on the north-western edge following a main fault or fault zone in the NE–SW direction. It also evidenced that barren quaternary sequences cover the Tacaratu Formation. Fig. 12 shows a cross-section representing an envisaged hydrogeologic model in which precipitation from past periods until the present was accompanied by evaporation in a semi-arid climate that enriched the soil with salts (e.g., halite). Then, during precipitation periods, which allowed recharge events, rainwater dissolved salt soil with the infiltration of saltwater recharging the Tacaratu Aquifer. Then, during flow paths, carbonate weathering contributed to groundwater loads. Besides, reverse ion exchange operated, where the infiltrated Na^+ rich groundwater is likely exchanged for Ca^{2+} in the aquifer surfaces. The groundwater is also being impacted qualitatively by NO_3^- contamination and quantitatively by exploitation, which disturbs the natural flow system associated with anthropogenic activities.

5. Concluding remarks

An interdisciplinary and holistic approach has been employed using geophysics, geochemistry, and isotopes together with MSA (viz., principal components and hierarchical cluster analyses), GIS, modeling (i.e., geochemical stability speciation), and groundwater indices. From this approach, the main results can be summarized as follows:

- VES data indicate that the Mirandiba Basin has a shallow depth (≤ 500 m) with a main fault or zone fault on the northwestern edge that suggests a half-graben structure. Resistivity values for the principal aquifer formation gave values between 31 and 246 Ωm (avg. thickness of ~ 205 m) indicating homogeneity through the basin.
- MSA, HCA and PCA, together with the evaluation of the geographic distribution allowed the recognition of three distinct clusters; the

proximity of samples of each is interpreted as related to common factors/processes operating.

- We argue that cyclic wetting/drying with soil salt concentration and subsequent leaching during natural recharge events is a common process in groundwater under arid to semi-arid conditions, and it has been confirmed in similar sedimentary basins and crystalline aquifers worldwide. In addition, integrated data indicate that carbonate dissolution (water-rock interaction), and ion exchange are other coexisting geochemical processes governing the presence of major ions in groundwater.
- Geochemical data, when compared to WHO guidelines, show that Mirandiba groundwater is generally within recommended limits. The spatial distribution of the water quality index computed from the sampled wells, reveal adequate water for drinking in most of the basin area.
- The data presented confirm that anthropogenic contamination likely from farming practices still occurs and may have increased. This is an important observation considering this is the main water source for the population supply, and there is unlikely to be any alternative in the foreseeable future, at least within the next few decades. However, although there is some evidence that anthropogenic activities result in groundwater contamination, these are still of little relevance and with limited impacts on the overall quality of Mirandiba's groundwater.
- All irrigation ion-based indexes showed that most groundwater is suitable for irrigation grounds.

Water quality results (i.e., indices and interpolated maps) should be used to provide knowledge to society and support decision-makers and water authorities. Although more than a decade has passed since the chemical data were collected, it contributes to the state of the art by addressing the current lack of hydrogeochemistry data for the Mirandiba Basin. This dataset will serve as a valuable baseline for future studies, enabling the assessment of groundwater quality trends associated with degradation processes. These results can assist in the optimization of monitoring programs for collecting updated information on water quality and quantity. Furthermore, the chemical data evidenced the

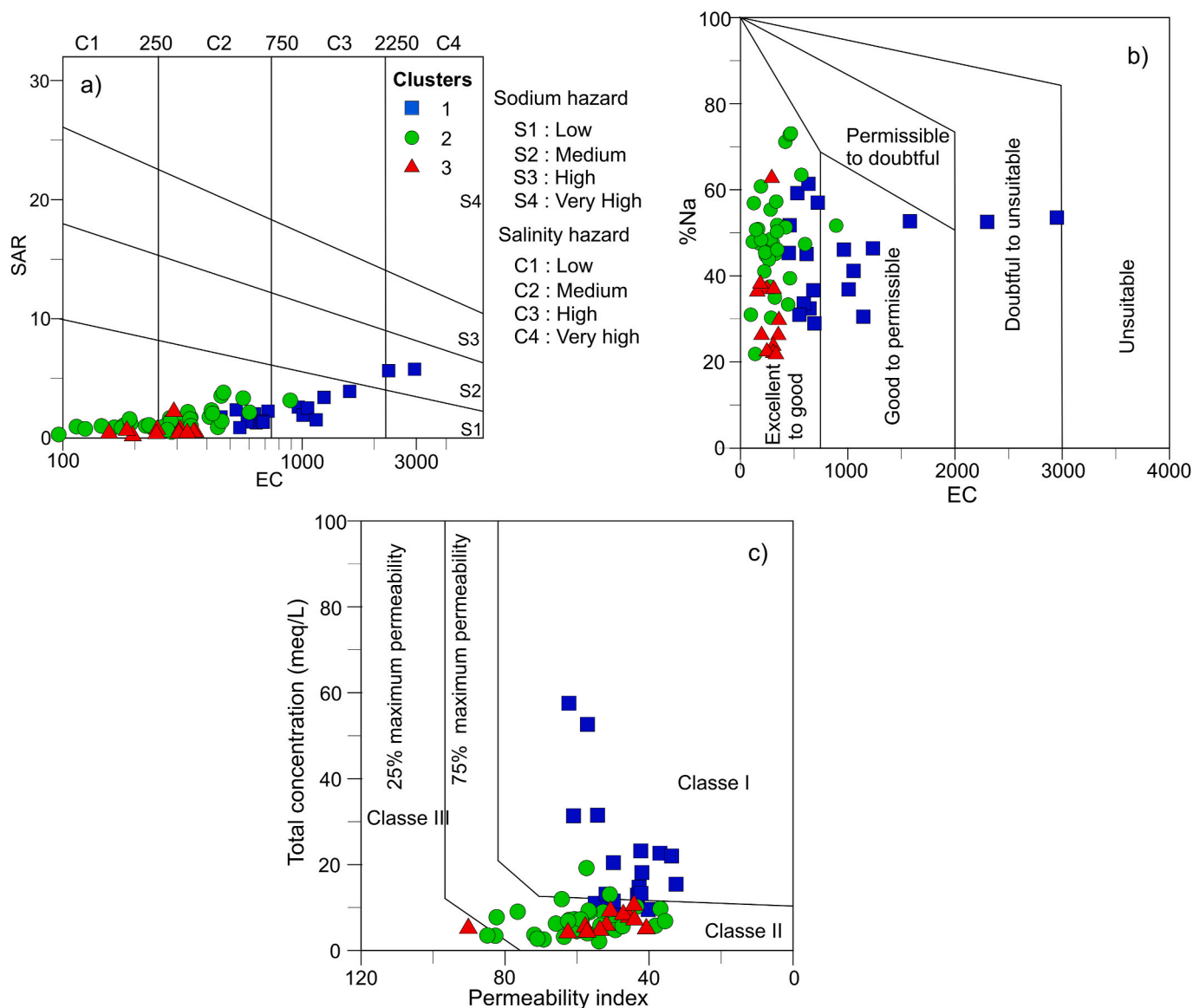


Fig. 10. Plots of irrigation water quality indices. (a) Sodium hazards versus EC. (b) %Na versus EC. (c) Permeability index versus total concentration.

main long-term geochemical processes operating within the ground-water system, including cyclic salt accumulation, rock weathering, and reverse ion exchange.

