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ORIGINAL ARTICLE

Comparative Study of Two Ferruginous Thermal Sources, Carbogaseous in the Eastern Rif, Morocco

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Abstract

Morocco possesses a valuable thermal heritage, particularly in the eastern region where numerous springs could constitute appreciable wealth due to the therapeutic properties of their waters. While some thermal springs attract interest, the majority remain largely underexploited. It is in this context that our study specifically focuses on the characteristics of two thermal springs, Ain Hamra and Ain El Haouamed. This selection is driven by the lack of scientific research on the Ain Hamra source and the absence of previous studies on the Ain El Haouamed source, making our research a pioneering initiative in this region. Water samples were collected seasonally during the years 2021 and 2022. The results indicate that the waters from both sources are hypothermal, with an acidic potential of Hydrogen ion (pH). These waters are rich in minerals, characterized by high concentrations of iron, reaching 5.10 mg/L in Ain El Haouamed and 1.75 mg/L in Ain Hamra. Additionally, they exhibit a high carbon dioxide content, measured at 935.83 mg/L in Ain El Haouamed and 803.28 mg/L in Ain Hamra. These special waters are beneficial for health. However, the high presence of certain elements can make them unsuitable for uncontrolled human consumption. Therefore, rigorous monitoring of the quality of these waters is of crucial importance. In this article, we have presented the characteristics of the waters from two sources, which are part of the valuable water resources that Morocco enjoys.

Keywords Thermal source · Ain El Haouamed · Ain Hamra · Therapeutic effect · Physico-chemical quality · Geological study

1 Introduction

Thermal sources are widely distributed across the entire world and have attracted great attention due to their potential therapeutic effects, which vary according to the characteristics of their waters. Many studies have been conducted globally to examine the physicochemical, bacteriological, and therapeutic characteristics of thermal waters [1–6]. They are extensively used for the treatment of many diseases. Thermal therapy is considered the ultimate natural medicine, combining several techniques, including both internal treatments, such as drinking cures found in almost all thermal spa resorts, and external treatments like baths, showers, inhalations, gargles, massages, mud treatments, etc. It has shown effective results in treating various pathologies [7–14]. Such as allergies, asthma, osteoarthritis, rheumatism, venous problems, depressive states, overweight, Intestinal Inflammation. Since 1986, the World Health Organization (WHO) has conferred official status on the International Federation of Thermalism and recognized thermal medicine's essential role by granting it genuine scientific validity [15]. In Morocco, there are several thermal sources with therapeutic properties of first quality, most of which are concentrated in the north of the country, central Morocco, Pre Rif, South Rif furrow and north-eastern Morocco [16], there is a noticeable lack of research dedicated to examining the quality of

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their water. Few of the sources that have been the subject of study, such as Ain Hamra in the Taza region [17–19], Ain Mkbrta [20], Moulay Yacoub [21] and Sidi Hrazem [14] in the Fez region.

The imperative of conducting an in-depth study on thermal waters arises from the need to assess their potability, especially due to their widespread consumption by a significant portion of the population, without considering their quality. It is crucial to raise awareness about potential health risks associated with the long-term consumption of untreated thermal water. Our study also aims to confer increased recognition for regions housing these thermal springs, in the hope of having positive impacts on the local economy. Therefore, it is imperative to pay heightened attention to the thermal sector, following the example of other nations that consistently prioritize it [22]. Our contribution to the advancement of scientific knowledge and a comprehensive understanding of the properties of thermal waters in Morocco is manifested through the implementation of a physico-chemical and hydrogeochemical study of these two ferruginous- carbogaseous sources located in the eastern region of Morocco.

