Environmental Earth Sciences (2024) 83:515
https://doi.org/10.1007/s12665-024-11798-6

ORIGINAL ARTICLE

Assessment of groundwater quality using hydrochemical process, GIS and multivariate statistical analysis at central Rif, North Morocco

Said Benyoussef[1,2] · Mourad Arabi[3] · Yassine El Yousfi[2] · Mohamed Makkaoui[4] · Hicham Gueddari[5] · Hossain El Ouarghi[2] · Abdellali Abdaoui[1] · Mohammad Ghalit[6] · Younes Filali Zegzouti[1,7] · Maryam Azirar[1] · Mahjoub Himi[8] · Abdennabi Alitane[9,10] · Mohamed Chahban[5] · Ali Ait Boughrous[1]

Received: 19 February 2024 / Accepted: 9 August 2024 / Published online: 28 August 2024

Abstract

This study investigated groundwater in the central Rif region of northern Morocco by analysing 55 water sampling points to assess its physicochemical and hydrogeochemical properties. Through hydrochemical analysis, GIS spatial exploration, and multivariate statistical analysis, a direct correlation was found between EC, TDS, and major ions, influencing overall water mineralization. The key findings included pH levels ranging from 6.10 to 8.52, EC from 828 to 4581 µS/cm, and varying concentrations of Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, HCO_2^{-}, Cl^{-}, N–NO_2^{-}, and SO_4^{2-}. Notably, TDS and TH ranged from 647.19–3609.36 mg/L and 64.23–1051.24 mg/L, respectively, with a significant portion of samples exceeding WHO guidelines, particularly chloride (61.81%), sulfate (92.72%), and nitrate (12.72%) samples. The Piper diagram highlights sodium chlorides (Na–Cl) as the predominant chemical facies (70.9%), while the Gibbs diagram emphasizes the impact of evaporation on water chemistry dynamics. This study revealed the complex influence of geological and anthropogenic factors on groundwater quality, potentially leading to seawater intrusion in coastal aquifers. The observed high mineralization and hardness levels, in addition to mild alkalinity, pose public health risks, underscoring the need for continuous monitoring and sustainable management practices in coastal groundwater management to protect human health and the environment.

Keywords Groundwater quality · Physicochemical properties · Mineralization · Hydrochemical analysis · Central Rif · Morocco

✉ Mahjoub Himi
himi@ub.edu

1 Research Team: Biology, Environment and Health, Department of Biology, Errachidia Faculty of Science and Technology, University of Moulay Ismaïl, 50000 Meknes, Morocco

2 Environmental Management and Civil Engineering Team, ENSAH, Abdelmalek Essaadi University, 93030 Tetouan, Morocco

3 Water, Environment and Health Team, Laboratory for Improvement of Agricultural Production, Biotechnology and Environment (LAPABE), Faculty of Science, Mohammed Premier University, BV M6, PB 717, 60000 Oujda, Morocco

4 Laboratory of Applied Geosciences, Department of Geology, Faculty of Science, Mohammed Premier University, BV M6, PB 717, 60000 Oujda, Morocco

5 OLMAN BPGE Laboratory, Multidisciplinary Faculty of Nador, Mohamed First University, 60000 Oujda, Morocco

6 Solid Mineral Chemistry, Applied Chemistry and Environment Laboratory, Faculty of Sciences, Mohammed First University, Oujda, Morocco

7 Research Team: Biology, Environment, and Health, Faculty of Science, Moulay International University of Meknes, Meknes, Morocco

8 Faculty of Geology, University of Barcelona, Marti I Franques S/N, 08028 Barcelona, Spain

9 Research Group “Water Sciences and Environment Engineering”, Geoengineering and Environment Laboratory, Geology Department, Faculty of Sciences, Moulay Institute University, Presidency, Marjane 2, P.O. Box 298, 50050 Meknes, Morocco

10 Hydrology and Hydraulic Engineering Department, Vrije Universiteit Brussels (VUB), 1050 Brussels, Belgium

Introduction

Water is a vital resource essential for human survival, social progress, and economic growth. However, the distribution of these resources is not always equitable, with hydrospheric groundwater accounting for 2.8% of freshwater resources, while lakes, reservoirs, and river systems only contribute 0.26%. Sustainable water resource management is crucial for ensuring universal access to clean and sufficient water (Shiklomanov 2000).

Groundwater, known for its superior quality, regularity, and natural protection, plays a critical role as a water source in various countries and regions. It often surpasses surface water in quality, making it a vital water supply source (Dole-Olivier et al. 2005). This invaluable resource has diverse applications that benefit both the environment and society, particularly in arid and semiarid regions (Li et al. 2016; Wu and Sun 2016; Zabala et al. 2016; Li and Qian 2018).

Climate change significantly impacts groundwater, altering its physical and chemical properties and leading to changes in water availability, increased salinity, and pollution from extreme weather events (Dao et al. 2023). These effects are particularly pronounced in hot, dry climates reliant on groundwater (Javadinejad et al. 2019). Predicting the complex impacts of climate change on groundwater resources requires enhanced observations, understanding of processes, and improved modelling capabilities (Earman and Dettinger 2011). Additionally, climate change can disrupt the hydrological system, resulting in issues such as groundwater overexploitation, water table depletion, and saltwater intrusion (Islam and Mostafa 2024). Moreover, according to He et al. (2019), the groundwater environment is significantly impacted by climate change and human activities such as rapid urbanization, intensive agricultural activities, and industrial development. Indeed, the overexploitation of natural resources, coupled with human activities, has deteriorated groundwater quality in the Mediterranean basin.

As the Mediterranean region is highly vulnerable to water scarcity (Margat 2008), ensuring an adequate groundwater supply has become crucial, and attention must also be directed towards preserving the quality of this vital resource (Aghazadeh and Mogaddam 2010; Neisi et al. 2018).

In Morocco, groundwater is a crucial source of water, particularly in the region of Al-Hoceima, which is located on the northern coast of the Mediterranean Sea. This area has high densities of natural sources for irrigation and drinking water consumption. However, poor water quality due to various types of contamination is a significant issue. The salinization of groundwater in Morocco has garnered increasing research interest in recent years (Elgettafi et al. 2012; Himi et al. 2017; Elmeknassi et al. 2021). The chemical composition of groundwater, resulting from interactions between the liquid phase and solid matrix, is a significant concern (Mahlknecht et al. 2017). To prevent further degradation of groundwater quality, a comprehensive understanding of its sources and salinization processes is imperative (Bouissa et al. 2021). Therefore, an in-depth understanding of the origin of this salinity is crucial for effective aquifer management (Kamal et al. 2021; Rochdane et al. 2022). Among the factors contributing to groundwater quality deterioration, natural and anthropogenic elements such as seawater intrusion, adjacent aquifer impacts, hydrodynamic conditions, dissolution of evaporitic rocks, upwelling of deep saline waters, and unregulated fertilizer use are prominent (Milnes 2011; Elgettafi et al. 2012; Giambastiani et al. 2013; Ledesma-Ruiz et al. 2015; Ouhamdouch et al. 2021). Scientists have investigated chemical interactions through hydrogeochemical approaches (Liu et al. 2017).

In groundwater studies, geochemical analysis of groundwater plays a crucial role in understanding water quality and salinization processes. Various studies have delved into this aspect in different regions. For instance, Panteleit et al. (2001) conducted a study on the Coastal Aquifer Test Field in North Germany, Slama et al. (2022) focused on the Korba coastal aquifer in Tunisia, and Maman Hassan and Firat Ersoy (2022) investigated the Çarşamba coastal aquifer in Turkey. These studies have shed light on seawater intrusion and agricultural contamination as significant factors contributing to salinization.

On the other hand, the utilization of cartographic tools such as the geographical information system (GIS) and multivariate statistical analysis has become prevalent in groundwater assessment. These tools allow for a comprehensive interpretation of groundwater quality and quantity. Previous studies have employed GIS-based multicriteria analysis to identify potential recharge areas, as seen in the work of Saidi et al. (2017) in Tunisia. Additionally, remote sensing techniques and Kohonen self-organizing maps were utilized by Abdelkarim et al. (2022) to pinpoint recharge areas, while Msaddek et al. (2019) employed multivariate statistical evaluation and the analytic hierarchy process to map recharge potential. Hence, by integrating geochemical analysis with cartographic tools and statistical methods, current research can provide a deeper understanding of groundwater dynamics, salinization processes, and recharge area delineation, contributing to informed decision-making in groundwater management and sustainability efforts.

Groundwater serves as a critical source of drinking water for rural populations, livestock, and irrigation in the central

Rif region of Morocco. However, ensuring the quality of drinking water remains a significant challenge across all regions of Morocco, particularly in rural areas. The utilization of untreated groundwater for drinking purposes poses serious health risks to rural communities. Therefore, it is imperative, as recommended by Laferriere (1996), to prioritize close monitoring of water pollution, which is a pressing concern regarding these vital water resources. This proactive approach to monitoring is essential for safeguarding public health and addressing the challenges associated with water quality in rural areas of Morocco.

The aim of our study is to assess groundwater quality in the central Rif region by conducting a detailed physicochemical analysis, exploring correlations between groundwater compositions, and utilizing point interpolation for spatial distribution mapping. Our objective is to identify salinization zones, understand contamination sources, and propose corrective measures to prevent groundwater quality deterioration in the study area.

Materials and methods

Study area

The study area is situated in the central Rif region and is located along the coast of the Al-Hoceima region in northern Morocco (Fig. 1).

The studied zone encompasses the western part of the Bokkoya Plain extending to the eastern side of the Ghis-Nekor Plain, bordered by the Mediterranean coast to the north and the Tisirenes Flysch to the south. It falls within the inner domain of the Rifian chain and was formed as a result of the Alpine orogeny (Talhaoui et al. 2005). The geological structure of the area consists of stacked structural units separated by abnormal contacts, including outer limestone ridges deposited on the ancient margin of the North African continent and partially transformed during the late Oligocene and Miocene (Frizon-De-Lamotte and Leikine 1985; Negro et al. 2007). The topography of the internal calcareous ridges is supported by tectonic cliffs featuring calcareous-dolomitic dorsal scales and klipps of the Sebtides and Gomarides units (Chalouan et al. 1995; Michard et al. 2002).

The area covers the westernmost part of the Bokkoya Plain to the eastern side of the Ghis-Nekor Plain, bordered by the Mediterranean coast to the north and the Tisirenes Flysch to the south (Fig. 2). It belongs to the inner domain of the Rifian chain and formed as a result of the Alpine orogeny (Talhaoui et al. 2005).

The geological structure of the study area is imbricated towards the south with the Tisirenes Flysch, with the presence of the Trougout Fault zone separating the Nekor basin from the Ras Tarf horst (Galindo-Zaldívar et al. 2015). The area comprises both shallow and deep aquifers, namely, the Bokkoya and Ghis-Nekor aquifers. The Bokkoya aquifer is drained by a network of oueds and tributaries, while the Ghis-Nekor aquifer is fed by the Ghis River in the west and

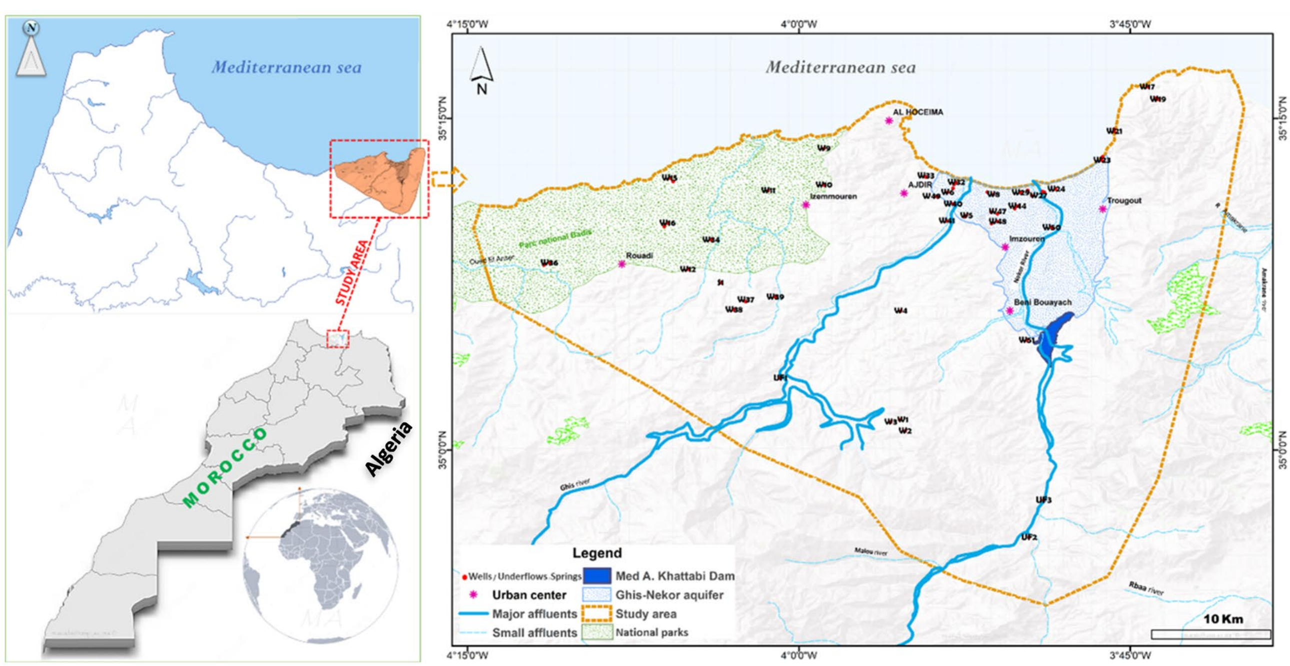


Fig. 1 Study area and location of drinking water sites in the central Rif (North Morocco)

the Nekor River in the east. The study area experiences a semiarid climate with alternating dry and wet seasons, characterized by an average annual rainfall of approximately 300 mm (Ghalit et al. 2017; Chafouq et al. 2018). The lithological data for the study area were provided by the Loukkos Hydraulic Basin Agency and Loukkos Regional Agricultural Development Office.

Groundwater sampling and analysis

In this study, groundwater samples were collected from both shallow and deep sources, including wells, underflows, and springs, across the central Rif region during 2020. The study area included a total of 55 monitored sites, with the locations of each sampling point indicated in Fig. 1. The hydrogen potential (pH), electrical conductivity (EC), and total dissolved solids (TDS) were measured in situ using a handheld multiparameter (HANNA, HI 991300). The collection of groundwater samples involved the use of presterilized 5 L capacity polyethylene bottles dedicated to physicochemical parameter analysis. Thus, to ensure the integrity of the samples, the bottles were thoroughly cleaned and then rinsed with the respective fresh groundwater samples before being filled on board. Subsequently, the plugs were securely fastened to prevent any gas exchange with the surrounding atmosphere. All the samples were quickly transported to the laboratory in coolers at a temperature below 4 °C and then stored in a refrigerator prior to the start of laboratory analysis. The analysis of these samples was conducted within a 48 h timeframe. Thereafter, the concentrations of the major components, including cations and anions, were determined in a laboratory setting using the methods recommended by Rodier et al. (2009). Hence, titration methods were used to examine chloride (Cl^-), bicarbonate (HCO_3^-), total hardness (TH), and calcium ions (Ca^{2+}). The concentration of magnesium (Mg^{2+}) was determined using the TH and calcium content. Flame spectrophotometry was used to determine the concentrations of sodium (Na^+) and potassium (K^+) (Banerjee and Prasad 2020), while UV spectrophotometry was used to measure the concentrations of nitrogen ions ($N{-}NO_3^-$ and $N{-}NH_4^+$) and sulfate (SO_4^{2-}) (Mulec et al. 2020).

The spatial variation in various groundwater parameters was represented using a geographic information system (GIS) (Abdelkarim et al. 2023), and the inverse distance weighting (IDW) interpolation technique was used to create spatial distribution maps via ArcGIS v10.8 software.