This study highlights the use of geochemistry and isotopes, GIS techniques, and multivariate statistical analyses to understand hydro-geochemical processes. When combined with geophysical results, these methods can be employed to develop a conceptual model aimed at effective groundwater management. This approach can also be applied to similar basins in arid to semi-arid climate conditions.

6. Recommendations

This study recognized the main processes causing salinization and contamination in the Mirandiba Basin. This knowledge allows us to propose some strategies and future studies to deepen the nature of groundwater mineralization, which can be summarized as follows:

- Improve the public sanitation system of the Mirandiba municipality, mainly the urban areas, to avoid sewage-related contamination.
- Development of a monitoring network for quality (groundwater and streams) and groundwater levels considering the well groups found

in this study to support strategies for water resources control and management.

- Regulate and diversify the types of fertilizers and manure applied to agriculture as well as reduce water loss with the use of micro-irrigation associated with GIS techniques (e.g., Siebert et al., 2010; Silva and Lima, 2023 and references therein).
- Improve the incomplete dataset with a seasonal evaluation by performing new chemical (major and minor elements including N, P, K, B, and Br), and isotopic studies (e.g., $\delta^{18}\text{O}(\text{H}_2\text{O})$, $\delta^2\text{H}(\text{H}_2\text{O})$, $\delta^{15}\text{N}(\text{NO}_3)$, $\delta^{18}\text{O}(\text{NO}_3)$, $\delta^{34}\text{S}(\text{SO}_4)$, $\delta^{18}\text{O}(\text{SO}_4)$, $\delta^{11}\text{B}$, $\delta^{81}\text{Br}$, $\delta^{37}\text{Cl}$, $\delta^{13}\text{C}$, $\delta^{14}\text{C}$, and ^3H) preferable using the future network wells to further evaluate the mineralization and contamination processes. Furthermore, obtain the isotopic signature of rainwater to determine the local meteoric water line on a hydrogeological cycle.
- Perform pump tests to adequately obtain the hydraulic characteristics (i.e., hydraulic conductivity, transmissivity, and storage coefficient) and detailed geophysical studies focusing on faults.
- Investigate soil contents and soil water infiltration evaluation.
- Implement alternative water management strategies such as Managed Aquifer Recharge (Dillon et al., 2018) to achieve groundwater replenishment.

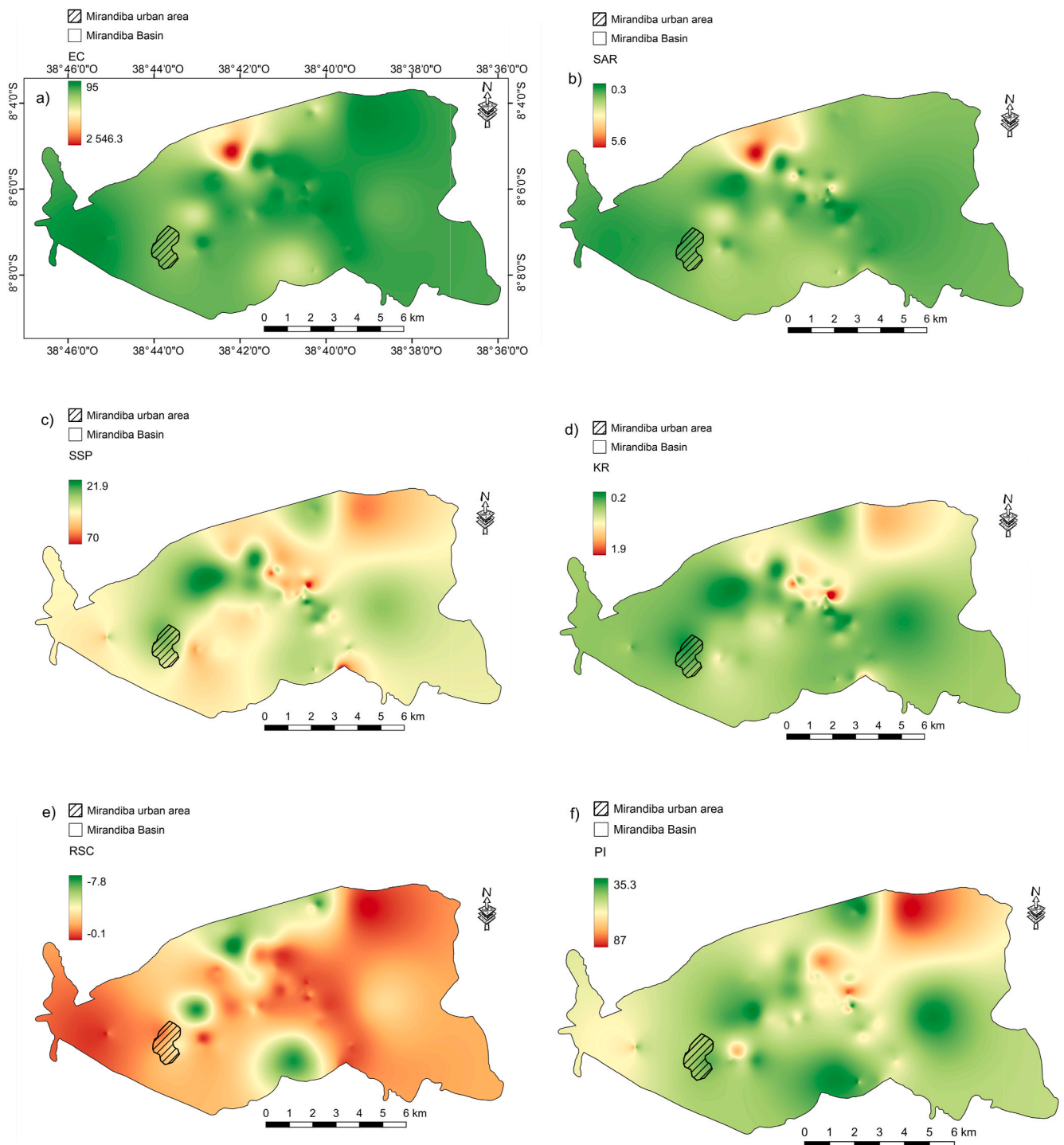


Fig. 11. Spatial irrigation indices distribution. (a) EC. (b) SAR. (c) SSP. (d) KR. (e) RSC. (f) PI.