2 The Geographical and Geological Framework of the Ain Hamra and Ain El Haouamed Sources

The Eastern Moroccan region contains a considerable number of thermal sources; more than 50% of them are located in the eastern Rif, such as: Ain Chifaa, Ain Zahra, Ain Hamra, Ain El Haouamed [23, 24]. The study area is characterized by short, hot, generally arid summers and long, cold, and partly cloudy winters. The Ain Hamra Thermal Source is located in the province of Taza exactly 1 km from the provincial road linking Aknoul to Bourd and a few kilometers from Ajdir (Fig. 1). Its Global Positioning System (GPS) coordinates (X = 03° 56′ 45″ West and Y = 34° 44′45″ North). The influx of people to the source of Ain Hamra has resulted in the emergence of a village of about 4403 inhabitants (High Commission for Planning (HCP) 2019). It is locally called Ain Arrahma (source of mercy) because of its therapeutic properties. The second thermal source of Ain El Haouamed is located in the Oriental Moroccan region, more exactly north of the city Guercif exactly 500 m from the provincial road linking Saka to Guercif. The GPS coordinates are X = 03° 21′ 05″ W and Y = 34° 35′ 15″ N (Fig. 1).

Fig. 1 Localization of the two sources: Ain El Hamra and Ain El Haouamed Source Google Eart)

2.1 Ain Hamra Source

The Ain Hamra region belongs to the Meso-Rifan and intra-Rifan units of the external Rifan domain. This region is called a "window zone" [25, 26]. The Rif units or units of intra-Rif origins such as Aknoul, Bouhaddoud and Taïneste, are completely uprooted units which rest on the autochthonous mesorifan (the olistostrom pre-rifan) and partly cover the internal Prerif in the eastern Rif. It includes at its stratigraphic base black pelites of Apto-Albian age and Cenomanian marl-limestones. The Turonian perhaps, and in any case the Senonian are represented by blue marls with calcareous loaves at Globotruncana. The top of the Eocene column consists of massive Upper Eocene limestones and marls that contain conglomeratic horizons (Fig. 2).

2.2 Ain El Haouamed Source

This thermal source is located at the limit of the Eastern External Prerif presenting gravitational layers with a marly-sandy matrix of Upper Miocene age (Benyaich, 1991) [28] and its foreland the Guercif basin, which is a Neogene basin (Miocene -pliocene) (Figs. 2, 3). Through the contact between the external Prerif and the basin, a diapir of red saliferous clays of Triassic age rises which outcrops on the surface in the form of a breccia containing conglomerates, salt, shale's and clays.

3 Materials and Methods

3.1 Sampling

The sampling was done seasonally during the years 2021–2022, in accordance with International Organization