The hydrochemical processes controlling groundwater mineralization and salinization in the central Rif were studied using a Piper diagram and binary diagrams in Aquachem software v12.0. (Sathish Mohan et al. 2017), while XLstat software v.2023.5.1 was used to construct a hydrochemical facies evolution diagram (HFE-D) and Gibbs diagram (Ayed et al. 2017). Finally, Pearson correlation analysis was conducted using IBM SPSS Statistics version 25 to identify potential relationships between the measured physicochemical parameters.

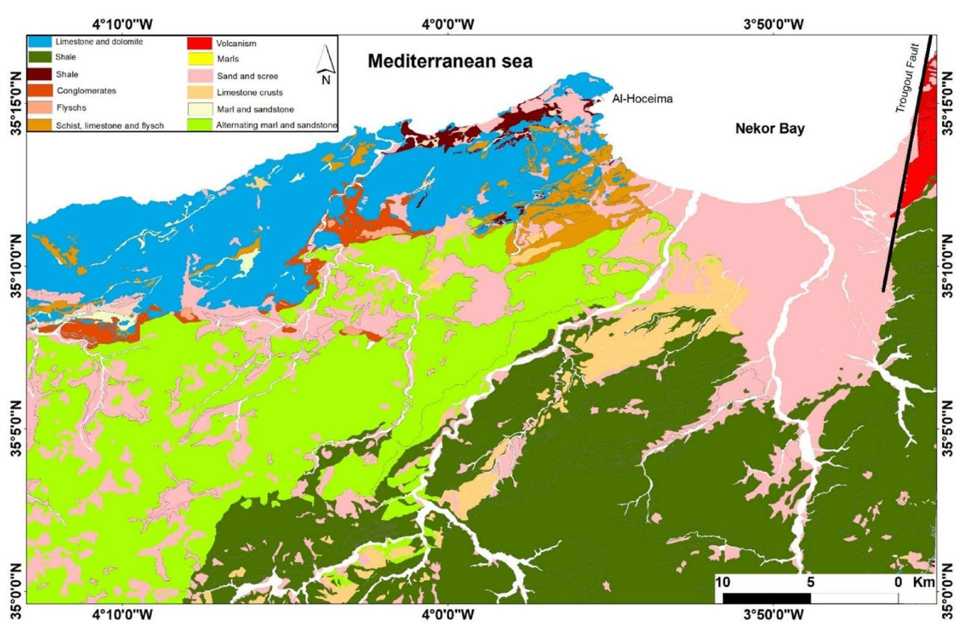


Fig. 2 Map of the geological structure of the study area (extracted from the geological maps of Rouadi and Al-Hoceima at 1:50,000)

Table 1 Summary of physicochemical data of the groundwater samples in central Rif and their comparison with WHO levels

ID	Water type	T (°C)	pH	EC (µS/cm)	TDS (mg/l)	O_2 (mg/l)	Ca^{2+}(mg/l)	Mg^{2+} (mg/l)	TH (mg CaCO3)	K^+ (mg/l)	Na^+ (mg/l)	NH_4^+ (mg/l)	HCO_{3-} (mg/l)	Cl− (mg/l)	SO_4^{2-} (mg/l)	NO_{3-} (mg/l)
W1	Ca–SO_4	18.0	6.70	1934	1825	7.90	318.3	97.2	1200.9	2.3	135.5	0.16	402.6	142.0	776.2	26.9
W2	Na–HCO_3	16.5	7.37	1022	505	2.29	88.1	60.0	470.4	1.6	153.5	0.01	542.9	88.7	50.4	13.8
W3	Na–HCO_3	19.1	7.02	1217	627	6.12	92.1	50.4	440.4	0.9	233.0	2.20	533.7	195.2	78.0	10.1
W4	Na–Cl	18.2	7.50	3694	3620	3.57	88.1	91.2	600.4	4.6	623.5	0.12	841.8	985.5	424.4	4.0
W5	Na–Cl	19.6	6.65	2170	1085	3.83	256.5	139.2	1221.2	8.0	394.0	0.10	384.3	710.0	741.8	22.3
W6	Ca–SO_4	20.1	7.02	1762	882	3.78	248.4	148.2	1238.7	12.2	339.0	0.10	457.5	426.0	726.5	8.1
W7	Na–Cl	18.7	7.17	4142	1806	4.22	328.6	201.6	1661.6	5.7	560.5	0.10	457.5	1029.5	1231.3	2.9
W8	Ca–SO_4	19.0	7.12	3640	2095	6.59	264.5	158.4	1321.3	4.5	452.5	0.13	402.6	674.5	944.5	6.6
W9	Na–Cl	15.0	8.32	872	436	4.19	56.1	16.8	210.2	0.4	133.0	0.13	79.3	147.0	56.9	14.8
W10	Ca–Cl	17.6	7.15	1263	632	3.87	120.2	24.0	400.6	2.8	102.0	0.12	274.5	213.0	48.5	50.4
W11	Na–Cl	19.0	7.60	1276	427	3.71	64.1	19.2	240.3	3.6	258.5	1.00	347.7	213.0	35.9	86.5
W12	Na–Cl	18.2	7.31	7153	2042	3.80	208.8	151.2	1152.1	18.3	789.0	0.90	512.4	2047.5	503.6	2.6
W13	Mg–HCO_3	17.5	7.22	854	453	3.77	72.1	62.4	440.3	5.0	68.5	0.17	305.0	112.0	38.4	41.1
W14	Na–Cl	18.2	7.24	3192	1605	3.80	144.2	67.2	640.7	8.9	372.5	0.05	445.3	603.5	104.0	13.9
W15	Na–Cl	17.8	7.31	3015	1515	3.86	112.2	62.4	540.5	4.2	384.5	0.11	463.6	497.0	140.7	56.3
W16	Na–HCO_3	18.0	7.53	1302	648	4.28	80.1	48.0	400.4	4.1	141.0	0.09	372.1	177.5	27.1	34.8
W17	Na–Cl	20.9	7.77	6618	3309	2.64	152.3	91.2	760.7	29.0	680.5	0.18	231.8	1473.2	598.8	9.3
W18	Ca–SO_4	21.3	7.20	3736	1867	2.58	296.5	129.6	1281.2	7.8	308.5	0.09	268.4	497.0	924.3	2.6
W19	Ca–SO_4	21.1	7.05	3795	1900	2.67	304.6	144.0	1361.5	10.3	314.0	0.04	311.1	426.0	842.4	3.3
W20	Na–Cl	25.4	7.41	2437	1220	2.75	128.2	81.6	660.6	9.6	217.5	0.05	305.0	390.5	83.3	6.5
W21	Na–Cl	26.6	7.06	2608	1304	2.58	136.2	81.6	680.6	8.6	229.0	0.05	292.8	461.0	103.1	5.6
W22	Na–Cl	21.3	7.44	10,210	4209	2.83	49.7	216.0	1024.2	33.1	785.5	0.12	457.5	2432.0	458.8	70.8
W23	Na–Cl	20.6	7.83	12,400	6204	5.52	48.0	292.8	1340.2	54.9	884.0	2.50	433.1	3150.0	623.1	4.1
W24	Na–Cl	21.0	7.79	2039	1021	2.67	208.4	129.6	1061.0	1.9	394.5	0.04	359.9	532.5	709.9	1.7
W25	Na–Cl	21.5	6.88	5440	2718	2.82	280.5	153.6	1341.4	5.7	501.0	0.15	634.4	887.5	704.1	3.2
W26	Na–Cl	21.8	7.04	2347	1162	2.80	216.4	120.0	1041.0	5.8	441.0	0.05	555.1	639.0	473.3	0.8
W27	Ca–SO_4	20.8	7.16	6472	2043	2.62	360.7	235.2	1881.8	6.1	596.5	0.04	445.3	1065.0	1571.6	0.8
W28	Na–Cl	23.0	7.56	5594	2803	2.56	344.6	182.4	1621.7	7.8	467.5	0.10	311.1	852.0	1108.8	1.2
W29	Na–Cl	21.7	7.28	3568	1784	2.62	248.4	115.2	1101.2	5.6	324.5	0.06	341.6	461.5	618.0	9.5
W30	Na–Cl	21.1	7.34	2586	1359	3.05	184.3	100.8	880.9	6.1	247.0	0.06	329.4	355.0	455.2	0.3
W31	Na–Cl	21.6	7.57	1632	815	2.67	224.4	110.4	1021.1	6.9	286.0	0.07	408.7	390.5	523.3	0.8
W32	Na–Cl	19.6	7.23	3508	1756	3.03	232.4	129.6	1121.1	4.7	308.5	0.07	396.5	781.0	608.4	0.8
W33	Na–Cl	21.4	7.80	4389	2200	2.93	96.1	86.4	600.4	39.2	501.5	0.04	244.0	852.0	382.9	33.3
W34	Na–Cl	19.0	7.57	1312	656	4.29	80.1	24.0	300.4	6.3	157.0	0.04	189.1	213.0	42.3	40.2
W35	Na–Cl	20.6	7.74	3411	1704	2.80	128.2	81.6	660.6	17.7	365.0	0.05	359.9	674.5	173.3	10.5
W36	Na–Cl	18.9	7.60	1931	964	2.86	128.2	48.0	520.6	6.9	249.0	0.03	359.5	390.5	89.4	4.8

Table 1 (continued)

ID	Water type	T (°C)	pH	EC (µS/cm)	TDS (mg/l)	O_2 (mg/l)	Ca^{2+}(mg/l)	Mg^{2+} (mg/l)	TH (mg CaCO3)	K^+ (mg/l)	Na^+ (mg/l)	NH_4^+ (mg/l)	HCO_{3-} (mg/l)	Cl– (mg/l)	SO_4^{2-} (mg/l)	NO_{3-} (mg/l)
W37	Na–Cl	20.3	7.26	7513	3881	2.54	228.4	189.6	1361.1	23.9	605.0	0.07	671.0	1904.0	232.0	128.4
W38	Na–Cl	19.5	8.89	2675	1064	2.59	56.1	57.6	380.2	26.6	436.5	0.09	701.5	603.5	133.9	115.4
W39	Na–Cl	22.1	7.32	10,240	5089	2.45	408.8	259.2	2102.0	20.2	657.5	0.13	390.4	2804.5	504.1	18.3
W40	Ca–Cl	21.1	7.17	1498	749	2.87	256.5	81.6	981.2	3.4	258.5	0.03	223.3	461.5	402.0	8.7
W41	Na–Cl	22.2	7.40	3212	1610	2.63	26.4	124.8	586.0	5.0	300.0	0.04	347.7	532.5	471.2	3.7
W42	Na–Cl	21.2	7.45	3684	1055	2.58	248.4	172.8	1341.2	8.6	357.5	0.04	359.9	532.5	654.1	20.9
W43	Na-Cl	20.2	7.35	3299	1230	2.62	232.4	115.2	1061.1	3.3	309.5	0.17	305.0	532.5	522.2	10.7
W44	Na–Cl	20.7	7.18	3467	1734	2.59	256.5	120.0	1141.2	3.2	316.0	0.09	311.1	568.0	541.4	12.3
W45	Na–Cl	20.7	6.74	6254	3129	2.54	360.7	230.4	1861.8	6.7	512.0	2.10	542.9	923.0	1156.7	29.0
W46	Na–Cl	21.0	6.97	5739	2871	2.54	328.6	216.0	1721.6	4.7	470.0	0.04	420.9	958.5	976.5	24.4
W47	Na–Cl	22.0	7.11	2983	1490	2.52	336.6	201.6	1681.6	4.6	474.5	0.07	427.0	958.5	1029.7	23.8
W48	Na–Cl	21.2	8.78	4335	2167	4.37	152.3	105.6	820.7	6.2	419.0	0.05	140.3	781.0	586.0	10.1
W49	Na–Cl	21.4	7.26	6746	3372	4.42	168.3	148.8	1040.8	18.5	603.0	0.03	54.9	1278.0	525.4	180.8
W50	Ca–Cl	22.1	7.15	2477	1236	2.87	352.7	177.6	1621.7	4.0	384.0	0.09	329.4	710.0	905.2	18.3
W51	Na–Cl	22.7	6.96	6264	3134	2.55	240.4	148.8	1221.2	8.7	544.5	0.04	628.3	1349.0	557.3	26.9
UF1	Ca–SO_4	23.1	7.63	2087	1043	4.95	176.3	91.2	820.8	2.8	148.0	0.05	353.8	248.5	381.3	0.5
UF2	Ca–SO_4	25.5	7.25	2424	1210	5.76	240.4	100.8	1021.2	4.0	136.0	0.03	323.3	177.5	576.5	2.0
UF3	Ca–SO_4	22.4	7.23	1604	802	7.46	336.6	38.4	1001.6	5.6	256.5	0.11	366.0	355.0	568.0	3.5
S1	Na–Cl	21.2	7.06	3292	1647	2.54	240.4	124.8	1121.2	12.9	563.0	0.00	414.8	1627.5	335.0	34.5
Max		15.0	6.65	854	427	2.29	26.4	16.8	210.2	0.4	68.5	0.00	54.9	88.7	27.1	0.3
Min		26.6	8.89	12,400	6204	7.90	408.8	292.8	2102.0	54.9	884.0	2.50	841.8	3150.0	1571.6	180.8
Average		20.6	7.36	3715.16	1812	3.50	200.7	121.0	1006.0	9.71	384.5	0.23	388.5	772.5	510.6	23.2
STDEV		2.1	0.42	2485.83	1201	1.30	101.0	63.4	456.2	10.3	187.5	0.52	144.2	657.6	355.7	34.6
WHO (2011)	Desirable permissible limit	<25	6.5–8.5	1500	500–1500	>6	75–200	50–150	100–500	30	200–600	0.2	600	200–600	200–400	50.0
	% Of samples falling above desirable limit	5.45	3.63	83.63	60	92.72	67.2	40.1	83.6	5.4	29.0	7.2	9.0	61.8	92.7	12.7

The table presents the physicochemical characteristics of groundwater in Central Rif, Morocco

The key parameters included temperature (15.02–26.67 °C), pH (6.65–8.89), EC (854–12,400 µS/cm), ion concentrations (Na^+, Cl^-, Ca^{2+}, Mg^{2+}, HCO_{2-}, SO_4^{2-}), total hardness (210.28–2102.03 mg/L), and conductivity

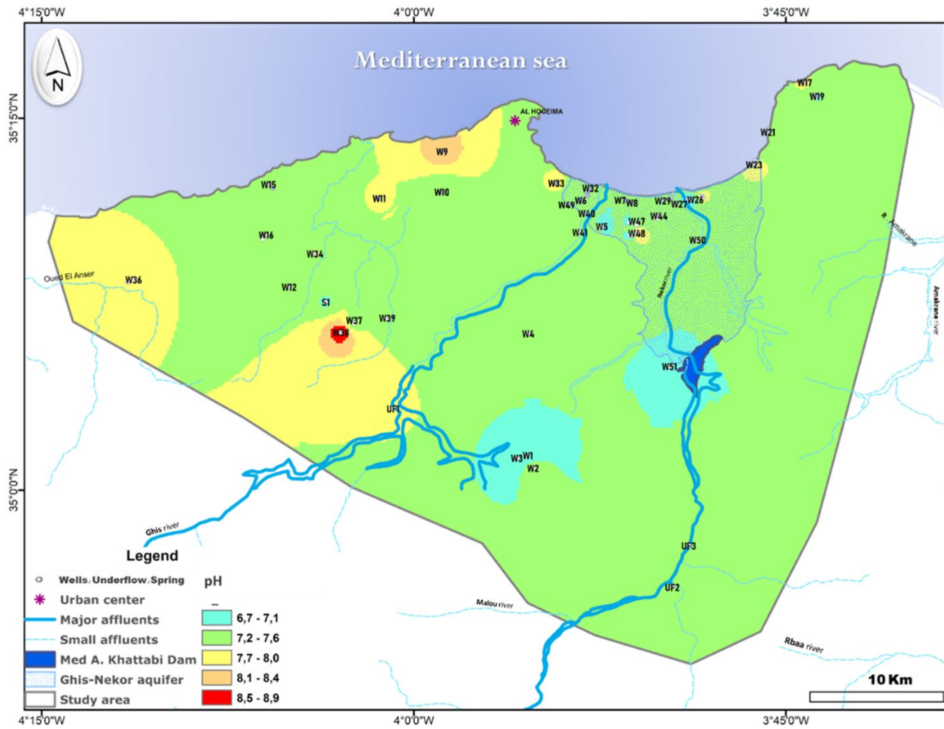


Fig. 3 Map of the spatial distribution of the hydrogen potential (pH) in the study area