- Promote the optimization and reduction of urban water uses near the population in general and main water consumers (e.g., industry), increasing the awareness regarding scarcity phenomena.

CRediT authorship contribution statement

Thyego R. Silva: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Mariucha M. Correia de Lima:** Writing – original draft, Visualization, Validation, Supervision, Project administration,

Methodology, Investigation, Formal analysis, Data curation. **Tiago N. Martins:** Writing – review & editing, Visualization, Validation, Methodology, Investigation, Formal analysis. **Waldir D. Costa:** Visualization, Investigation, Formal analysis. **Mateus S.C. Albuquerque:** Investigation, Formal analysis, Data curation. **Manoel Júlio da T.G. Galvão:** Visualization, Investigation, Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence

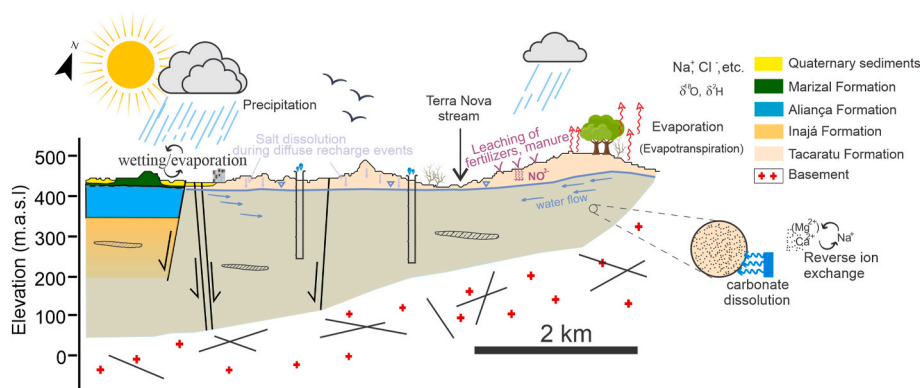


Fig. 12. Conceptual hydrogeologic model of the Mirandiba Sedimentary Basin.

the work reported in this paper.

Acknowledgments

We sincerely thank the Editor-in-Chief, Prof. Elisa Sacchi, for excellent editorial handling and anonymous reviewers for their comments that contributed to the improvement of this manuscript. The World Bank is acknowledged for the loan agreement No. 7778-BR through the Pernambuco Water Sustainability Project (UGP/PSHPE) under contract PSHPE No. 003/2017. The Project “Hydrogeological Research in Sedimentary Basins of Northeast of Brazil”, which was performed by the Geological Survey of Brazil – SGB/CPRM through the PAC (Growth Acceleration Program of Federal Government of Brazil) is acknowledged. We thank Dr. Teresa E. Leitão (LNEC) for discussion and comments in an early version of this manuscript and undergraduate students Elaine Lourenço and Syllas Santana for helping during office work as interns.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.apgeochem.2025.106572>.