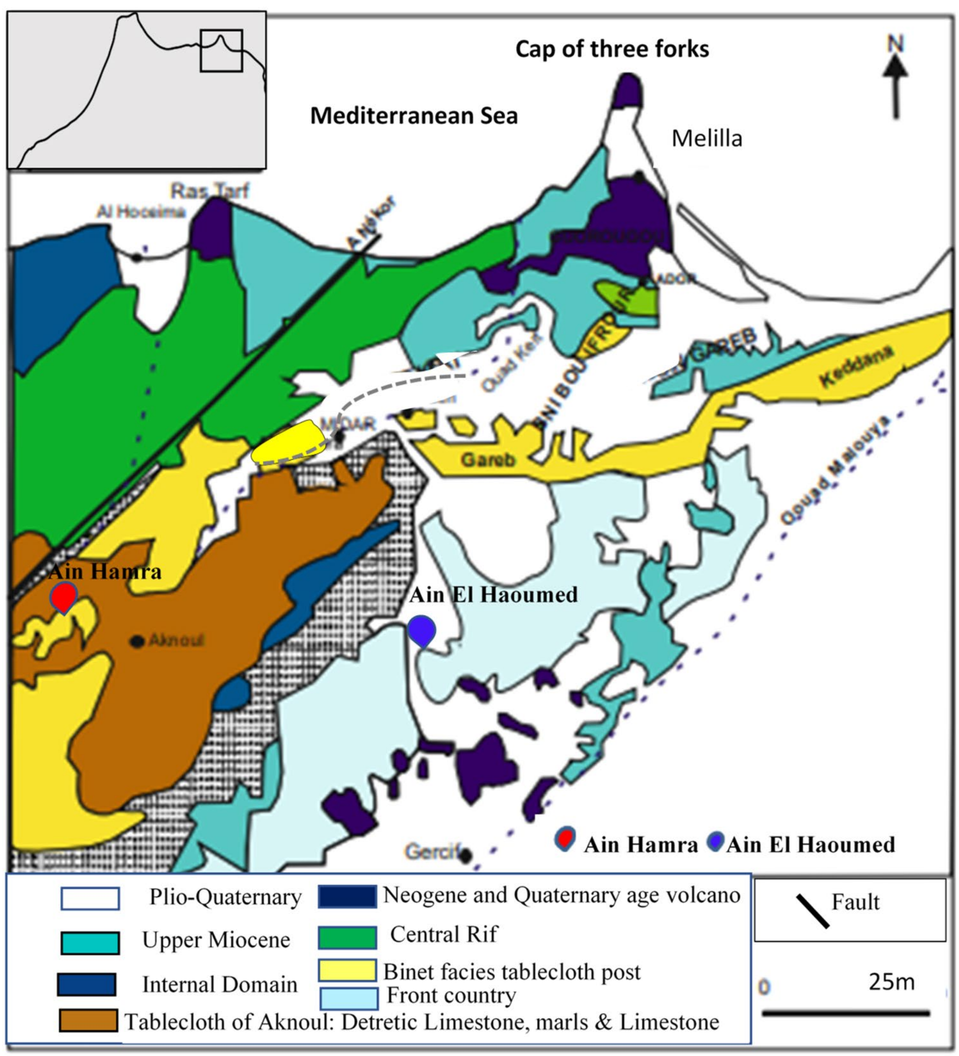

Fig. 2 The geological map of the Eastern Rif. After Frizon de Lamotte, 1985 [18, 27], redrawn and modified