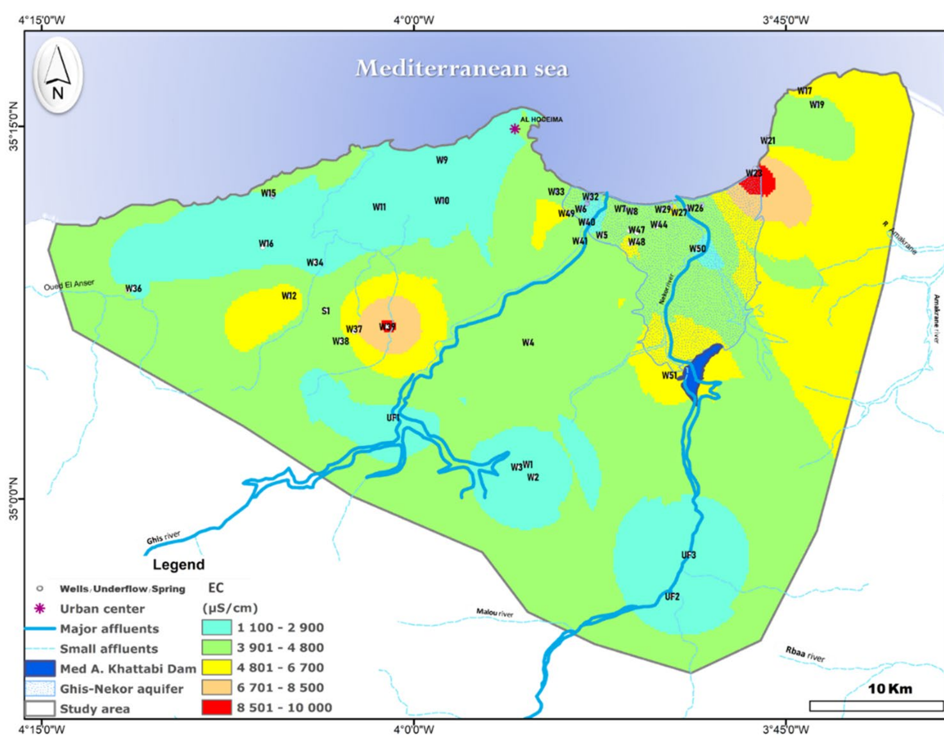


Fig. 4 Map of the spatial distribution of electrical conductivity (EC) in the study area

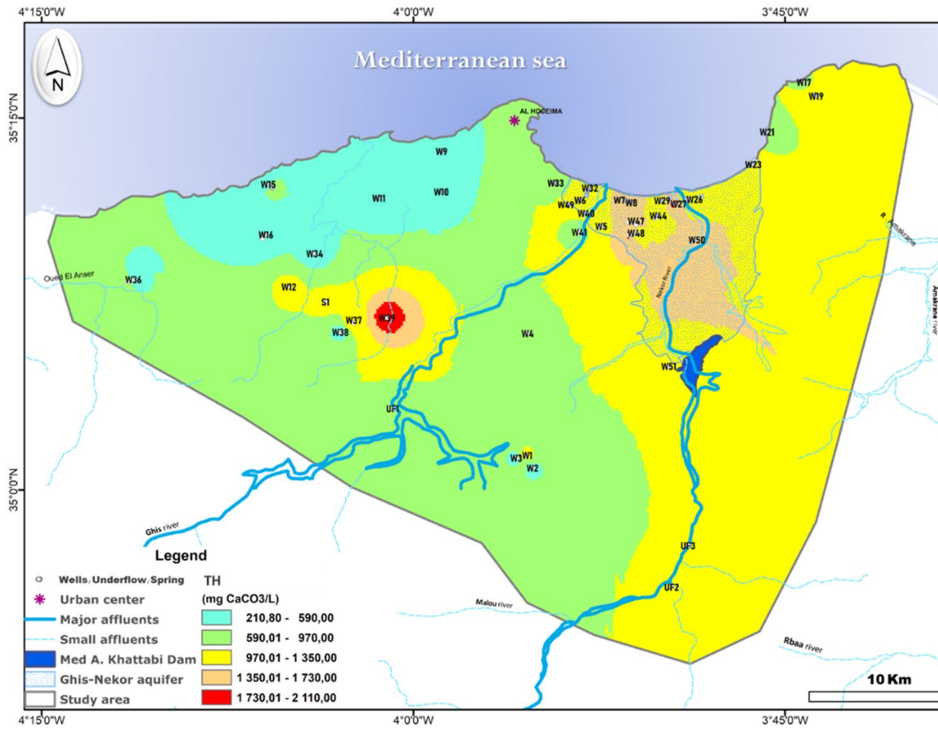


Fig. 5 Map of the spatial distribution of total hardness (TH) in the study area

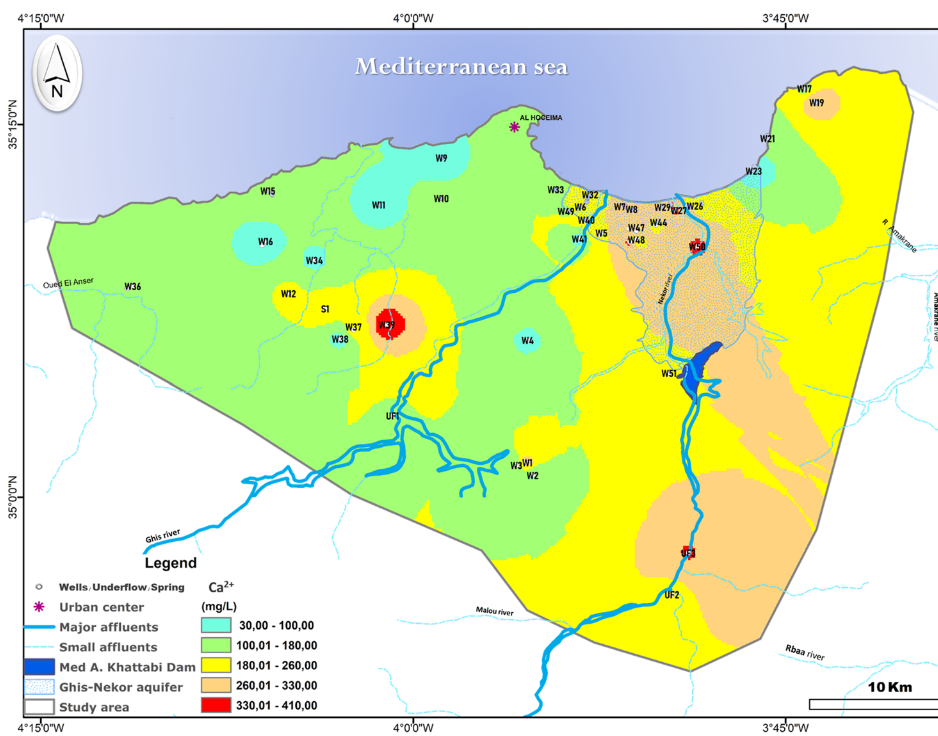


Fig. 6 Map of the spatial distribution of calcium (Ca^{+2}) in the study area

Fig. 7 Map of the spatial distribution of magnesium (Mg^{+2}) in the study area

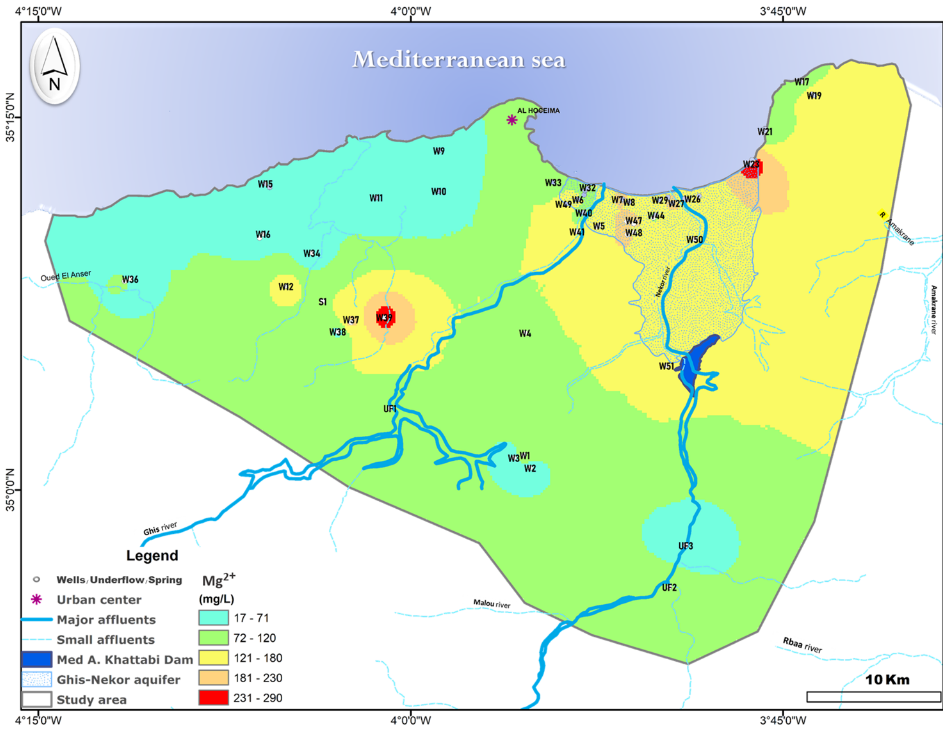
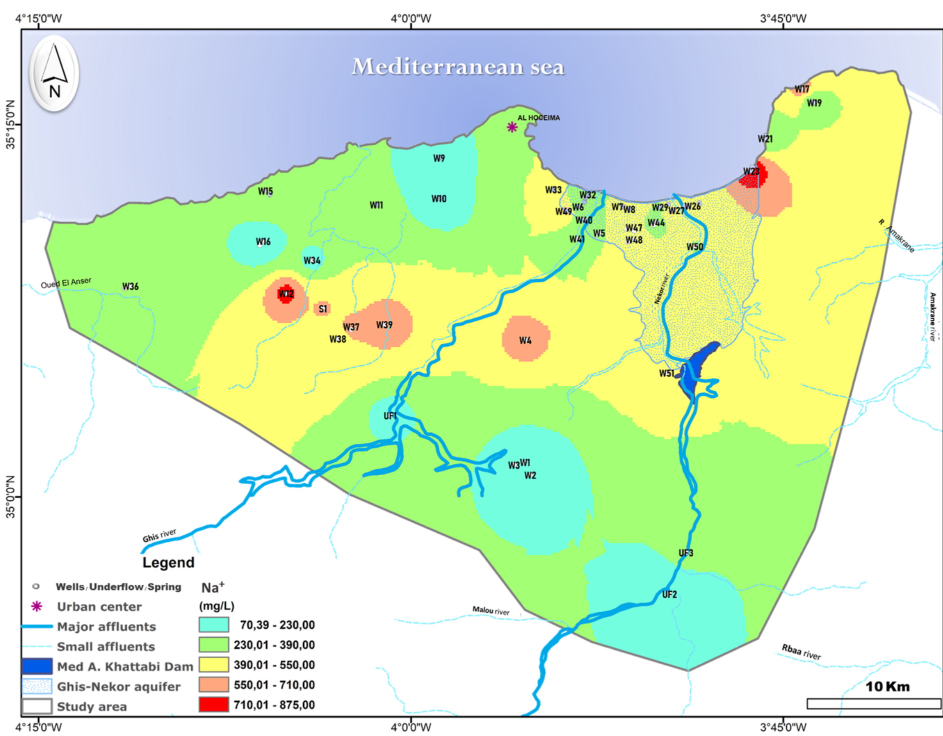


Fig. 8 Map of the spatial distribution of sodium ions (Na^{+}) in the study area



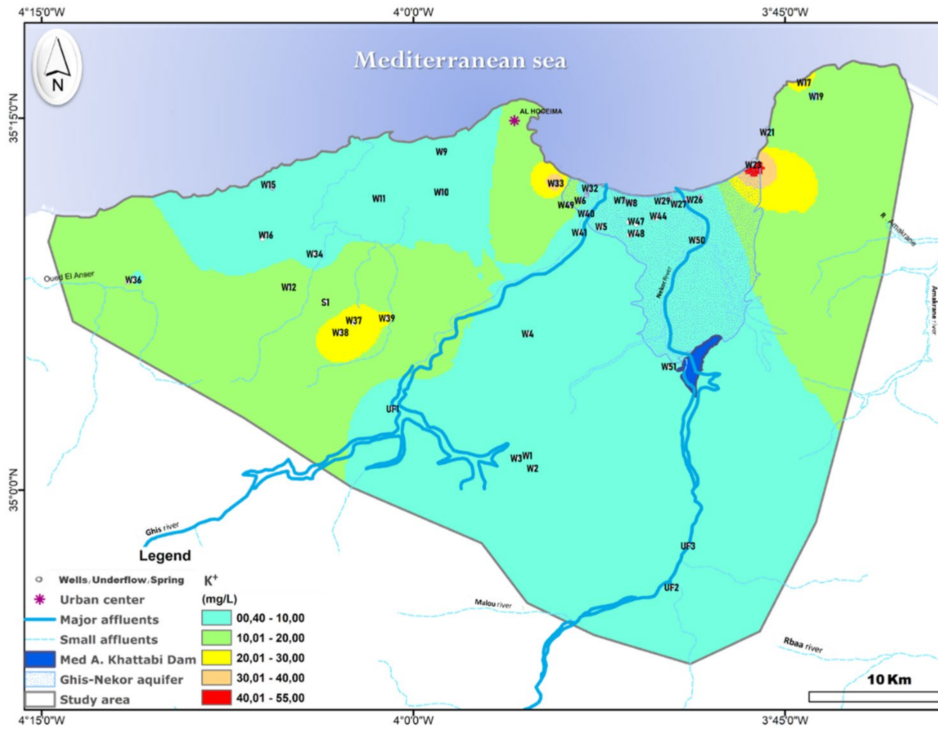


Fig. 9 Map of the spatial distribution of potassium (K^+) in the study area

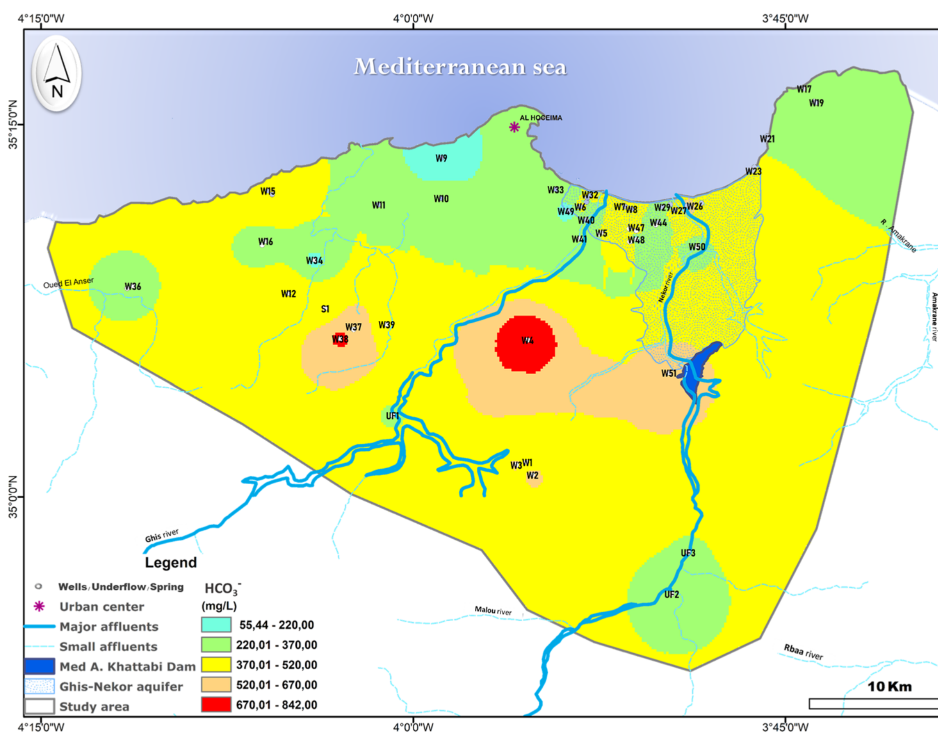


Fig. 10 Map of the spatial distribution of bicarbonate (HCO_3^-) in the study area