Data availability

All data has been provided as supplementary material

References

- Adams, S., Titus, R., Pietersen, K., Tredoux, G., Harris, C., 2001. Hydrochemical characteristics of aquifers near sutherland in the Western Karoo, South Africa. *J. Hydrol.* 241, 91–103. [https://doi.org/10.1016/S0022-1694\(00\)00370-X](https://doi.org/10.1016/S0022-1694(00)00370-X).
- Adimalla, N., 2019. Groundwater quality for drinking and irrigation purposes and potential health risks assessment: a case study from semi-arid region of South India. *Expo. Health* 11, 109–123. <https://doi.org/10.1007/s12403-018-0288-8>.
- Adimalla, N., Dhakate, R., Kasarla, A., Taloor, A.K., 2020. Appraisal of groundwater quality for drinking and irrigation purposes in central Telangana, India. *Groundw. Sustain. Dev.* 10, 100334. <https://doi.org/10.1016/j.gsd.2020.100334>.
- Ahmad, A.Y., Saleh, I.A., Balakrishnan Al-Ghouti, M.A., 2021. Comparison GIS-based interpolation methods for mapping groundwater quality in the state of Qatar. *Groundw. Sustain. Dev.* 13, 100573. <https://doi.org/10.1016/j.gsd.2021.100573>.
- APHA, 2005. Standard Methods for the Examination of Water and Wastewater, twenty-first ed. American Public Health Association/American Water Works Association/Water Environment Federation, Washington DC.
- Appelo, C.A.J., Postma, D., 2005. *Geochemistry, Groundwater and Pollution*, second ed. A.A. Balkema, p. 634.
- Argamasilla, M., Barberá, J.A., Andreo, B., 2017. Factors controlling groundwater salinization and hydrogeochemical processes in coastal aquifers from southern Spain. *Sci. Total Environ.* 580, 50–68. <https://doi.org/10.1016/j.scitotenv.2016.11.173>.
- Avilés, G.P.F., Descloîtres, M., Duwig, C., Rossier, Y., Spadini, L., Legchenko, A., Soruco, A., Argollo, J., Pérez, M., Medinaceli, W., 2020. Insight into the Katari-Lago Menor Basin aquifer, Lake Titicaca-Bolivia, inferred from geophysical (TDEM), hydrogeological and geochemical data. *J. S. Am. Earth Sci.* 99, 102479. <https://doi.org/10.1016/j.jsames.2019.102479>.
- Bahir, M., Ouazar, D., Goumih, A., Ouhamdouch, S., 2019. Evolution of the chemical and isotopic composition of groundwater under a semi-arid climate; the case of the Cenomano-Turonian aquifer within the Essaouira basin (Morocco). *Environ. Earth Sci.* 78, 353. <https://doi.org/10.1007/s12665-019-8349-2>.
- Ball, L.B., Ge, S., Caine, J.S., Revil, A., Jardani, A., 2010. Constraining fault-zone hydrogeology through integrated hydrological and geoelectrical analysis. *Hydrogeol. J.* 18, 1057–1067. <https://doi.org/10.1007/s10040-010-0587-z>.
- Barbosa, N.S., Silva-Barbosa, N., Salles, L.Q., 2017. Stable isotopes ($\delta^2\text{H}$ e $\delta^{18}\text{O}$) assessment methods in hydrology: a review. *Terrae Didactica* 14, 157–172. <https://doi.org/10.20396/td.v14i2.8649972>.
- Benson, D., Gain, A.K., Giupponi, C., 2020. Moving beyond water centrality? Conceptualizing integrated water resources management for implementing sustainable development goals. *Sustain. Sci.* 15, 671–681. <https://doi.org/10.1007/s11625-019-00733-5>.
- Bertrand, G., Hirata, R., Auler, A., Cruz, F., Cary, L., Petelet-Giraud, E., Chatton, E., Aquilina, L., Moquet, J.S., Bustamante, M.G., Millo, C., Martins, V., Montenegro, S., Celle-Jeanton, H., 2017. Groundwater isotopic data as potential proxy for Holocene paleohydroclimatic and paleoecological models in NE Brazil. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 469, 92–103. <https://doi.org/10.1016/j.palaeo.2017.01.004>.
- Bobachev, A.A., Modin, I.N., Shevnev, V.A., 2003. IPI2win v. 2 for VES Data Interpretation, User's Guide. Geoscan-M Ltd., Moscow, Russia, 25pp.
- Brazil, 2011. Conselho Nacional de Meio Ambiente. Portaria n° 2 (914) de 12 de dezembro de 2011 [National Environment Council. Ordinance No. 2,914, of December 12, 2011]. Brasília, 2011. https://bvsms.saude.gov.br/bvs/saudelegis/gm/2011/prt2914_12_12_2011.html.
- Calvi, C., Carol, E., Fennell, L., Naipauer, M., 2024. Assessment of hydrological systems associated with groundwater discharges in arid high mountain environments of the Argentine Andes. *Groundw. Sustain. Dev.* 26, 101218. <https://doi.org/10.1016/j.gsd.2024.101218>.
- Cartwright, I., Weaver, T.R., 2005. Hydrogeochemistry of the Goulburn Valley region of the Murray Basin, Australia: implications for flow paths and resource vulnerability. *Hydrogeol. J.* 13, 752–770. <https://doi.org/10.1007/s10040-003-0318-9>.
- Cartwright, I., Weaver, T.R., Fulton, S., Nichol, C., Reid, M., Cheng, X., 2004. Hydrogeochemical and isotopic constraints on the origins of dryland salinity, Murray Basin, Victoria, Australia. *Appl. Geochem.* 19, 1233–1254. <https://doi.org/10.1016/j.apgeochem.2003.12.006>.
- Cary, L., Petelet-Giraud, E., Bertrand, G., Kloppmann, W., Aquilina, L., Martins, V., Hirata, R., Montenegro, S., Pauwels, H., Chatton, E., Franzen, M., Aurouet, A., the team, 2015. Origins and processes of groundwater salinization in the urban coastal aquifers of Recife (Pernambuco, Brazil): a multi-isotope approach. *Sci. Total Environ.* 530–531, 411–429. <https://doi.org/10.1016/j.scitotenv.2015.05.015>.
- Chaudhuri, S., Ale, S., 2014. Temporal evolution of depth-stratified groundwater salinity in municipal wells in the major aquifers in Texas, USA. *Sci. Total Environ.* 472, 370–380. <https://doi.org/10.1016/j.scitotenv.2013.10.120>.
- Cheng, H., Sinha, A., Cruz, F.W., Wang, X., Edwards, R.L., Horta, F.M., Ribas, C.C., Vuille, M., Stott, L.D., Auler, A.S., 2013. Climate change patterns in Amazonia and biodiversity. *Nat. Commun.* 4, 1411. <https://doi.org/10.1038/ncomms2415>.
- Choudhury, K., Saha, D.K., 2004. Integrated geophysical and chemical study of saline water intrusion. *Groundwater* 42, 671–677. <https://doi.org/10.1111/j.1745-6584.2004.tb02721.x>.
- Choudhury, K., Saha, D.K., Chakraborty, C., 2001. Geophysical study for saline water intrusion in a coastal alluvial terrain. *J. Appl. Geophys.* 46, 189–200. [https://doi.org/10.1016/S0926-9851\(01\)00038-6](https://doi.org/10.1016/S0926-9851(01)00038-6).
- Cloutier, V., Lefebvre, R., Therrien, R., Savard, M.M., 2008. Multivariate statistical analysis of geochemical data as indicative of the hydrogeochemical evolution of groundwater in a sedimentary rock aquifer system. *J. Hydrol.* 353, 294–313. <https://doi.org/10.1016/j.jhydrol.2008.02.015>.
- Craig, H., 1961. Isotopic variations in meteoric waters. *Science* 133, 1702–1703. <https://doi.org/10.1126/science.133.3465.1702>.
- Dassi, L., 2011. Investigation by multivariate analysis of groundwater composition in a multilayer aquifer system from North Africa: a multi-tracer approach. *Appl. Geochem.* 26, 1386–1398. <https://doi.org/10.1016/j.apgeochem.2011.05.012>.