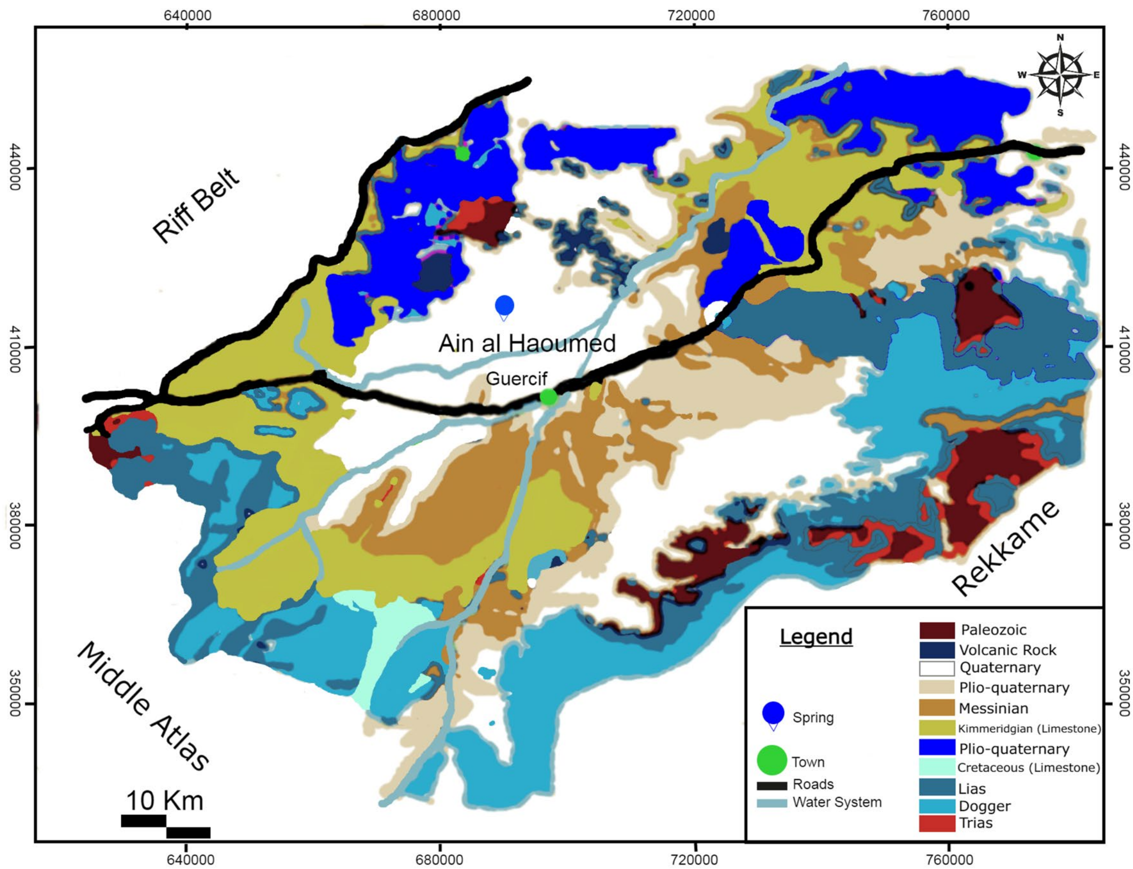

Fig. 3 The geological map of the Guercif basin and its surrounding borders (Colo., 1961) [29]

for Standardization (ISO) 5667-3:2016 standards, which establish the general requirements for sampling, preservation, handling, transport, and storage of all samples [30]. The water samples were collected from two sources (Fig. 4) and placed into 500 mL plastic bottles. To maintain sample integrity, they were stored in an isothermal enclosure at a temperature of 5 ± 3 °C and promptly transported to the laboratory, where they were analyzed within 24 h of collection to ensure accurate and reliable results. Additionally, some parameters, such as pH, electrical conductivity, and temperature are measured directly in situ.

3.2 Physico-Chemical Analysis

The physico-chemical study focused on the analysis of various parameters of the water. On-site measurements were conducted for pH, electrical conductivity, and temperature using a multiparameter Waterproof Meter analyzer, Type HANNA Instruments. For certain major elements, including Turbidity, Hardness, Ammonium (NH_4^+), Nitrates (NO_3^-), Nitrite (NO_2^-), Ortho phosphate (PO_4^{3-}), Silica (SiO_2), Sulfate (SO_4^{2-}), Chlorides (Cl^-), Bicarbonate (HCO_3^-), Calcium (Ca), Magnesium (Mg), Carbon dioxide (CO_2) and total Nitrogen (N_2), the measurements were carried out in the laboratory according to the standards recorded in Table 1. Additionally, the assessment of metal content, including Fe (Iron), Na^+ (Sodium), K^+ (Potassium), Al (Aluminum), Li (Lithium), Mn (Manganese), Ni (Nickel), and Sr (Strontium), was conducted using the ICP technique (Inductively Coupled Plasma Spectrometry). This analysis was carried out at the innovation city of Fez.

4 Results and Discussion

4.1 Hydrogeological Interpretations

All the collected data are the subject of a hydro-chemical study with the aim of describing the composition of the waters studied according to the chemical classification. From a graphic representation of these data, several representations can be used, among which are the Piper diagram, the Schöeller-Berkaloff semi-logarithmic diagram, the Stiff diagram, the radiant coordinate diagram, and others.