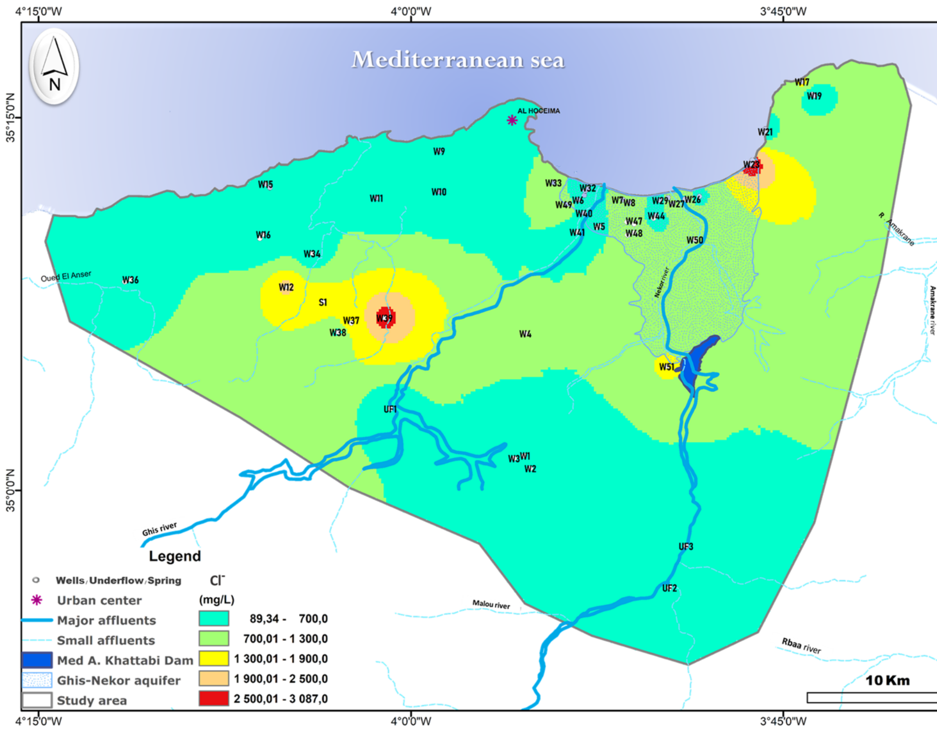


Fig. 11 Map of the spatial distribution of chloride (Cl^-) in the study area

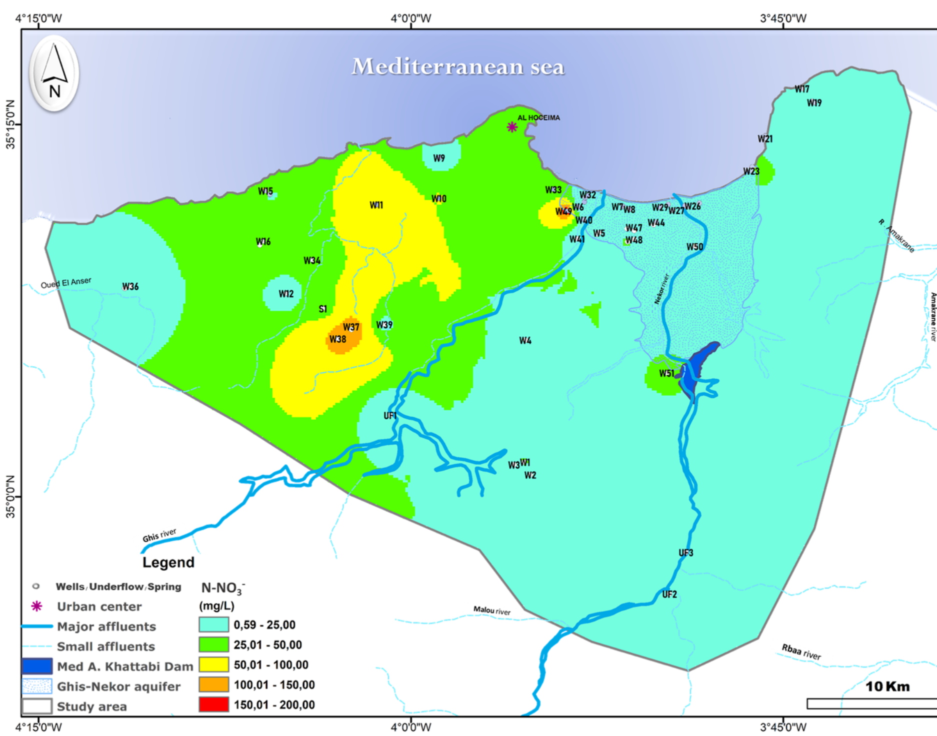


Fig. 12 Map of the spatial distribution of nitrate ($N–NO_3^-$) in the study area

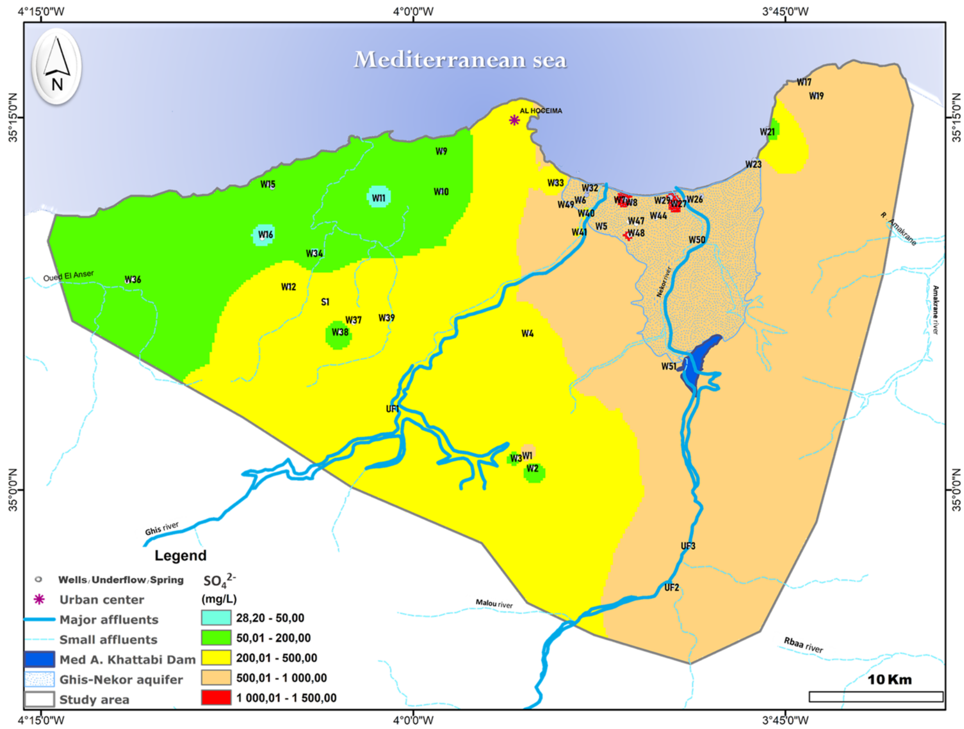


Fig. 13 Map of the spatial distribution of sulfate (SO_4^{2-}) in the study area

Table 2 Classification of groundwater samples in the study area according to TDS

TDS (mg/L)	Mineralization	Number of samples	% of samples
< 50	Very low	0	0.00
50–500	Low	3	5.45
500–1000	Moderate	10	18.18
1000–1500	High	13	23.64
> 1500	Very high	29	52.73

Results and discussion

Physicochemical characterization

The physicochemical qualities of the sampled groundwater were compared with WHO standards (Table 1). The spatial distributions of major element concentrations in the groundwater of the central Rif, such as pH, TDS, EC, TH, Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, HCO_3^{-}, Cl^{-}, N–NO_3^{-}, and SO_4^{2-}, are presented in Figs. 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13.

Hydrogen potential (pH)

The pH values of the groundwater samples collected from the study area ranged from 6.65 to 8.89, with an average of 7.36 (Fig. 3). Most of the samples exhibit slightly alkaline values (Table 1), which is in accordance with prior research (Chafouq et al. 2018; Bouaissa et al. 2020; Benyoussef et al. 2022; El Yousfi et al. 2023).

The observed low alkalinity of the groundwater in the study area, likely due to seawater infiltration into the coastal aquifer, aligns with findings by Chafouq et al. (2018) and Güner et al. (2021). While most groundwater samples fall within the permissible pH range of 6.5 to 8.5 set by the World Health Organization (WHO), a small percentage (3.63%) exceeded the recommended limits set by the WHO in this study. The issue of deteriorating groundwater quality, particularly concerning pH levels, is a significant concern across various regions. For instance, in the Zegoum region of Algeria, Hiouani et al. (2020) discovered that the majority of groundwater samples exhibited mediocre to poor quality, characterized by elevated levels of calcium and sulfates leading to a low alkalinity for groundwater. However, it is worth noting that in the same area, Bouhout et al. (2023) reported a pH ranging between 7.25 and 7.7, which falls within the acceptable range for drinking water. This variability highlights the importance of considering local factors and specific studies when assessing groundwater quality and its suitability for different purposes.

Total dissolved solids (TDS)

Groundwater potability and suitability for consumption and agriculture are influenced by the total cation and anion

Table 3 The groundwater samples in the study area were classified according to EC (Detay and Carpenter 1997)

EC (μS/cm)	Mineralization	Number of samples	% of samples
< 1000	Very weakly mineralized water	2	3.64
1000–2000	Weakly mineralized water	12	21.82
2000–4000	Lightly mineralized water	25	45.45
4000–6000	Moderately mineralized water	5	9.10
6000–10000	Highly mineralized water	8	14.54
> 10000	Excessively mineralized water	3	5.45

concentrations known as total dissolved solids (TDS) (Van der Aa 2003; Rajesh et al. 2015). In this study, the TDS content ranged from 749 to 6204 mg/L, with an average value of 1960.45 mg/L. Approximately 60% of the groundwater samples exceeded the World Health Organization's desired limit of 500–1500 mg/L (WHO 2011) and were unsuitable for consumption due to their high TDS values. However, 40% of the samples fell within the desired limit and were considered potable. Additionally, only 18.18% of the samples showed moderate mineralization, as classified by Van der Aa (2003) (Table 2).

The high levels of mineralization observed in the groundwater samples from the study area can be attributed to various factors, as indicated by previous findings. Water—rock interactions, influenced by the geological substrate and bottom salts, play a significant role in the mineralization process (Dar et al. 2011; Tiwari and Singh 2014). Additionally, nutrient supply and water—rock interactions are predominant in aquifers, contributing to the observed mineralization levels (Ghalit 2017).

In karst aquifers, intense water exploitation can lead to changes in hydrogeochemistry, further impacting the mineral content of groundwater (Bicalho 2010). The lithology, water movement patterns, and recharge-discharge zones also influence the mineralization of groundwater (Simoes 2003). Moreover, the substratum type in catchment areas can affect the mineral content of rivers, highlighting the complex interplay between geological factors and water quality (Drive et al. 1989).

The observed increase in salinity in the groundwater samples may be attributed to the dissolution of soluble minerals present in tertiary materials, underscoring the geological influences on groundwater quality (Merchán et al. 2015). Additionally, significant TDS values (surrounding 6000 mg/L) were found in coastal zones or originating from deep aquifers, as highlighted in the study by Abdelkarim et al. (2023), further emphasizing the impact of geological and hydrological factors on groundwater mineralization.

Electrical conductivity

The electrical conductivity (EC) is a critical parameter used to measure the amount of dissolved substances present in water, indicating the level of inorganic contaminants in water (Morrison et al. 2001; Li et al. 2021). The EC is determined by measuring the water's ability to conduct an electrical current. The more dissolved salts and minerals present in water, the greater the electrical conductivity will be. The concentration of ions, such as calcium, magnesium, sodium, and chloride, influences the electrical conductivity of water. The spatial distribution of electrical conductivity in the study area is illustrated in Fig. 4. Thus, the groundwater EC in the central Rif region ranged from 854 to 12400 μS/cm, with an average of 3715.15 μS/cm.

The elevated levels of electrical conductivity (EC) in groundwater samples, with 83.63% exceeding the WHO permissible limits, as indicated in Table 1, raise concerns about water quality and potential health risks. The WHO guidelines specify that acceptable EC levels in drinking water should not surpass 1000 μS/cm. High EC in water can lead to adverse health effects such as hypertension, cardiovascular disease, and kidney problems, as highlighted by Fried (1991). Moreover, it can impact the suitability of water for irrigation and other purposes. Notably, 14.54% of the samples exhibited high mineralization levels, as noted by Detay and Carpenter (1997) in Table 3. Hence, various studies conducted in different regions, including Sukkur city, Pakistan (Laghari et al. 2018); Oriental Mindoro, Philippines (Kumara et al. 2020); Qambar city, Pakistan (Lanjwani et al. 2020); and Cuddalore Old Town, Tamilnadu (Selvaraju et al. 2022), have reported concerning levels of contamination in groundwater in terms of EC levels. Additionally, the presence of high mineralization levels in a notable percentage of samples further supports this issue, emphasizing the importance of monitoring and managing groundwater quality to safeguard human health and environmental well-being.

Table 4 The classification of groundwater was based on the TH (Sawyer and McCarty 1967)

Total hardness as CaCO3 (mg/L)	Hardness class	Number of samples	% of samples
< 75	Soft	0	0.00
75–150	Moderately high	0	0.00
150–300	Hard	2	3.63
300	Very hard	53	96.36

Furthermore, an increase in EC indicates high groundwater salinity. Thus, elevated levels of dissolved salts and minerals in water can reduce the effectiveness of irrigation and cause soil salinization, which can impact crop yields and lead to long-term environmental degradation. Several factors affect water conductivity, including ion exchange, aquifer solubilization, and anthropogenic activities such as agricultural runoff and industrial activities (Panaskar et al. 2007; Ramesh and Elango 2012). In addition, the phenomenon of corrosion of the mother rock favoured in an acidic medium can greatly contribute to the enrichment of groundwater in ions since the corrosive potential of the water is increased by a low pH (Boyd 2015). This may be the case at many sampling points (W12, W17, W37, W49 and W51), where the pH ranged between 6.9 and 7.7, especially for wells W23 and W39, which had pH values of 7.83 and 7.32 and EC values of 12,400 µS/cm and 10,240 µS/cm, respectively (Table 1). Furthermore, anthropogenic activities such as irrigation, the use of fertilizers, and the application of pesticides can result in the accumulation of salts and minerals in groundwater, leading to increased electrical conductivity.

Total hardness (TH)

The total hardness (TH) of water, measured in mg $CaCO_3$, is a critical characteristic of domestic water and is equivalent to the sum of Ca^{2+} and Mg^{2+} concentrations. In this study, the TH values of the collected groundwater samples ranged from 210.28 to 2102.03 mg/L, with an average of 1006.04 mg/L (Fig. 4).

Approximately 83.63% of the samples exceeded the drinking water limit set by the World Health Organization (WHO 2011) (Table 1). Based on the classification proposed by Sawyer and McCarty (1967) (Table 4), 96.36% of the samples fall under the category of very hard water, while only 3.63% fall under the hard water category.

These results suggest that the majority of groundwater samples analysed in the study area are unsuitable for human consumption due to their exceptionally high hardness levels. This exceedance of drinking water standards is a prevalent issue in many Moroccan groundwater resources, particularly in the semiarid regions of Morocco. For this purpose, numerous studies have consistently reported that a significant proportion of groundwater samples surpass the World Health Organization's drinking water limits, exhibiting elevated levels of total hardness and salinity, namely, in the Essaouira Basin (Ouarani et al. 2020), Ouazi Basin (Bahir et al. 2021; El Mountassir et al. 2022) and Souk El Arbaa (Ghachoui et al. 2024).