- Dillon, P., Stuyfzand, P., Grischek, T., Lloria, M., Pyne, R.D.G., Jain, R.C., Bear, J., Schwarz, J., Wang, W., Fernandez, E., Stefan, C., Pettenati, M., van der Gun, J., Sprenger, C., Massmann, G., Scanlon, B.R., Xanke, J., Jokela, P., Zheng, Y., Rossetto, R., Shamruk, M., Pavelic, P., Murray, E., Ross, A., Bonilla Valverde, J.P., Palma Nava, A., Ansems, N., Posavec, K., Ha, K., Martin, R., Sapiano, M., 2018. Sixty years of global progress in managed aquifer recharge. *Hydrogeol. J.* 27, 1–30. <https://doi.org/10.1007/s10040-018-1841-z>.
- Diniz, J.A.O., Silva, J.C., 2014. Projeto IREP: implantação de rede estratégica de poços no semiárido brasileiro. *Tech. Rep.* 416. Brasília. <https://rigeo.cprm.gov.br/handle/doc/22101?mode=full>.
- Doneen, L.D., 1964. Notes on water quality in agriculture. *Water Science and Engineering*. University of California, Davis, p. 96.
- Dougherty, J.P., 1975. Texas water development board. Report 192 Evaporation Data in Texas: Compilation. Report January 1907–December 1970.
- Eaton, F.M., 1950. Significance of carbonates in irrigation waters. *Soil Sci.* 69, 123–134. <https://doi.org/10.1097/00010694-195002000-00004>.
- Ebraheem, A.-A.M., Senosy, M.M., Dahab, K.A., 1997. Geoelectrical and hydrogeochemical studies for delineating ground-water contamination due to salt-water intrusion in the Northern part of the Nile Delta, Egypt. *Groundwater* 35, 216–222. <https://doi.org/10.1111/j.1745-6584.1997.tb00077.x>.
- Edmunds, W.M., Guendouz, A.H., Mamou, A., Moulla, A., Shand, P., Zouari, K., 2003. Groundwater evolution in the Continental intercalaire aquifer of southern Algeria and Tunisia: trace element and isotopic indicators. *Appl. Geochem.* 18, 805–822. [https://doi.org/10.1016/S0883-2927\(02\)00189-0](https://doi.org/10.1016/S0883-2927(02)00189-0).
- Famiglietti, J.S., 2014. The global groundwater crisis. *Nat. Clim. Change* 4, 945–948. <https://doi.org/10.1038/nclimate2425>.
- Figueroa, R., Viguier, B., Taucare, M., Yáñez, G., Arancibia, G., Sanhueza, J., Daniele, L., 2021. Deciphering groundwater flow-paths in fault-controlled semi-arid mountain front zones (Central Chile). *Sci. Total Environ.* 771, 145456. <https://doi.org/10.1016/j.scitotenv.2021.145456>.
- Flath, H., 1963. Five-layer master curves for the hydrogeological interpretation of geoelectrical resistivity measurements above a two-storey aquifer. *Geophys. Prospect.* 11, 471–490. <https://doi.org/10.1111/j.1365-2478.1963.tb02048.x>.
- Francés, A.P., Ramalho, E.C., Fernandes, J., Groen, M., Hugman, R., Khalil, M.A., De Plaen, J., Monteiro Santos, F.A., 2015. Contributions of hydrogeophysics to the hydrogeological conceptual model of the Albufeira-Ribeira de Quarteira coastal aquifer in Algarve, Portugal. *Hydrogeol. J.* 23, 1553–1572. <https://doi.org/10.1007/s10040-015-1282-x>.
- Freeze, R.A., Cherry, J.A., 1979. *Groundwater*. Prentice-Hall Inc., Englewood Cliffs, Vol. 7632, 604.
- Fu, Y., Dong, Y., Wang, L., Bour, O., Klepikova, M.V., Zong, Z., Xu, Z., Zhou, Z., 2022. Characteristics of hydraulic conductivity in mountain block systems and its effects on mountain block recharge: insights from field investigation and numerical modelling. *J. Hydrol.* 612, 128184. <https://doi.org/10.1016/j.jhydrol.2022.128184>.
- Gaillardet, J., Dupré, B., Louvat, P., Allègre, C.J., 1999. Global silicate weathering and CO₂ consumption rates deduced from the chemistry of large rivers. *Chem. Geol.* 159, 3–30. [https://doi.org/10.1016/S0009-2541\(99\)00031-5](https://doi.org/10.1016/S0009-2541(99)00031-5).
- Galvão, M.J.T.G., 2013. Projeto “Pesquisa Hidrogeológica em Bacias Sedimentares Do Nordeste Brasileiro”: Hidrogeologia Da Bacia Sedimentar De Mirandiba - PE. CPRM, Recife. Available in: <https://rigeo.cprm.gov.br/handle/doc/22099>.
- Gamboa, C., Godfrey, L., Herrera, C., Custodio, E., Soler, A., 2019. The origin of solutes in groundwater in a hyper-arid environment: a chemical and multi-isotope approach in the Atacama desert, Chile. *Sci. Total Environ.* 690, 329–351. <https://doi.org/10.1016/j.scitotenv.2019.06.356>.
- Geyh, M., 2000. Environmental isotopes in the hydrological cycle. Principles and applications. Groundwater: saturated and unsaturated zone. *Intl. Hydrol. Program.* N° 39, 199. IV.
- Ghazaryan, K., Movsesyan, H., Gevorgyan, A., Minkina, T., Sushkova, S., Rajput, V., Mandzhieva, S., 2020. Comparative hydrochemical assessment of groundwater quality from different aquifers for irrigation purposes using IWQI: a case study from Masis province in Armenia. *Groundw. Sustain. Dev.* 11, 100459. <https://doi.org/10.1016/j.gsd.2020.100459>.
- Giri, S., Tiwari, A.K., Mahato, M.K., Singh, A.K., 2021. Integrated approaches to identify the major controlling factors of groundwater chemistry and quality assessment for suitability of different uses in West Singhbhum, India. *Environ. Earth Sci.* 80, 756. <https://doi.org/10.1007/s12665-021-09981-0>.
- Gomes, H.A., 2001. *Geologia E Recursos Minerais Do Estado De Pernambuco*. Ministério De Minas E Energia. Secretaria De Minas E Metalurgia. CPRM – Serviço Geológico do Brasil, 127pp.
- Greenacre, M., 2021. Compositional data analysis. *Ann. Rev. Statist. Appl.* 8, 271–299. <https://doi.org/10.1146/annurev-statistics-042720-124436>.
- Grünfeld, D.A., Gilbert, D., Hou, J., Jones, A.M., Lee, M.J., Kibbey, T.C.G., O’Carroll, D. M., 2024. Underestimated burden of per- and polyfluoroalkyl substances in global surface waters and groundwaters. *Nat. Geosci.* 17, 340–346. <https://doi.org/10.1038/s41561-024-01402-8>.
- Güler, C., Thyne, G.D., 2004. Hydrologic and geologic factors controlling surface and groundwater chemistry in Indian wells–owens valley area, southeastern California, USA. *J. Hydrol.* 285, 177–198. <https://doi.org/10.1016/j.jhydrol.2003.08.019>.
- Güler, C., Thyne, G.D., McCray, J.E., Turner, A.K., 2002. Evaluation of graphical and multivariate statistical methods for classification of water chemistry data. *Hydrogeol. J.* 10, 455–474. <https://doi.org/10.1007/s10040-002-0196-6>.
- Güler, C., Kurt, M.A., Alpaslan, M., Akbulut, C., 2012. Assessment of the impact of anthropogenic activities on the groundwater hydrology and chemistry in Tarsus coastal plain (Mersin, SE Turkey) using fuzzy clustering, multivariate statistics and GIS techniques. *J. Hydrol.* 414 (415), 435–451. <https://doi.org/10.1016/j.jhydrol.2011.11.021>.