Calcium and magnesium ions (Ca^{2+} and Mg^{+2})

Calcium (Ca^{2+}) and magnesium (Mg^{+2}) are vital hydrochemical constituents of groundwater (Razowska-Jaworek 2014) that contribute to water hardness and may be associated with rock geochemistry (Olasehinde et al. 2015). However, excessive amounts of these elements can have detrimental impacts on human health. The calcium levels in the groundwater samples collected in the study area ranged from 26.43 to 408.81 mg/L, with an average value of 200.73 mg/L (Fig. 6). Similarly, the Mg^{2+} concentrations varied from 16.80 to 292.80 mg/L, with an average value of 121.01 mg/L (Fig. 7).

According to the WHO guidelines (2011), 67.27% of the groundwater samples (Table 1) exceeded the desired calcium limit, whereas 40% of the samples surpassed the recommended magnesium level (50–150 mg/L).

The principal sources of calcium (Ca^{2+}) in the study area seem to be gypsum, dolomite, and limestone (Ghalit et al. 2017). Indeed, water in contact with gypsum can reach higher calcium levels, increasing the solubility of gypsum in salt water (Bhakar and Singh 2019), while dolomite and rock mafic minerals (amphiboles) are sources of magnesium in natural waters (Kwami et al. 2019).

Sodium ions (Na^+)

Sodium ions occur naturally in groundwater due to geological processes such as rock weathering, soil salt dissolution from evaporation, agricultural activities and human inputs (Wagh et al. 2016; Abbasnia et al. 2019; Bhakar and Singh 2019). The high sodium content in some samples may result from cation exchange processes with other minerals (Abbasnia et al. 2019).

In the study area, as presented in Fig. 8, the groundwater samples had variable sodium concentrations ranging from 68.5 to 884 mg/L, with an average of 384.54 mg/L (Table 1).

According to these results, over a quarter (29.09%) of the samples exceeded the WHO limits (2011), posing potential health risks to susceptible populations (Marghade et al. 2011). Abnormally high sodium concentrations could be attributed to the alteration of plagioclase feldspar or exchange with sodium clay deposits (Ghalit et al. 2017; Kwami et al. 2019).

Potassium ions (K^+)

Potassium ions are essential nutrients for both plants and animals, and their presence in groundwater can have natural or anthropogenic origins. Natural sources include the weathering of rocks and the dissolution of minerals, while anthropogenic sources include chemical fertilizers and domestic sewage (Morán-Ramírez et al.

2016; Chandran et al. 2017). In this study, the average concentration of potassium in the groundwater samples was 9.71 mg/L, with a range of 0.4 to 54.9 mg/L. Only 5.45% of the samples exceeded the consumption standards established by the World Health Organization (WHO) in 2011 (as shown in Fig. 9 and Table 1).

Although most of the groundwater samples had potassium levels within acceptable limits, a small percentage of the samples exceeded the recommended limits for human consumption, which could pose a health risk to those who rely on groundwater as their primary source of drinking water. Thus, the presence of elevated potassium levels in certain samples underscores the importance of continued monitoring and management of groundwater resources, especially in areas where anthropogenic sources are prevalent. Overall, this study highlights the importance of monitoring potassium levels in groundwater, as excessive potassium can have negative impacts on human health and the environment. Additionally, this study underscores the need for sustainable management practices to minimize the anthropogenic sources of potassium in groundwater.

Bicarbonates (HCO_3^-)

The groundwater bicarbonate content in the study area varied widely, with an average of 379.10 mg/L and values ranging from 54.9 to 634.4 mg/L (Table 1). However, a small proportion (9.09%) of the samples fell below the WHO recommended level for drinking (WHO 2011). Figure 10 illustrates the spatial distribution of HCO_3^-.

The concentration of bicarbonate in groundwater is primarily influenced by the presence of carbonate minerals in soils and aquifers, such as calcite and dolomite, as well as the dissolution of CO_2 gas from the atmosphere and soils of recharge basins (Förstner and Wittmann 2012; Wagh et al. 2016).

Human activities can also contribute to elevated bicarbonate concentrations (Zilberbrand et al. 2001). Although most of the groundwater samples had bicarbonate levels within the recommended limits, the presence of low bicarbonate levels in some samples could affect the taste and overall quality of the water. On the other hand, high bicarbonate concentrations can lead to water hardness and scaling in pipes, which can increase maintenance costs.

Therefore, it is important to continue monitoring and managing groundwater resources to ensure that bicarbonate levels remain within acceptable limits for drinking water. Moreover, future studies could investigate the impact of anthropogenic activities, such as land use change and fertilizer application, on the bicarbonate levels in groundwater in the study area.

Chlorides (Cl^-)

Chloride is an important inorganic anion that can originate from various anthropogenic and natural sources. Anthropogenic sources include industrial and domestic wastewater such as agricultural wastewater, fertilizer use, and septic tank leachate, while natural sources include interactions between water, soil, and rocks as well as marine intrusion (Valdes et al. 2007; Ahmad and Bajahlan 2009; Taiwo et al. 2011; Abbasnia et al. 2019). In this study, the average chloride concentration in the water samples was 772.59 mg/L, ranging from 88.75 to 3150 mg/L (Fig. 11 and Table 1).

A significant proportion (61.81%) of the samples exceeded the World Health Organization's recommended limit for drinking water (WHO 2011). The high chloride concentrations in the water samples could be attributed to anthropogenic activities such as the discharge of domestic and industrial wastewater into the groundwater system. Fertilizers, particularly chloride-containing fertilizers, could also be potential sources of high chloride concentrations in water samples. Moreover, the presence of high chloride concentrations in some of the water samples could also be due to natural sources such as marine intrusion due to existing fault zones in the study area, as demonstrated by (Galindo-Zaldívar et al. 2015), interactions between water, soil, and rocks. The spatial distribution of chloride in the study area is shown in Fig. 11.

The presence of high chloride concentrations in groundwater samples could pose health risks to humans and animals. High chloride concentrations can impart a salty taste to water, making it unpalatable and unsuitable for drinking. While chloride (Cl^-) helps maintain the balance of electrolytes in blood plasma, elevated levels can lead to physiological disorders (Garg et al. 2008).

Excessive intake of chloride has been associated with the development of various health conditions, such as essential hypertension, increased risk of stroke, left ventricular hypertrophy, osteoporosis, renal stones, and asthma. (McCarthy 2004). The results of this study underscore the need for regular monitoring of groundwater quality, particularly in areas where anthropogenic activities and natural sources contribute to high chloride concentrations. Thus, effective management and control measures are required to prevent further degradation of groundwater quality and to safeguard public health.

Nitrates ($N–NO_3^-$)

Nitrate pollution is a global concern and has been identified as a major contaminant of groundwater due to intensive agricultural activities, large amounts of mineral fertilizers, and local hydrogeological structures (Qin et al. 2013; Su et al. 2017; Zhai et al. 2017a). The presence of nitrates in groundwater can adversely affect human health and disrupt groundwater quality. In this study, the concentrations of $N–NO_3^-$ in the groundwater ranged from 0.36 to 180.88 mg/L, with an average value of 23.28 mg/L (Fig. 12 and Table 1). While most of the samples were within the limits allowed by the WHO (2011), 12.72% of the samples analysed exceeded the limit of 50 mg/L. Hence, water with nitrate concentrations above the permissible limit should be treated before it can be used as drinking water. The increased nitrate concentrations at these sites are likely due to anthropogenic activity, including agricultural activity and urban development recorded at the sites, and the presence of uncontrolled septic tanks (Chafouq et al. 2018).

Various natural processes and human activities contribute to water pollution from both point and nonpoint sources of nitrates. Point sources include septic tanks, dairy lagoons, wastewater effluents, and intensive livestock farming, while nonpoint sources include fertilizers, pesticides, manure application, heavy metals, and atmospheric deposition.

These sources of contamination have been reported in many developing and developed countries and regions around the world (Qasemi et al. 2018a, b; Zhai et al. 2017a, b).

Urban development, including the use of septic tanks and the overpumping of groundwater due to high population density, can contribute to nitrate pollution. This study revealed that anthropogenic activities, such as agriculture and urban development, and the presence of uncontrolled septic tanks were significant contributors to nitrate pollution in the study area. The effective management of agricultural activities and urban development is needed to minimize contamination,

Table 5 Groundwater types and their respective sampling locations in the study area

Water type	Number of samples	% Sample	Sample location
$Ca–SO_4$	6	10.9	W1, W18, W19, UF1, UF2, UF3
$Na–HCO_3$	3	5.45	W2, W3, W16
$Na–SO_4$	3	5.45	W6, W8, W27
Ca–Cl	3	5.45	W10, W40, W50
$Mg–HCO_3$	1	1.81	W13
Na–Cl	39	70.9	W4, W5, W7, W9, W11, W12, W14, W15, W17, W20, W21, W22, W23, W24, W25, W26, W28, W29, W30, W31, W32, W33, W34, W35, W36, W37, W38, W39, W41, W42, W43, W44, W45, W46, W47, W48, W49, W51, S1

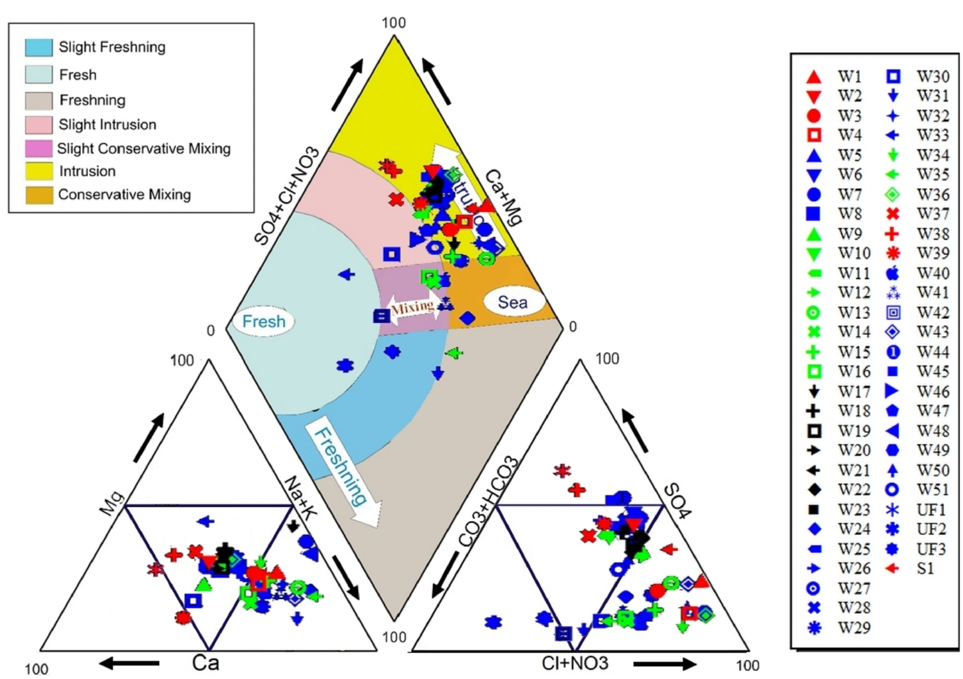


Fig. 14 Piper plot showing major-ion types of groundwater samples in the central Rif aquifer

and regular monitoring of groundwater quality is essential to ensure safe drinking water for the population.

Sulfate ions (SO_4^{2-})

In addition to calcium and magnesium, sulfate is an important factor in water hardness. In this study, the sulfate concentrations in the investigated groundwater samples were found to be high, with an average of 510.61 mg/L and ranging from 27.11 to 1571.61 mg/L (Table 1). Notably, 92.72% of the samples exceeded WHO guidelines (2011). The spatial distribution of sulfate indicates that the concentration of this anion increases near the sea (Fig. 13) due to intense agricultural and septic activities (Boateng et al. 2016).

One possible explanation for the observed high levels of sulfate in the groundwater samples is the presence of sedimentary rocks containing gypsum and anhydrite in the studied sites (Bhakar and Singh 2019). These rocks may be a natural source of sulfate, contributing to the elevated levels in the groundwater. Anthropogenic activities such as the use of fertilizers and wastewater discharge can also lead to increased sulfate levels in groundwater (Akhtar et al. 2021). However, sulfate deficiency was observed in some samples, especially W11 and W16, with values of 35.9 mg/L and 27.11 mg/L, respectively.

This may indicate a low impact of anthropogenic activities (Barakat et al. 2020). High levels of sulfate in groundwater samples may have negative impacts on human health and the environment. Sulfates have a laxative effect that leads to dehydration, especially in infants. However, over time, people and young livestock become acclimated to sulfate, and symptoms disappear (Bashir et al. 2012). In addition, sulfate can cause eutrophication and algal blooms in surface waters, leading to decreased oxygen levels and harm to aquatic organisms (Carpenter et al. 1998).

Overall, the high levels of sulfate observed in the groundwater samples in this study may have negative impacts on both human health and the environment. Further studies are needed to determine the sources and impacts of sulfate in groundwater in this region. In addition, the significant increase in sulfate concentration is most likely related to the presence of gypsum and anhydrite in the sedimentary rocks

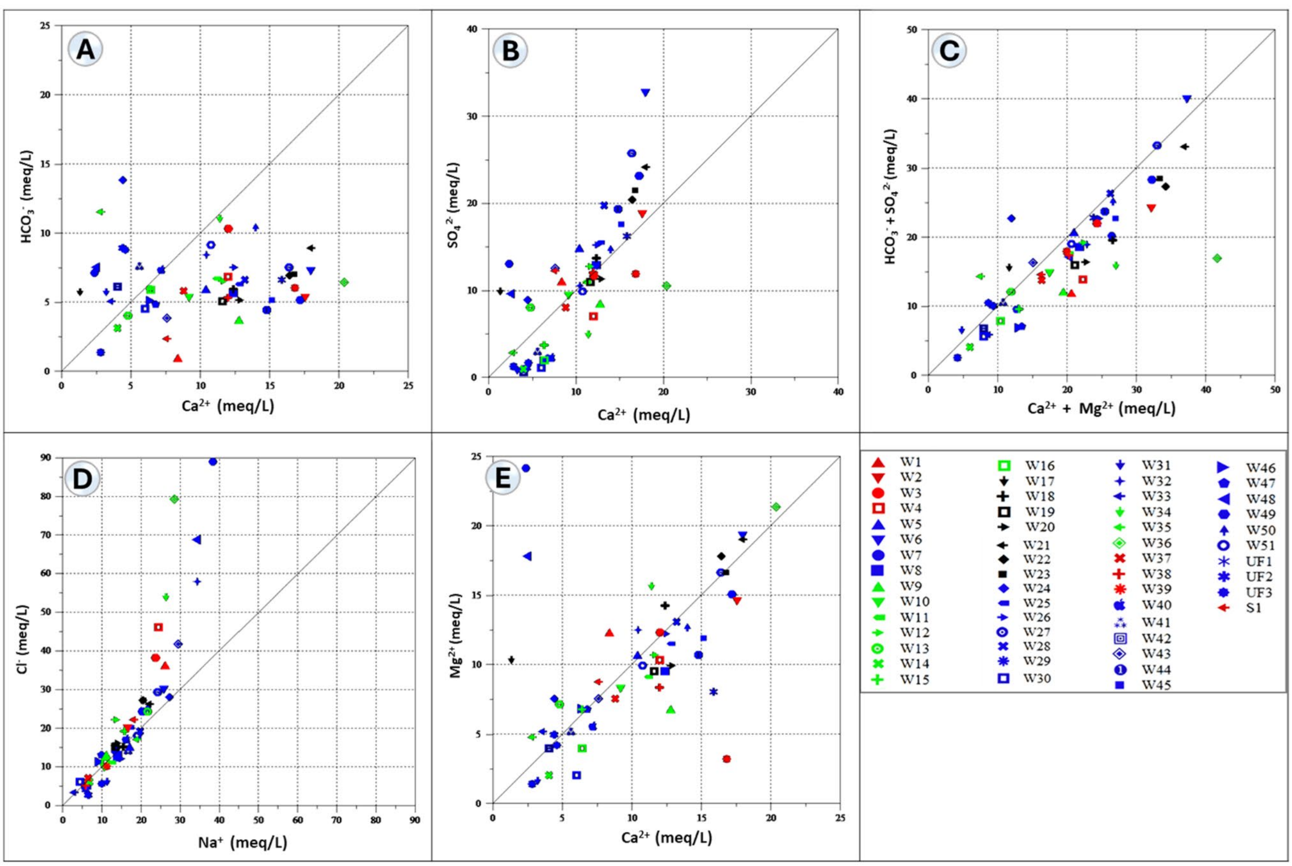


Fig. 15 Binary diagrams between, **A** HCO_3^- vs. Ca^{2+}; **B** SO_4^{2-} vs. Ca^{2+}; **C** ($HCO_3^- + SO_4^{2-}$) vs. ($Ca^{2+} + Mg^{2+}$); **D** Cl^- vs. Na^+ and **E** Mg^{2+} vs. Ca^{2+}

that occupy some of the sites studied (Bhakar and Singh 2019). However, sulfate deficiency indicates a low impact of anthropogenic activities (Barakat et al. 2020).

General hydrochemical characteristics

Groundwater hydrochemical facies and water type

The main cations and anions are represented on a trilinear Piper diagram (Piper 1944) to understand the hydrochemical evolution and identify the predominant groundwater types (Table 5) in the study area.

Figure 14 shows three hydrogeochemical facies: the sodium chloride facies (Na–Cl) represents 70.9% of the water points studied (first facies), while 10.9% of the water samples belong to the sulfated calcium facies (Ca–SO_4) (second facies). The third facies is represented by 5.45% sodium bicarbonate water (Na–HCO_3). However, the remainder of the samples surveyed could correspond to fresh groundwater influenced by ion exchange.

These facies highlight the complexity of the hydrogeochemical processes that control groundwater salinity in the Central Rif, including water mixing, evaporation and the dissolution of evaporites such as halite, gypsum and anhydrite (Sajilkumar and James 2016).

Ionic ratio

The hydrogeochemical characteristics of an aquifer system are influenced by various chemical reactions, frequently resulting in changes in ionic concentrations (Verma et al. 2021). The ionic ratios were established (Fig. 15) to assess the origin of water mineralization (Ghalit et al. 2023) and to determine the possibility of seawater intrusion (Edet 2016; Aladejana et al. 2021) in the study area.

The bivariate plot of Ca^{2+} versus HCO_3^- (Fig. 15A) shows that the weathering of carbonate minerals (calcite) resulted in more Ca^{2+} ion release than the weathering of carbonic acid (silicate) in most water samples. In addition, the correlation between (Ca^{2+} + Mg^{2+}) and (HCO_3^- + SO_4^{2-}) was used to examine the effect of the distribution of sulfate and carbonate minerals in the system. Figure 15C shows that most samples follow the 1:1 line, suggesting that these ions in the central Rif groundwater originate from the dissolution of these minerals rather than the weathering of silicates.

The Na^+/Cl^- ratio plot (Fig. 15D) shows that a significant number of samples strongly approach the 1:1 line, suggesting halite dissolution or possibly seawater intrusion (El Yousfi et al. 2022). Nevertheless, the reverse ion exchange process could explain the scattered points below this line, where Ca^{2+} replaces Na^+ in the groundwater of the Central Rif. The Ca^{2+}/Mg^{2+} molar ratio indicates the presence of calcite and the dissolution of dolomite (Kumar et al. 2006). The graphical representation of this Ca^{2+}/Mg^{2+} ratio (Fig. 15E) reveals a predominance of calcite dissolution over silicate weathering.

Sulfate ions (SO_4^{2-}) are frequently present in groundwater and have mainly natural and anthropogenic origins. Figure 15B illustrates the correlation between Ca^{2+} and SO_4^{2-} concentrations in the sampled waters. This correlation could be linked to the potential presence of gypsum and/or anhydrite, thus suggesting a possible contribution of these minerals to the mineralization of the waters in the central Rif aquifer. Nevertheless, it is important to note that a group of samples falls outside the 1:1 line, indicating an excess of SO_4^{2-} ions over Ca^{2+} ions in a few waters studied. This discrepancy can be attributed to other possible sources of these ions, such as seawater intrusion and anthropogenic sources.

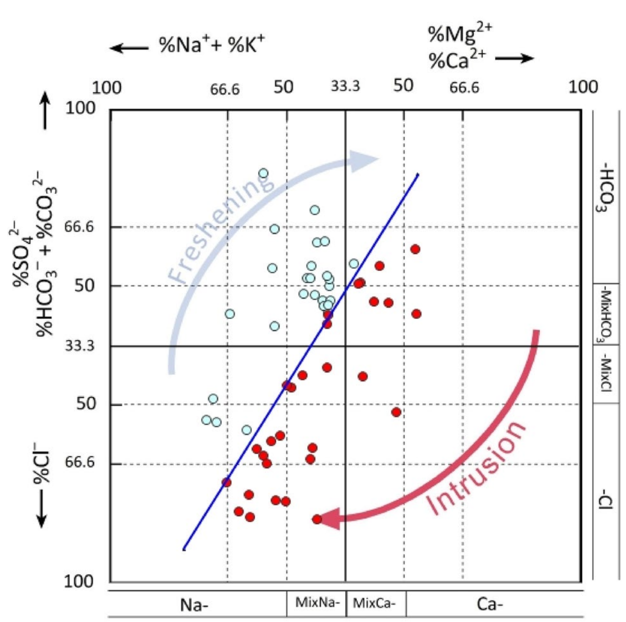


Fig. 16 Representation of central Rif groundwater samples in the HFE-D

Hydrochemical facies evolution (HFE-D)

The hydrochemical facies evolution (HFE-D) was used to interpret and analyse possible hydrochemical facies and evolutionary processes in coastal areas while taking into consideration the percentage of the most significant ions and their relationships (Giménez-Forcada and Sánchez San Román 2015). The results of the HFE plots indicate the dissolution of salt marsh evaporites in aquifer materials, which are rich in sulfate and chloride (Fig. 16).

The plot shows that more than half of the samples are projected in the lower part of Fig. 16 (52.72% of the total

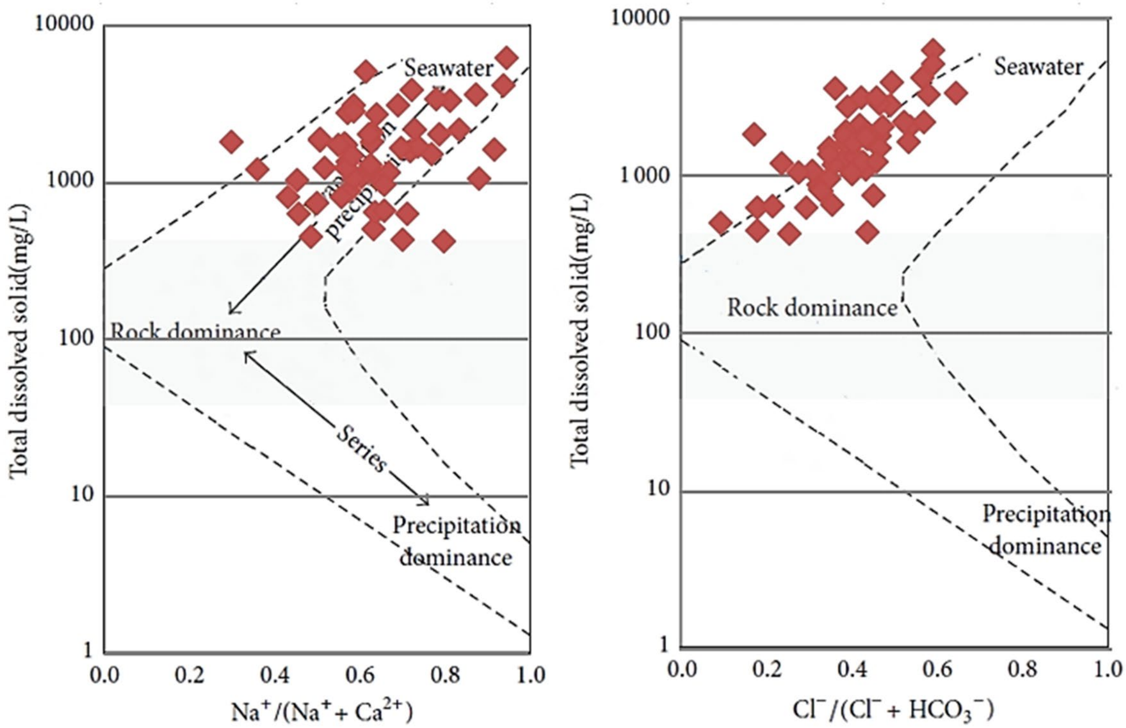


Fig. 17 Gibbs diagram of anions and cations versus TDS

samples), representing the intrusion phase, while 47.27% of the total samples represent the refreshment phase. Indeed, water samples from the central Rif are of the Na–Cl type (41.37%) and belong to saltwater intrusion facies affected to some extent by the reverse cation exchange reaction (Na^+/Ca^{2+}), as indicated by the presence of MixCa–Cl-type waters in the aquifer in the study area. On the other hand, 34.61% of the fresh groundwater in the central Rif is MixNa–HCO_3 and is influenced by direct cation exchange reactions. Indeed, factors such as the distance from the sea, intensive water demand and hydrogeological characteristics of the aquifer affect the degree of contamination of the aquifer by marine intrusion (Yin et al. 2021; Benaafi et al. 2022).

Gibbs diagram

Gibbs diagrams (Gibbs 1970) are widely used to identify the processes controlling groundwater geochemistry, including precipitation, evaporation, rock−water interactions, and seawater intrusion. Figure 17 shows the correlation between cation and anion levels and TDS.

As shown by the plot of chemical data on the Gibbs diagram, most groundwater samples in the study area fell within the evaporation dominance zone and were closer to seawater, revealing an interaction between groundwater and seawater (Huang et al. 2013).

Multivariate statistical analysis

To understand the relationships among the measured hydrochemical parameters, Pearson correlation analysis (r) was performed on 12 selected parameters to identify and verify their origin. The results are presented in Table 6.

The correlation matrix reflects a strong positive correlation between EC and TDS with major ions, indicating the contribution of these ions to the overall mineralization of the predicted groundwater (Elumalai et al. 2020).

A significant correlation among TDS, TH, Ca^{2+} and Mg^{2+} suggests that the host rock is the result of carbonate and dolomite dissolution (Qin et al. 2013). It should also be noted that TDS, EC, Na^+ and Cl^- are strongly positively correlated, which represents possible marine intrusion along the coastal aquifer, and this correlation can be explained by the precipitation/evaporation properties of the minerals contained in the predicted waters (Rakib et al. 2020).

In addition, the mobilization of water from saline formations by the overexploitation of aquifers (Giménez-Forcada et al. 2010) and pollution due to anthropic activities (septic tank effluents, use of synthetic fertilizers) may be responsible for the relationship between these parameters and the salinity of these waters (Re et al. 2013). It was confirmed that pH, HCO_3^- and N–NO_3^- had no correlation with the other measured hydrochemical parameters. Since N–NO_3^- and other metrics did not significantly correlate,

Table 6 Correlation analysis of physicochemical parameters (Bold values indicate a correlation of more than 50%)

		pH	EC (µS/cm)	Ca_2^+ (mg/L)	Mg_2^+ (mg/L)	Na^+ (mg/L)	K^+ (mg/L)	HCO_3^- (mg/L)	Cl^- (mg/L)	$N–NO_3^-$ (mg/L)	SO_4^{2-} (mg/L)	TDS (mg/L)	TH (Mg of $CaCO_3$)
Correlation	pH	**1.000**											
	EC	− 0.059	**1.000**										
	Ca_2^+	− 0.443	0.178	**1.000**									
	Mg_2^+	− 0.288	**0.782**	0.556	**1.000**								
	Na^+	0.014	**0.868**	0.174	**0.718**	**1.000**							
	K^+	0.255	**0.708**	− 0.250	0.383	**0.669**	**1.000**						
	HCO_3^-	− 0.098	0.186	0.058	0.234	0.352	0.081	**1.000**					
	Cl^-	− 0.043	**0.926**	0.125	**0.723**	**0.899**	**0.734**	0.241	**1.000**				
	$N–NO_3^-$	0.078	0.170	− 0.255	− 0.047	0.167	0.286	0.004	0.173	**1.000**			
	SO_4^{2-}	− 0.245	0.363	**0.774**	0.733	0.410	− 0.037	0.067	0.234	− 0.277	**1.000**		
	TDS	− 0.009	**0.942**	0.157	**0.724**	**0.817**	**0.668**	0.245	**0.875**	0.160	0.325	**1.000**	
	TH	− 0.412	**0.552**	**0.876**	**0.888**	**0.512**	0.084	0.168	0.488	− 0.169	**0.854**	**0.507**	**1.000**

human activity is likely the primary contributor to groundwater nitrate contamination (Helena et al. 1999).

Conclusion

This study of the hydrogeochemical properties of groundwater in the central Rif region, northern Morocco, reveals intricate relationships among various influences. Physicochemical analysis of 55 groundwater points highlights interactions between hydrogeochemical processes, geological factors, and anthropogenic influences. The study of water mineralization processes, employing Piper, HFE-D, Gibbs, and binary diagrams, demonstrated that water mineralization results from evaporite (gypsum and halite) and carbonate (limestone and dolomite) dissolution, silicate alteration, and cation exchange.

Key findings point to increasing mineralization, with a significant proportion of samples exceeding WHO guidelines for essential ions such as chloride, sulfates, nitrates, sodium, and potassium. The predominant presence of sodium chloride (Na–Cl) as the primary chemical facies and the impact of evaporation on water chemistry dynamics underscore the complexity of groundwater composition. Furthermore, this research suggests that seawater intrusion at the *Trougout* Zone Fault could contribute to heightened mineralization trends. Acknowledging seawater as a potential factor for elevated mineral content enhances the understanding of regional groundwater intricacies.

Given these findings, the importance of continuous monitoring and informed management strategies is emphasized, ensuring the responsible use and preservation of coastal groundwater reserves. The urgency lies in the potential repercussions for public health and environmental balance. Thus, this study underscores the necessity of a proactive approach to groundwater governance and decision-making, not only in the central Rif region but also in a broader context.

Author contributions S. B.: conceptualization, software, writing original draft M. A.: methodology, formal analysis, writing original draft. Y. E.: software, writing original draft M. M.:writing original draft, H. G.: data curation H. E.: funding acquisition A. A.: formal analysis M. G.: resources, project administration Y. F.: software M. A.: validation M. H.: methodology, investigation visualization A. A.: validation, M. C.:data curation A. A.: supervision, visualization All autors reviewed the manuscript.

Funding Open Access funding provided thanks to the CRUE-CSIC agreement with Springer Nature.

Data availability No datasets were generated or analysed during the current study.

Declarations

Conflict of interest The authors declare no competing interests.