- Hakimi, Y., Orban, P., Deschamps, P., Brouyere, S., 2021. Hydrochemical and isotopic characteristics of groundwater in the Continental intercalaire aquifer system: insights from Mzab Ridge and surrounding regions, North of the Algerian Sahara. *J. Hydrol.: Reg. Stud.* 34, 100791. <https://doi.org/10.1016/j.ejrh.2021.100791>.
- Hastenrath, S., 2012. Exploring the climate problems of Brazil’s Nordeste: a review. *Clim. Change* 112, 243–251. <https://doi.org/10.1007/s10584-011-0227-1>.
- Hernandez, P.G.L., Athayde, J., et al. Muller Athayde, G.B., Licht, O.A.B., 2021. Effect of the interpolation of hydrogeological data in sedimentary aquifers: a case study in the state of Paraná. *Águas Subterrâneas* 35, 1–11.
- Hirata, R., Conicelli, B.P., 2012. Groundwater resources in Brazil: a review of possible impacts caused by climate change. *Ann. Brazilian Acad. Sci.* 84, 297–312. <https://doi.org/10.1590/S0001-37652012005000037>.
- Hoefs, J., 2009. *Stable Isotope Geochemistry*, sixth ed. Springer–Verlag, Berlin, Heidelberg. <https://doi.org/10.1007/978-3-540-70708-0>.
- Hoogesteger, J., 2022. Regulating agricultural groundwater use in arid and semi-arid regions of the global south: challenges and socioenvironmental impacts. *Curr. Opin. Environ. Sci. Health* 27, 100341. <https://doi.org/10.1016/j.coesh.2022.100341>.
- INMET, 2020 – Instituto Nacional de Meteorologia, 2020. Banco de Dados Meteorológicos. <https://bdmep.inmet.gov.br>. (Accessed 2 January 2021).
- Jasechko, S., Birks, S.J., Gleeson, T., Wada, Y., Fawcett, P.J., Sharp, Z.D., McDonnell, J. J., Welker, J.M., 2014. The pronounced seasonality of global groundwater recharge. *Water Resour. Res.* 50, 8845–8867. <https://doi.org/10.1002/2014WR015809>.
- Jasechko, S., Seybold, H., Perrone, D., Fan, Y., Shamsudduha, M., Taylor, R.G., Fallatah, O., Kirchner, J.W., 2024. Rapid groundwater decline and some cases of recovery in aquifers globally. *Nature* 625, 715–721. <https://doi.org/10.1038/s41586-023-06879-8>.
- Jasrotia, A.S., Taloor, A.K., Andotra, U., Kumar, R., 2019. Monitoring and assessment of groundwater quality and its suitability for domestic and agricultural use in the Cenozoic rocks of Jammu Himalaya, India: a geospatial technology based approach. *Groundw. Sustain. Dev.* 8, 554–566. <https://doi.org/10.1016/j.gsd.2019.02.003>.
- Jolliffe, I.T., Cadima, G., 2016. Principal component analysis: a review and recent developments. *Philosophical Trans. Royal Soc. A* 374, 20150202. <https://doi.org/10.1098/rsta.2015.0202>.
- Karangoda, R.C., Nanayakkara, K.G.N., 2023. Use of the water quality index and multivariate analysis to assess groundwater quality for drinking purpose in Ratnapura district, Sri Lanka. *Groundw. Sustain. Dev.* 21, 100910. <https://doi.org/10.1016/j.gsd.2023.100910>.
- Kazakis, N., Pavlou, A., Vargemezis, G., Voudouris, K.S., Soulios, G., Pliakas, F., Tsokas, G., 2016. Seawater intrusion mapping using electrical resistivity tomography and hydrochemical data. An application in the coastal area of eastern Thessaloniki Gulf, Greece. *Sci. Total Environ.* 543, 373–387. <https://doi.org/10.1016/j.scitotenv.2015.11.041>.
- Kazakis, N., Mattas, C., Pavlou, A., Patrikaki, O., Voudouris, K., 2017. Multivariate statistical analysis for the assessment of groundwater quality under different hydrogeological regimes. *Environ. Earth Sci.* 76, 349. <https://doi.org/10.1007/s12665-017-6665-y>.
- Kelley, W.P., 1951. *Alkali Soils: Their Formation Properties and Reclamations*. Reinhold, New York, p. 176.
- Lee, S., Wolberg, G., Shin, S.Y., 1997. Scattered data interpolation with multilevel B-splines. *IEEE Trans. Visual. Comput. Graph.* 3, 228–244. <https://doi.org/10.1109/2945.620490>.
- Li, P., Wu, J., Qian, H., 2015. Hydrochemical appraisal of groundwater quality for drinking and irrigation purposes and the major influencing factors: a case study in and around Hua County, China. *Arabian J. Geosci.* 9, 15. <https://doi.org/10.1007/s12517-015-2059-1>.
- Li, P., Karunanidhi, D., Subramani, T., Srinivasamoorthy, K., 2021. Sources and consequences of groundwater contamination. *Arch. Environ. Contam. Toxicol.* 80, 1–10. <https://doi.org/10.1007/s00244-020-00805-z>.
- Liu, Y.-C., Fei, Y.-H., Li, Y.-S., Bao, X.-L., Zhang, P.-W., 2024. Pollution source identification methods and remediation technologies of groundwater: a review. *China Geol.* 7, 125–137. <https://doi.org/10.31035/cg2022080>.
- Loke, M.H., Chambers, J.E., Rucker, D.F., Kuras, O., Wilkinson, 2013. Recent developments in the direct-current geoelectrical imaging method. *J. Appl. Geophys.* 95, 135–156. doi:10.1016/j.jappgeo.2013.02.017.
- Marengo, J.A., Galdos, M.V., Challinor, A., Cunha, A.P., Marin, F.R., Vianna, M.S., Alvala, R.C.S., Alves, L.M., Moraes, O.L., Bender, F., 2021. Drought in Northeast Brazil: a review of agricultural and policy adaptation options for food security. *Climate Res. Sustain.* 1, e17. <https://doi.org/10.1002/cli2.17>.
- Martins, T., Oliveira, M.M., Leitão, T.E., 2022. Comparação de métodos para a delimitação das áreas de excedência na avaliação do estado químico de massas de água subterrânea. Livro de resumos do 13º Seminário sobre Águas Subterrâneas. Lisboa, V. 1. pp. 143–148. <https://www.aprh.pt/13sas/docs/Livro-de-resumos-13SAS.pdf>.
- Matos, R.M.D., 1999. History of the Northeast Brazilian Rift System: Kinematic Implications for the break-up Between Brazil and West Africa, vol. 153. Geological Society, London, Special Publications, pp. 55–73. <https://doi.org/10.1144/GSL.SP.1999.153.01.04>.
- Mayer, A.M., Poljakoff-Mayber, A., 1982. *The Germination of Seeds*, third ed. Pergamon, p. 224.
- Menció, A., Mas-Pla, J., 2008. Assessment by multivariate analysis of groundwater–surface water interactions in urbanized Mediterranean streams. *J. Hydrol.* 252, 255–266. <https://doi.org/10.1016/j.jhydrol.2008.01.014>.
- Merritt, A.J., Chambers, J.E., Wilkinson, P.B., West, L.J., Murphy, W., Gunn, D., Uhlemann, S., 2016. Measurement and modelling of moisture–electrical resistivity relationship of fine-grained unsaturated soils and electrical anisotropy. *J. Appl. Geophys.* 124, 155–165. <https://doi.org/10.1016/j.jappgeo.2015.11.005>.