References

Abbasnia A, Yousefi N, Mahvi AH, Nabizadeh R, Radfard M, Yousefi M, Alimohammadi M (2019) Evaluation of groundwater quality using water quality index and its suitability for assessing water for drinking and irrigation purposes: case study of Sistan and Baluchistan province (Iran). Hum Ecol Risk Assess 25(4):988–1005. https://doi.org/10.1080/10807039.2018.1458596

Abdelkarim B, Telahigue F, Agoubi B (2022) Assessing and delineation of groundwater recharge areas in coastal arid area southern Tunisia. Groundw Sustain Dev 18:100760. https://doi.org/10.1016/j.gsd.2022.100760

Abdelkarim B, Telahigue F, Abaab N, Boudabra B, Agoubi B (2023) AHP and GIS for assessment of groundwater suitability for irrigation purpose in coastal-arid zone: Gabes region, southeastern Tunisia. Environ Sci Poll Res 30(6):15422–15437. https://doi.org/10.1007/s11356-022-23193-4

Aghazadeh N, Mogaddam AA (2010) Assessment of groundwater quality and its suitability for drinking and agricultural uses in the Oshnavieh area, Northwest of Iran. J Environ Prot Sci 1:30–40. https://doi.org/10.4236/jep.2010.11005

Ahmad M, Bajahlan AS (2009) Quality comparison of tap water vs. bottled water in the industrial city of Yanbu (Saudi Arabia). Environ Monit Assess 159(1):1–14. https://doi.org/10.1007/s10661-008-0608-8

Akhtar N, Syakir Ishak MI, Bhawani SA, Umar K (2021) Various natural and anthropogenic factors responsible for water quality degradation: a review. Water 13(19):2660. https://doi.org/10.3390/w13192660

Aladejana JA, Kalin RM, Sentenac P, Hassan I (2021) Groundwater quality index as a hydrochemical tool for monitoring saltwater intrusion into coastal freshwater aquifer of Eastern Dahomey basin. Southwestern Nigeria Groundw Sustain Dev 13:100568. https://doi.org/10.1016/j.gsd.2021.100568

Ayed B, Jmal I, Sahal S, Mokadem N, Saidi S, Boughariou E, Bouri S (2017) Hydrochemical characterization of groundwater using multivariate statistical analysis: the Maritime Djeffara shallow aquifer (Southeastern Tunisia). Environ Earth Sci 76:1–22. https://doi.org/10.1007/s12665-017-7168-6

Bahir M, El Mountassir O, Ouazar D, Carreira PM (2021) Hydrochemical analysis and evaluation of groundwater quality in Ouazi basin (Essaouira, Morocco). In: Abrunhosa M, Chambel A, Peppoloni S, Chaminé HI (eds) Advances in geoethics and groundwater management theory and practice for a sustainable development. Advances in science, technology & innovation. Springer, Cham. https://doi.org/10.1007/978-3-030-59320-9_50

Banerjee P, Prasad B (2020) Determination of concentration of total sodium and potassium in surface and ground water using a flame photometer. App Water Sci 10:1–7. https://doi.org/10.1007/s13201-020-01188-1

Barakat A, Hilali A, Baghdadi ME, Touhami F (2020) Assessment of shallow groundwater quality and its suitability for drinking purpose near the Béni-Mellal wastewater treatment lagoon (Morocco). Hum Ecol Risk Assess 26(6):1476–1495. https://doi.org/10.1080/10807039.2019.1584029

Bashir MT, Ali S, Bashir A (2012) Health effects from exposure to sulfates and chlorides in drinking water. Pakistan J Medical Health Sci 6(3):648–652

Benaafi M, Tawabini B, Abba SI, Humphrey JD, Al-Areeq AM, Alhulaibi SA, Usman AG, Aljundi IH (2022) Integrated hydrogeological, hydrochemical, and isotopic assessment of seawater intrusion into coastal aquifers in Al-Qatif area. Eastern Saudi Arabia Mol 27(20):6841. https://doi.org/10.3390/molecules27206841

Benyoussef S, Arabi M, El Ouarghi H, Ghalit M, El Yousfi Y, Azirar M, Ait Boughrous A (2022) Qualitative assessment of the waters of the coastal aquifer ghis-nekor (central Rif, Northern Morocco) in view of agricultural use. J Water Land Dev 52:245–250. https://doi.org/10.24425/jwld.2022.140395

Bhakar P, Singh AP (2019) Groundwater quality assessment in a hyper-arid region of Rajasthan, India. Nat Resour Res 28:505–522. https://doi.org/10.1007/s11053-018-9405-4

Bicalho, C.C., (2010) Hydrochemical characterization of transfers in karst aquifers by natural and anthropogenic tracers. Example of a Mediterranean karst system, the Lez karst aquifer (Southern France).

Boateng TK, Opoku F, Acquaah SO, Akoto O (2016) Groundwater quality assessment using statistical approach and water quality index in Ejisu-Juaben municipality. Ghana Environ Earth Sci 75:489. https://doi.org/10.1007/s12665-015-5105-0

Bouaissa M, Ghalit M, Taupin JD, El khattabi J, Gharibi E (2020) Assessment of groundwater quality in the Bokoya Massif (Central Rif, Northern Morocco) using several analytical techniques. EuroMediterr J Environ Integr 6(9):1–11. https://doi.org/10.1007/s41207-020-00208-5

Bouaissa M, Gharibi E, Ghalit M, Taupin JD, El Khattabi J (2021) Identifying the origin of groundwater salinization in the Bokoya massif (central Rif, northern Morocco) using hydrogeochemical and isotopic tools. Groundw Sustain Dev 14:100646. https://doi.org/10.1016/j.gsd.2021.100646

Bouhout S, Haboubi K, El Abdouni A, El Hammoudani Y, Haboubi C, Dimane F, Hanafi I, Elyoubi MS (2023) Appraisal of groundwater quality status in the Ghiss-Nekor coastal plain. J Ecol Eng. 10:121. https://doi.org/10.12911/22998993/169847

Boyd CE (2015) Water quality: an introduction. Springer, Berlin

Carpenter SR, Caraco NF, Correll DL, Howarth RW, Sharpley AN, Smith VH (1998) nonpoint pollution of surface waters with phosphorus and nitrogen. Ecol Appl 8:559–568

Chafouq D, Mandour A, Elgettafi M, HimiChouikri MI, Casas A (2018) Hydrochemical and isotopic characterization of groundwater in the Ghis-Nekor plain (northern Morocco). J Afr Earth Sci 139:1–13. https://doi.org/10.1016/j.jafrearsci.2017.11.007

Chalouan, A., Benmakhlouf, M., Mouhir, L., Ouazani-Touhami, A., Saji, R., Zaghloul, M., (1995) Les étapes tectoniques de la structuration alpine du Rif interne (Maroc). IV^{ème} Colloque international Sobre el enlace fijo del estrecho de Gibraltar, Sevilla, spain, May 16–18.

Chandran S, Karmegam M, Kumar V, Dhanasekarapandian M (2017) Evaluation of groundwater quality in an untreated wastewater irrigated region and mapping—a case study of Avaniyapuram sewage farm. Madurai Arab J Geosci 10:159. https://doi.org/10.1007/s12517-017-2900-9

Dao PU, Heuzard AG, Le TX, Zhao J, Yin R, Shang C, Fan C (2023) The impacts of climate change on groundwater quality: a review. Sci Tot Environ 912:169241. https://doi.org/10.1016/j.scitotenv.2023.169241

Dar IA, Sankar K, Shafi T, Dar MA (2011) Investigation of groundwater quality in hardrock terrain using geoinformation system. Environ Monit Assess 176:575–595. https://doi.org/10.1007/s10661-010-1605-2

Detay M, Carpenter M (1997) Water wells: implementation, maintenance and restoration. Wiley, London, p 379

Dole-Olivier MJ, Malard F, Ferreira D, Gibert J (2005) Biodiversité dans les eaux souterraines. Houille Blanche 3:39–44. https://doi.org/10.1051/lhb:200503005

Drive E, Basaguren A, Bikuña BG, Cacho M (1989) A comparative study of water mineralization and nutrient status in the main water courses of biscay (basque country). Water Res 23:705–710. https://doi.org/10.1016/0043-1354(89)90203-0

Earman S, Dettinger MD (2011) Potential impacts of climate change on groundwater resources—a global review. J Water Clim Change 2:213–229. https://doi.org/10.2166/WCC.2011.034

Edet A (2016) Hydrogeology and groundwater evaluation of a shallow coastal aquifer, southern Akwa Ibom State (Nigeria). Appl Water Sci 7:2397–2412. https://doi.org/10.1007/s13201-016-0432-1

El Mountassir O, Bahir M, Chehbouni AG, Dhiba D, El Jiar H (2022) Assessment of groundwater quality and the main controls on its hydrochemistry in a changing climate in Morocco (Essaouira basin). Sustainability. https://doi.org/10.3390/su14138012

El Yousfi Y, Himi M, El Ouarghi H, Elgettafi M, Benyoussef S, Gueddari H, Aqnouy M, Salhi A, Alitane A (2022) Hydrogeochemical and statistical approach to characterize groundwater salinity in the Ghiss-Nekkor coastal aquifers in the Al Hoceima province. Morocco Groundw Sustain Dev 19:100818. https://doi.org/10.1016/j.gsd.2022.100818

El Yousfi Y, Himi M, El Ouarghi H, Aqnouy M, Benyoussef S, Gueddari H, Ait Hmeid H, Alitane A, Chaibi M, Zahid M, Essahlaoui N, Hitouri S, Essahlaoui A, Elaaraj A (2023) Assessment and prediction of the water quality index for the groundwater of the Ghiss-Nekkor (Al Hoceima, Northeastern Morocco). Sustainability 15:402. https://doi.org/10.3390/su15010402

Elgettafi M, Elmandour A, HimiCasas i Ponsatí MA, Elhaouadi B (2012) Messinian salinity crisis impact on the groundwater quality in Kert aquifer NE Morocco: hydrochemical and statistical approaches. Int J Water Res Environ Eng 4(11):339–351. https://doi.org/10.5897/IJWREE12.002

Elmeknassi M, El Mandour A, Elgettafi M, Himi M, Tijani R, El Khantouri FA, Casas A (2021) A GIS-based approach for geospatial modelling of groundwater vulnerability and pollution risk mapping in Bou-Areg and Gareb aquifers, northeastern Morocco. Environ Sci Pollut Control Ser 28(37):51612–51631. https://doi.org/10.1007/s11356-021-14336-0

Elumalai V, Nethononda VG, Manivannan V, Rajmohan N, Li P, Elango L (2020) Groundwater quality assessment and application of multivariate statistical analysis in Luvuvhu catchment, Limpopo. South Africa J Afr Earth Sci 171:103967. https://doi.org/10.1016/j.jafrearsci.2020.103967

Förstner U, Wittmann GT (2012) Metal pollution in the aquatic environment, 2nd edn. Springer, Berlin, pp 194–194

Fried J (1991) Nitrates and their control in the EEC aquatic environment, NATO ASI series. Nitrate contamination: exposure, consequence, and control. Springer-Verlag, Berlin, pp 3–11

Frizon-De-Lamotte D, Leikine M (1985) Métamorphisme miocène du Rif oriental (Maroc) et individualization de la nappe gravitaire d'Aknoul. Rev Géogr Phys Géol Dyn 26(1):29–42

Galindo-Zaldívar J, Azzouz O, Chalouan A, Pedrera A, Ruano P, Ruiz-Constán A, Benmakhlouf M (2015) Extensional tectonics, graben development and fault terminations in the eastern Rif (Bokoya–Ras Afraou area). Tectonophysics 663:140–149. https://doi.org/10.1016/j.tecto.2015.08.029

Garg VK, Suthar S, Singh S, Sheoran A, Garima M, Jain S (2008) Drinking water quality in villages of southwestern Haryana, India: assessing human health risks associated with hydrochemistry. Environ Geol 58(6):1329–1340. https://doi.org/10.1007/s00254-008-1636-y

Ghachoui E, Taouil H, Naser RS, Said IA (2024) Spatial assessment of groundwater quality for drinking In Souk El Arbaa. Morocco Water Supp 24(4):1267–1281. https://doi.org/10.2166/ws.2024.059

Ghalit M, Elkhadir G, Taupin JD, Lamhamdi A (2017) Mineralization process of spring in carbonate coastal aquifer in the massif Bokkoya (Central Rif, Morocco). Mor J Chem 5(1):105–119. https://doi.org/10.48317/IMIST.PRSM/morjchem-v5i1.6650

Ghalit M, Bouaissa M, Gharibi E, Taupin JD, Patris N (2023) Hydrogeochemical characteristics and isotopic tools used to identify the mineralization processes of bottled mineral water in Morocco. Geosci 13(2):38. https://doi.org/10.3390/geosciences13020038

Giambastiani BMS, Colombani N, Mastrocicco M, Fidelibus M (2013) Characterization of the lowland coastal aquifer of Comacchio (Ferrara, Italy): hydrology, hydrochemistry and evolution of the system. J Hydrol 501:35–44. https://doi.org/10.1016/j.jhydrol.2013.07.037

Gibbs RJ (1970) Mechanisms controlling world water chemistry. Science 170(3962):1088–1090

Giménez-Forcada E, Román SS (2015) An excel macro to plot the HFE-diagram to identify sea water intrusion phases. Groundwater 53(5):819–824. https://doi.org/10.1111/gwat.12280

Giménez-Forcada E, Bencini A, Pranzini G (2010) Hydrogeochemical considerations about the origin of groundwater salinization in some coastal plains of Elba Island (Tuscany, Italy). Environ Geochem Health 32:243–257. https://doi.org/10.1007/s10653-009-9281-2

Güner ED, Cekim HO, Seçkin G (2021) Determination of water quality assessment in wells of the Göksu plains using multivariate statistical techniques. Environ Forensics 22(1–2):172–188. https://doi.org/10.1080/15275922.2020.1834025

He X, Wu J, He S (2019) Hydrochemical characteristics and quality evaluation of groundwater in terms of health risks in luohe aquifer in Wuqi county of the Chinese loess plateau, northwest China. Hum Ecol Risk Assess 25(1–2):32–51. https://doi.org/10.1080/10807039.2018.1531693

Helena BA, Vega M, Barrado E, Pardo R, Fernández L (1999) A case of hydrochemical characterization of an alluvial aquifer influenced by human activities. Water Air Soil Pollut 112:365–387. https://doi.org/10.1023/A:1005065422156

Himi M, Tapias J, Benabdelouahab S, Salhi A, Rivero L, Elgettafi M, El Mandour A, Stitou J, Casas A (2017) Geophysical characterization of saltwater intrusion in a coastal aquifer: the case of Martil-Alila plain (north Morocco). J Afr Earth Sci 126:136–147. https://doi.org/10.1016/j.jafrearsci.2016.11.011

Hiouani F, Bouzidi Y, Aissaoui S, Rechachi ZM (2020) Assessment of groundwater quality used for irrigation in the region of zegoum oued souf Algeria. Ponte. https://doi.org/10.21506/j.ponte.2020.7.8

Huang G, Sun J, Zhang Y, Chen Z, Liu F (2013) Impact of anthropogenic and natural processes on the evolution of groundwater chemistry in a rapidly urbanized coastal area South China. Sci Total Environ 463–464:209–221. https://doi.org/10.1016/j.scitotenv.2013.05.078

Islam MS, Mostafa MG (2024) Impacts of climate change on global freshwater quality and availability: a comprehensive review.