- Mirzavand, M., Walter, J., 2024. Delineating the mechanisms controlling groundwater salinization using chemo-isotopic data and meta-heuristic clustering algorithms (case study: saguenay-lac-saint-jean region in the Canadian shield, Quebec, Canada). *Environ. Sci. Pollut. Res.* 31, 42406–42427. <https://doi.org/10.1007/s11356-024-33922-6>.
- Mirzavand, M., Ghasemieh, H., Sadatinejad, S.J., Bagheri, R., 2020a. Delineating the source and mechanism of groundwater salinization in crucial declining aquifer using multi-chemo-isotopes approaches. *J. Hydrol.* 586, 124877. <https://doi.org/10.1016/j.jhydrol.2020.124877>.
- Mirzavand, M., Ghasemieh, H., Sadatinejad, S.J., Bagheri, R., 2020b. An overview on source, mechanism and investigation approaches in groundwater salinization studies. *Int. J. Environ. Sci. Technol.* 17, 2463–2476. <https://doi.org/10.1007/s13762-020-02647-7>.
- Moitinho, D.E.R., Barbosa, N.S., Debruyne, D., Gomes, M.C.R., Barbosa, N., Gomes, L.A., Carmo, J.C.C., Santos, C.B., 2024. Deciphering hydrogeochemical evolution in the multilayered Ilhas-São Sebastião aquifer system, Brazil: implications for groundwater resources management. *Groundw. Sustain. Dev.* 26, 101253. <https://doi.org/10.1016/j.gsd.2024.101253>.
- Morais, D.M.F., Oliveira, R.G., Lages, G.A., Galvão, M.J.T.G., 2021. The geometry, sedimentary filling and depth estimate of the Mirandiba Basin, Pernambuco, Brazil: new insights about the depositional regional gap of rift phases in the interior basins. *J. Geol. Survey Brazil* 4, 1–21. <https://doi.org/10.29396/jgsb.2021.v4.n1.1>.
- Niculescu, B.M., Andrei, G., 2019. Using vertical electrical soundings to characterize seawater intrusions in the southern area of Romanian black sea coastline. *Acta Geophys.* 67, 1845–1863. <https://doi.org/10.1007/s11600-019-00341-y>.
- Pacheco Castro, R., Ávila, J.P., Ye, M., Sansores, A.C., 2018. Groundwater quality: analysis of its temporal and spatial variability in a karst aquifer. *Groundwater* 58, 62–72. <https://doi.org/10.1111/gwat.12546>.
- Parasnis, D.S., 1986. *Principles of Applied Geophysics*, fourth ed. Chapman and Hall, London, New York, p. 402. <https://doi.org/10.1007/978-94-009-4113-7>.
- Parkhurst, D.L., Appelo, C.A.J., 1999. User's guide to PHREEQC (Version 2): a computer program for speciation, batch reaction, one-dimensional transport, and inverse geochemical calculations. *USGS Water-Resources Investigations Report-99-4259*. U. S. Geological Survey. <https://doi.org/10.3133/wri994259>. Denver, Colorado.
- Patel, D., Pamidimukkala, P., Chakraborty, D., 2024. Groundwater quality evaluation of Narmada district, Gujarat using principal component analysis. *Groundw. Sustain. Dev.* 24, 101050. <https://doi.org/10.1016/j.gsd.2023.101050>.
- Prasanna, M.V., Chidambaram, S., Hameed, A.S., Srinivasamoorthy, K., 2011. Hydrogeochemical analysis and evaluation of groundwater quality in the Gadilam river basin, Tamil Nadu, India. *J. Earth Syst. Sci.* 120, 85–98. <https://doi.org/10.1007/s12040-011-0004-6>.
- Rakotondrabe, F., Ngoupayou, J.R.N., Mfonka, Z., Rasolomanana, E.H., Abolo, A.J.N., Ako, A.A., 2018. Water quality assessment in the Bétaré-Oya gold mining area (East-Cameroon): Multivariate Statistical Analysis approach, 610–611 *Science of The Total Environment* 831–844. <https://doi.org/10.1016/j.scitotenv.2017.08.080>.
- Ravenscroft, P., Lytton, L., 2022. Seeing the Invisible: a Strategic Report on Groundwater Quality. *World Bank Group*, p. 94. <http://hdl.handle.net/10986/37197>.
- Rebouças, A.C., 1997. Água na região Nordeste: desperdício e escassez. *Dossiê Nordeste I • Estudos Avançados* 11, 127–154. <https://doi.org/10.1590/S0103-40141997000100007>.
- Richards, L.A., 1954. *Diagnosis and Improvement of Saline and Alkali Soils*. U.S. Department of Agriculture Handbook, Washington USA, p. 60, 160. <https://www.ars.usda.gov/ARSUserFiles/20360500/hb60.pdf/hb60complete.pdf>.
- Sanford, R.F., Pierson, C.T., Crovelli, R.A., 1993. An objective replacement method for censored geochemical data. *Math. Geosci.* 25, 59–80. <https://doi.org/10.1007/BF00890676>.
- Siebert, S., Burke, J., Faures, M., Frenken, K., Hoogeveen, J., Döll, P., Portmann, F.T., 2010. Groundwater use for irrigation – a global inventory. *Hydrol. Earth Syst. Sci.* 14, 1863–1880. <https://doi.org/10.5194/hess-14-1863-2010>.
- Silva, T.R., Lima, M.M.C., 2023. Water quality assessment and hydrogeochemistry of a sedimentary basin in a semi-arid area under increasing exploitation: insights from multivariate statistical analyses, GIS, and modeling. *Appl. Geochem.* 150, 105593. <https://doi.org/10.1016/j.apgeochem.2023.105593>.
- Silva, T.R., Leitão, T.E., Lima, M.M.C., Martins, T.N., Oliveira, M.M., Albuquerque, M.S.C., Costa, W.D., 2021. Hydrogeochemistry and isotope compositions of multi-layered aquifer systems in the Recife Metropolitan Region, Pernambuco (NE Brazil): an integrated approach using multivariate statistical analyses. *J. S. Am. Earth Sci.* 109, 103323. <https://doi.org/10.1016/j.jsames.2021.103323>.
- Sonkamble, S., Sahya, A., Mondal, N.C., Harikumar, P., 2012. Appraisal and evolution of hydrochemical processes from proximity basalt and granite areas of Deccan Volcanic Province (DVP) in India. *J. Hydrol.* 438–439, 181–193. <https://doi.org/10.1016/j.jhydrol.2012.03.022>.
- Tabi, R.N., Gibrilla, A., Boakye, P., Agyemang, F.O., Foaah, A.A., Oduro-Kwarteng, S., 2024. Appraisal of groundwater quality and hydrochemistry in three regions of Ghana: implications for drinking purposes. *Groundw. Sustain. Dev.* 26, 101193. <https://doi.org/10.1016/j.gsd.2024.101193>.
- Taucare, M., Daniele, L., Viguier, B., Vallejos, A., Arancibia, G., 2020. Groundwater resources and recharge processes in the Western Andean front of central Chile. *Sci. Total Environ.* 722, 137824. <https://doi.org/10.1016/j.scitotenv.2020.137824>.
- Tefera, A., Wassie, A.B., Sinshaw, B.G., Defersha, D.T., Takele, T.A., Atanaw, S.B., Tesfaye, A.T., Getu, E., Fenta, H.M., Atinkut, H.B., Enku, T., Sahilu, D., Melesse, A. M., 2021. Groundwater quality evaluation of the alluvial aquifers using GIS and water quality indices in the upper Blue Nile Basin, Ethiopia. *Groundw. Sustain. Dev.* 14, 100636. <https://doi.org/10.1016/j.gsd.2021.100636>.
- Telford, W.M., Geldart, L.P., Sheriff, R.E., 1990. *Applied Geophysics*, second ed. Cambridge University Press, Cambridge, p. 744.
- Tellam, 1995. Hydrochemistry of the saline groundwaters of the lower mersey Basin permo-triassic sandstone aquifer, UK. *J. Hydrol.* 165, 45–84. [https://doi.org/10.1016/0022-1694\(94\)02583-W](https://doi.org/10.1016/0022-1694(94)02583-W).
- Todd, D.K., 1980. *Groundwater Hydrology*. Wiley, New York, p. 535.
- Torres-Martínez, J.A., Mora, A., Knappett, P.S.K., Ornelas-Soto, N., Mahlknecht, J., 2020. Tracking nitrate and sulfate sources in groundwater of an urbanized valley using a multi-tracer approach combined with a Bayesian isotope mixing model. *Water Res.* 182, 115962. <https://doi.org/10.1016/j.watres.2020.115962>.
- Torres-Martínez, J.A., Mora, A., Mahlknecht, J., Daesslé, L.W., Cervantes-Avilés, P.A., Ladesma-Ruiz, R., 2021. Estimation of nitrate pollution sources and transformations in groundwater of an intensive livestock-agricultural area (Comarca Lagunera), combining major ions, stable isotopes and MixSIAR model. *Environ. Pollut.* 269, 115445. <https://doi.org/10.1016/j.envpol.2020.115445>.
- Tuinstra, J., van Wensem, J., 2014. Ecosystem services in sustainable groundwater management. *Sci. Total Environ.* 485–486, 798–803. <https://doi.org/10.1016/j.scitotenv.2014.03.098>.
- Vasanthavigar, M., Srinivasamoorthy, K., Vijayaragavan, K., Ganthi, R.R., Chidambaram, S., Anandhan, P., Manivannan, R., Vasudevan, S., 2010. Application of water quality index for groundwater quality assessment: thirumanimuttar sub-basin, Tamilnadu, India. *Environ. Monit. Assess.* 171, 595–609. <https://doi.org/10.1007/s10661-009-1302-1>.
- Vidal Silva, C.M.S., Santiago, M.M.F., Frischkorn, H., Filho, J.M., Veríssimo, L.S., 2007. Isótopos ambientais como identificadores de aquíferos explotados na Bacia Sedimentar do Cariri. *XVII Simpósio Brasileiro de Recursos Hídricos* 1–10.
- Viguier, B., Jourde, H., Yáñez, G., Lira, E.S., Leonardi, V., Moya, C.E., García-Pérez, T., Maringue, J., Lictevoit, E., 2018. Multidisciplinary study for the assessment of the geometry, boundaries and preferential recharge zones of an overexploited aquifer in the Atacama Desert (Pampa del Tamarugal, Northern Chile). *J. S. Am. Earth Sci.* 86, 366–383. <https://doi.org/10.1016/j.jsames.2018.05.018>.
- WHO, 1996. *Guidelines for drinking-water quality*. In: *International Programme on Chemical Safety*, second ed., p. 973.
- WHO, 2008. *Guidelines for drinking-water quality*. In: *Incorporating the First and Second Addenda Recommendations*, third ed., vol. 1, p. 515.
- WHO, 2011. *Guidelines for drinking-water quality*, fourth ed., p. 541.
- Wilcox, L.V., 1955. *Classification and Use of Irrigation Waters*. US Department of Agriculture, New York, p. 19.
- Wood, W.W., 2019. Geogenic groundwater solutes: the myth. *Hydrogeol. J.* 27, 2729–2738. <https://doi.org/10.1007/s10040-019-02057-1>.
- Zaidi, F.K., Nazzal, Y., Jafri, M.K., Naem, M., Ahmed, I., 2015. Reverse ion exchange as a major process controlling the groundwater chemistry in an arid environment: a case study from northwestern Saudi Arabia. *Environ. Monit. Assess.* 187, 607. <https://doi.org/10.1007/s10661-015-4828-4>.
- Zhu, G.F., Li, Z.Z., Su, Y.H., Ma, J.Z., Zhang, Y.Y., 2007. Hydrogeochemical and isotope evidence of groundwater evolution and recharge in Minqin Basin, Northwest China. *J. Hydrol.* 333, 239–251. <https://doi.org/10.1016/j.jhydrol.2006.08.013>.
- Zohdy, A.A.R., 1989. A new method for the automatic interpretation of Schlumberger and Wenner sounding curves. *Geophysics* 54, 245–253. <https://doi.org/10.1190/1.1442648>.
- Zohdy, A.A.R., Eaton, G.P., Mabey, D.R., 1974. *Applications of surface geophysics to groundwater investigations*. US Geol. Survey 2, 116 book.