J Water Environ Technol 22(1):1–26. https://doi.org/10.2965/jwet.23-036
Javadinejad S, Dara RN, Jafary F (2019) Impacts of extreme events on water availability. Annals Geogr Stud. 2(3):16–24. https://doi.org/10.22259/2642-9136.0203003
Kamal S, Sefiani S, Laftouhi NE, El Mandour A, Moustadraf J, Elgettafi M, Himi M, Casas A (2021) Hydrochemical and isotopic assessment for characterizing groundwater quality and recharge processes under a semiarid area: case of the Haouz plain aquifer (central Morocco). J Afr Earth Sci 174:104077. https://doi.org/10.1016/j.jafrearsci.2020.104077
Kumar M, Ramanathan AL, Rao MS, Kumar B (2006) Identification and evaluation of hydrogeochemical processes in the groundwater environment of Delhi. India Environ Geol 50:1025–1039. https://doi.org/10.1007/s00254-006-0275-4
Kumara P, Johnsona BA, Dasguptaa R, Magcale-Macandogb DB, Pletob JV (2020) Groundwater quality in coastal oriental mindoro: results from 35 well samples. Sea (meter) 34(6220):979
Kwami I, Ishaku J, Hamza Y, Bello A, Mukkafa S (2019) Application of multivariate statistical techniques for the interpretation of groundwater Quality in Gombe and environs. North-East Nigeria J Geomat Geosci 7:9–14
Laferriere M (1996) Pollution agricole: l'industrie porcine et les risques reliés à la santé humaine. Vecteur Environ 29(3):27–31
Laghari AN, Siyal ZA, Bangwar DK, Soomro MA, Walasai GD, Shaikh FA (2018) Groundwater quality analysis for human consumption: a case study of Sukkur city, Pakistan. Eng Technol App Sci Res 8:2616–2620. https://doi.org/10.48084/ETASR.1768
Lanjwani MF, Khuhawar MY, Jahangir Khuhawar TM, Lanjwani AH, Jagirani MS, Kori AH, Rind IK, Khuhawar AH, Muhammad Dodo J (2020) Risk assessment of heavy metals and salts for human and irrigation consumption of groundwater in Qambar city: a case study. Geol Ecol and Landsc 4:23–39. https://doi.org/10.1080/24749508.2019.1571670
Ledesma-Ruiz R, Pasten-Zapata E, Parra R, Harter T, Mahlknecht J (2015) Investigation of the geochemical evolution of groundwater under agricultural land: a case study in northeastern Mexico. J Hydrol 521:410–423. https://doi.org/10.1016/j.jhydrol.2014.12.026
Li P, Qian H (2018) Water resources research to support a sustainable China. Int J Water Resour Dev 34(3):327–336. https://doi.org/10.1080/07900627.2018.1452723
Li P, Li X, Meng X, Li M, Zhang Y (2016) Appraising groundwater quality and health risks from contamination in a semiarid region of northwest China. Expo Health 8:361–379. https://doi.org/10.1007/s12403-016-0205-y
Li Y, Dong H, Li L, Tang L, Tian R, Li R, Chen J, Xie Q, Jin Z, Xiao J, Xiao S, Zeng G (2021) Recent advances in wastewater treatment through transition metal sulfides-based advanced oxidation processes. Water Res 192:116850. https://doi.org/10.1016/j.watres.2021.116850
Liu Y, Jiao JJ, Liang W, Kuang X, Table S, Table S, Figure S (2017) Supplemental materials for hydrogeochemical characteristics in coastal groundwater mixing zone. Appl Geochem 85:49–60. https://doi.org/10.1016/j.apgeochem.2017.09.002
Mahlknecht J, Merch'an D, Rosner M, Meixner A, Ledesma-Ruiz R (2017) Assessing seawater intrusion in an arid coastal aquifer under high anthropogenic influence using major constituents Sr and B isotopes in groundwater. Sci Total Environ. https://doi.org/10.1016/j.scitotenv.2017.02.137
Maman Hassan A, Fırat Ersoy A (2022) Hydrogeochemical and isotopic investigations on the origins of groundwater salinization in Çarşamba coastal aquifer (North Turkey). Environ Earth Sci 81:128. https://doi.org/10.1007/s12665-022-10248-5
Margat, J., 2008. L'eau des Méditerranéens : situation et perspectives, L'Harmattan Ed., coll. Prospective, série Prospective appliquée, Paris, pp. 1–288.
Marghade D, Malpe D, Zade A (2011) Geochemical characterization of groundwater from northeastern part of Nagpur urban. Central India Environ Earth Sci 62:1419–1430. https://doi.org/10.1007/s12665-010-0627-y
McCarthy MF (2004) Should we restrict chloride rather than sodium? Med Hypotheses 63:138–148. https://doi.org/10.1016/j.mehy.2003.11.005
Merchán D, Auqué L, Acero P, Gimeno MJ, Causapé J (2015) Geochemical processes controlling water salinization in an irrigated basin in Spain: identification of natural and anthropogenic influence. Sci Tot Environ 502:330–343. https://doi.org/10.1016/j.scitotenv.2014.09.041
Michard A, Chalouan A, Feinberg H, Goffé B, Montigny R (2002) How does the alpine belt end between Spain and Morocco? Bull Soc Géol Fr 173(1):3–15. https://doi.org/10.2113/173.1.3
Milnes E (2011) Process-based groundwater salinization risk assessment methodology: application to the Akrotiri aquifer (Southern Cyprus). J Hydrol 399(1–2):29–47. https://doi.org/10.1016/j.jhydrol.2010.12.032
Morán-Ramírez J, Ledesma-Ruiz R, Mahlknecht J, Ramos-Leal J (2016) Rock–water interactions and pollution processes in the volcanic aquifer system of Guadalajara, Mexico, using inverse geochemical modelling. Appl Geochem 68:79–94. https://doi.org/10.1016/j.apgeochem.2016.03.008
Morrison G, Fatoki O, Persson L, Ekberg A (2001) Assessment of the impact of point source pollution from the Keiskammahoek Sewage Treatment Plant on the Keiskamma River-pH, electrical conductivity, oxygen-demanding substance (COD) and nutrients. Water SA 27(4):475–480. https://doi.org/10.4314/wsa.v27i4.4960
Msaddek, M. H., Souissi, D., Moumni, Y., Chenini, I., Dlala, M., (2019) Multivariate statistical evaluation of groundwater recharge potential in arid region, Southern Tunisia. In Advances in sustainable and environmental hydrology, hydrogeology, hydrochemistry and water resources: Proceedings of the 1st Springer Conference of the Arabian Journal of Geosciences (CAJG-1), Tunisia 2018 (pp. 347–350). Springer. Cham https://doi.org/10.1007/978-3-030-01572-5_81
Mulec AO, Mladenovič A, Pranjić AM, Oprčkal P, Ščančar J, Milačič R (2020) Study of interferences and procedures for their removal in the spectrophotometric determination of ammonium and selected anions in coloured wastewater samples. Anal Methods 12(39):4769–4782. https://doi.org/10.1039/D0AY01361G
Negro F, Agard P, Goffé B, Saddiqi O (2007) Tectonic and metamorphic evolution of the Temsamane units, external Rif (northern Morocco): implications for the evolution of the Rif and the Betic-Rif arc. J Geol Soc 164(4):829–842. https://doi.org/10.1144/0016-76492006-112
Neisi A, Mirzabeygi M, Zeyduni G, Hamzezadeh A, Jalili D, Abbasnia A, Yousefi M, Khodadadi R (2018) Data on fluoride concentration levels in cold and warm season in city area of Sistan and Baluchistan province. Iran Data Brief 18:713–718. https://doi.org/10.1016/j.dib.2018.03.060
Olasehinde P, Amadi A, Dan-Hassan M, Jimoh M, Okunlola I (2015) Statistical assessment of groundwater quality in Ogbomosho Southwest Nigeria. Am J Min Metall. 3:21–28. https://doi.org/10.12691/ajmm-3-1-4
Ouarani M, Bahir M, Mulla DJ, Ouazar D, Chehbouni AG, Dhiba D, Ouhamdouch S, El Mountassir O (2020) Groundwater quality characterization in an overallocated semi-arid coastal area using an integrated approach: case of the Essaouira basin, Morocco. Water. https://doi.org/10.3390/w12113202

Ouhamdouch S, Bahir M, Ouazar O (2021) Seawater intrusion into coastal aquifers from semiarid environments, case of the alluvial aquifer of Essaouira basin (Morocco). Carbonates Evaporites 36:1–12. https://doi.org/10.1007/s13146-020-00663-9

Panaskar D, Yedekar D, Deshpande S (2007) Assessment of groundwater quality of Nanded city. Maharashtra Gondwana Geol Mag 11:77–86

Panteleit, B., Kessels, W., Kantor, W., Schulz, H.D., (2001). Geochemical characteristics of salinization-zones in the coastal aquifer test field (CAT-Field) in North-Germany. First International Conference on Saltwater Intrusion and Coastal Aquifers, p. 11. May 2014.

Piper AM (1944) A graphic procedure in the geochemical interpretation of water-analyses. Eos Trans Am Geophys Union 25(6):914–928

Qasemi M, Afsharnia M, Farhang M, Bakhshizadeh A, Allahdadi M, Zarei A (2018a) Health risk assessment of nitrate exposure in groundwater of rural areas of Gonabad and Bajestan. Iran Environ Earth Sci 77(551):6. https://doi.org/10.1007/s12665-018-7732-8

Qasemi M, Farhang M, Biglari H, Afsharnia M, Ojrati A, Khani F, Zarei A (2018b) Health risk assessments due to nitrate levels in drinking water in villages of Azadshahr, northeastern Iran. Environ Earth Sci 77:1–9. https://doi.org/10.1007/s12665-018-7973-6

Qin R, Wu Y, Xu Z, Xie D, Zhang C (2013) Assessing the impact of natural and anthropogenic activities on groundwater quality in coastal alluvial aquifers of the lower Liaohe river plain, NE China. J Appl Geochem 31:142–158. https://doi.org/10.1016/j.apgeochem.2013.01.001

Rajesh R, Brindha K, Elango L (2015) Groundwater quality and its hydrochemical characteristics in a shallow weathered rock aquifer of southern India. Water Qual Expo Health 7:515–524. https://doi.org/10.1007/s12403-015-0166-6

Rakib M, Sasaki J, Matsuda H, Quraishi SB, Mahmud MJ, Bodrud-Doza M, Ullah AA, Fatema KJ, Newaz MA, Bhuiyan MA (2020) Groundwater salinization and associated cocontamination risk increase severe drinking water vulnerabilities in the southwestern coast of Bangladesh. Chemosphere 246:125646. https://doi.org/10.1016/j.chemosphere.2019.125646

Ramesh K, Elango L (2012) Groundwater quality and its suitability for domestic and agricultural use in Tondiar river basin, Tamil Nadu. India Environ Monit Assess 184:3887–3899. https://doi.org/10.1007/s10661-011-2231-3

Razowska-Jaworek L (2014) Calcium and magnesium in groundwater: occurrence and significance for human health, 1st edn. CRC Press, Taylor & Francis Group, London

Re V, Sacchi E, Martin-Bordes J, Aureli A, El Hamouti N, Bouchnan R, Zuppi G (2013) Processes affecting groundwater quality in arid zones: the case of the Bou-Areg coastal aquifer (North Morocco). Appl Geochem 34:181–198. https://doi.org/10.1016/j.apgeochem.2013.03.011

Rochdane S, Elgettafi M, El Mandour A, Himi M, Casas A, Daafi Y, Karroum M, Chouikri I (2022) Contribution of electrical resistivity tomography in the study of aquifer geometry and groundwater salinization of Eastern Haouz and upstream Tassaout domain. Morocco Environ Earth Sci 81(4):1–17. https://doi.org/10.1007/s12665-022-10246-7

Rodier J, Legube B, Merlet N (2009) L'analyse de l'eau; Eaux naturelles, eaux résiduaires, eau de mer, 9ème. Dunod, Paris

Saidi S, Hosni S, Mannai H, Jelassi F, Bouri S, Anselme B (2017) GIS-based multicriteria analysis and vulnerability method for the potential groundwater recharge delineation, case study of Manouba phreatic aquifer. NE Tunisia Environ Earth Sci 76:1–20. https://doi.org/10.1007/s12665-017-6840-1

Sajilkumar PJ, James EJ (2016) Identification of hydrogeochemical processes in Coimbatore district, Tamil Nadu. India Hydrol Sci J 61(4):19–31. https://doi.org/10.1080/02626667.2015.1022551

Sathish Mohan B, Jagadeesh Babu M, Jhansi Rani S, SatyaSree G (2017) Water quality assessment of groundwater samples in Bobbili region, Andhrapadesh. India Asia J Sci Technol 8(8):5223–5230

Sawyer CN, Mccarty PL (1967) Chemistry for sanitary engineers, 2nd edn. McGraw-Hill, New York

Selvaraju R, Anitha BM, Anandalakshmi K (2022) Correlation and regression analysis to determine the percentage existence of physicochemical parameters on electrical conductivity in the industrial area drinking water around Cuddalore old town, Tamilnadu. Int J Cur Res Rev. https://doi.org/10.31782/ijcrr.2022.14402

Shiklomanov IA (2000) Appraisal and assessment of world water resources. Water Int 25(1):11–32. https://doi.org/10.1080/02508060008686794

Simoes M (2003) On the hydrogeology of the Lower Tagus Basin and its Cenozoic geologic evolution. Ciências Terra Rev Univ Nova de Lisboa 15:239–248

Slama F, Nasri N, Bouhlila R (2022) Delineating the origins and processes of groundwater salinization and quality degradation in a coastal irrigated plain, Korba (Northeastern Tunisia). Mar Pollut Bull 181:113914. https://doi.org/10.1016/j.marpolbul.2022.113914

Su H, Kang W, Xu Y, Wang J (2017) Evaluation of groundwater quality and health risks from contamination in the north edge of the loess plateau, Yulin city Northwest China. Environ Earth Sci 76:467. https://doi.org/10.1007/s12665-017-6781-8

Taiwo A, Adeogun A, Olatunde K, Adegbite K (2011) Analysis of groundwater quality of hand-dug wells in peri-urban area of Obantoko, Abeokuta, Nigeria for selected physico-chemical parameters. Pac J Sci Technol 12(1):527–534

Talhaoui A, Aberkan M, Brahim I, El Mouraouah A (2005) Risques géologiques et activité sismique dans la région d'Al Hoceima (Maroc): Approche de la quantification des facteurs responsables du déclenchement des instabilités de terrain geological hazards and seismic activity within the area of Al Hoceima (Morocco): approach of quantifying factors responsible for the triggering of the ground instabilities. Pangea Infos, Société Géologique De France 43(44):3–18

Tiwari AK, Singh AK (2014) Hydrogeochemical investigation and groundwater quality assessment of Pratapgarh district. Uttar Pradesh J Geol Soc India 83:329–343. https://doi.org/10.1007/s12594-014-0045-y

Valdes D, DuPont JP, Laignel B, Ogier S, Leboulanger T, Mahler BJ (2007) A spatial analysis of structural controls on Karst groundwater geochemistry at a regional scale. J Hydrol 340(3–4):244–255. https://doi.org/10.1016/j.jhydrol.2007.04.014

Van Der Aa M (2003) Classification of mineral water types and comparison with drinking water standards. Environ Geol 44:554–563. https://doi.org/10.1007/s00254-003-0791-4

Verma A, Yadav BK, Singh NB (2021) Hydrochemical exploration and assessment of groundwater quality in part of the Ganga-Gomti fluvial plain in northern India. Groundw Sustain Dev 13:100560. https://doi.org/10.1016/j.gsd.2021.100560

Wagh VM, Panaskar DB, Varade AM, Mukate SV, Gaikwad SK, Pawar RS, Muley AA, Aamalawar ML (2016) Major ion chemistry and quality assessment of the groundwater resources of Nanded tehsil, a part of southeast Deccan Volcanic province, Maharashtra. India Environ Earth Sci 75:1418. https://doi.org/10.1007/s12665-016-6212-2

WHO (2011) Guidelines for drinking water quality, 3rd edn. WHO chronicle, Geneva, pp 1–688

Wu J, Sun Z (2016) Evaluation of shallow groundwater contamination and associated human health risk in an alluvial plain impacted by agricultural and industrial activities, mid-west China. Expos Health 8:311–329. https://doi.org/10.1007/s12403-015-0170-x

Yin Z, Luo Q, Wu J, Xu S, Wu J (2021) Identification of the long-term variations of groundwater and their governing factors based on hydrochemical and isotopic data in a river basin. J Hydrol 592:125604. https://doi.org/10.1016/j.jhydrol.2020.125604

Zabala ME, Martínez S, Manzano M, Vives L (2016) Groundwater chemical baseline values to assess the recovery plan in the Matanza-Riachuelo river basin. Argentina Sci Total Environ 541:1516–1530. https://doi.org/10.1016/j.scitotenv.2015.10.006

Zhai Y, Lei Y, Wu J, Teng Y, Wang J, Zhao X, Pan X (2017a) Does the groundwater nitrate pollution in China pose a risk to human health? A critical review of published data. Environ Sci Pollut Res 24:3640–3653. https://doi.org/10.1007/s11356-016-8088-9

Zhai Y, Zhao X, Teng Y, Li X, Zhang J, Wu J, Zuo R (2017b) Groundwater nitrate pollution and human health risk assessment by using HHRA model in an agricultural area, NE China. Ecotoxicol Environ Saf 137:130–142. https://doi.org/10.1016/j.ecoenv.2016.11.010

Zilberbrand M, Rosenthal E, Shachnai E (2001) Impact of urbanization on hydrochemical evolution of groundwater and on unsaturated-zone gas composition in the coastal city of Tel Aviv Israel. J Contam Hydrol 50(3–4):175–208. https://doi.org/10.1016/S0169-7722(01)00118-8