For our study, the triangular diagram of Piper was used to identify this classification. It makes it possible to illustrate

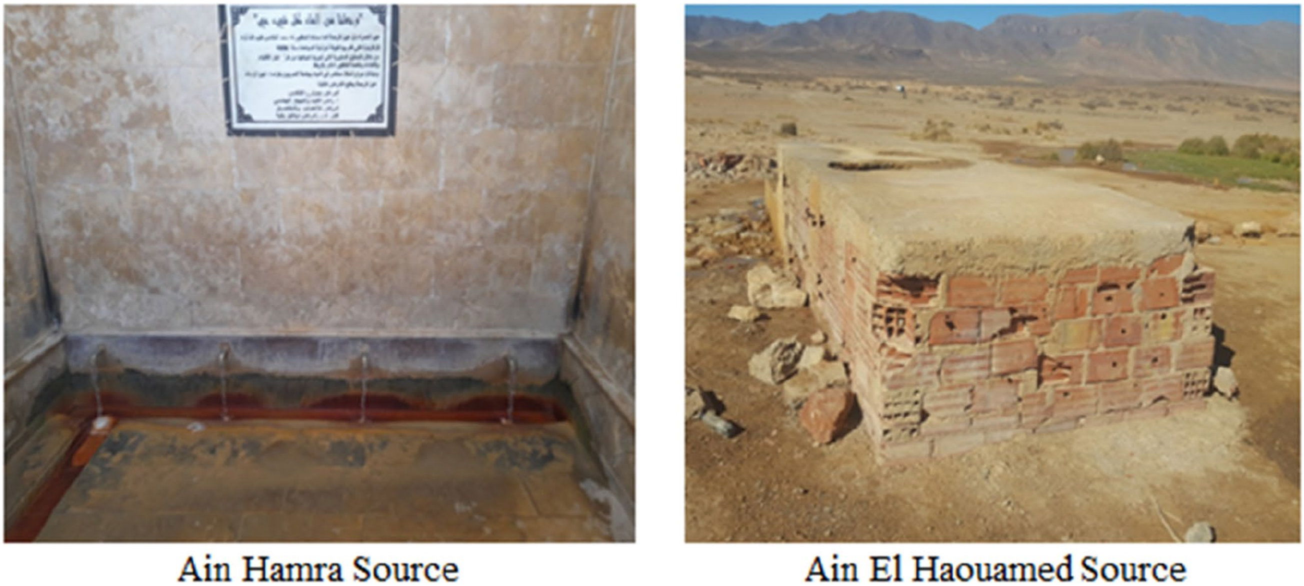

Fig. 4 Pictures of both Sources: Ain Hamra and Ain El Haouamed

Table 1 Physico-chemical water analysis methods

Parameter	References of analyzes methods	Brand and model of instruments
Hydrogen potential (pH)	Moroccan standards (NM) ISO 10523 Version 2012	pH meter HQ411d Type HACH
Electrical Conductivity	NM ISO 7888 V 2001	Conductivity Meter HQ430d Type HACH
Turbidity	NM ISO 7027-1 V 2019	TurbidiMeter 2100N type HACH
Nitrate	Rodier and al 9th edition: Molecular absorption spectrometry method	Cary 60 UV–vis spectrophotometer type Agilent Technologies
Nitrites	French standards (NF) European standards (EN) 26777V 1993 Molecular absorption spectrometry method	Cary 60 UV–Vis spectrophotometer type Agilent Technologies
Ammonium	NM ISO 7150-1V 1999 Spectrometric method	Cary 60 UV–vis spectrophotometer type Agilent Technologies
Orthophosphate	NM ISO 6878V 2012 Ammonium molybdate spectrometric method	Cary 60 UV–vis spectrophotometer type Agilent Technologies
Silica	NF T90-007V 2001 Molecular absorption spectrometry method	Cary 60 UV–vis spectrophotometer type Agilent Technologies
dissolved oxygen	NF EN 25813V 1993 Iodometric method	–
Free CO_2	NM 03.7.031V 1995	–
total nitrogen	DPD (diethyl-p-phenylenediamine) method	KJELDAHL ANALYZER Type Gerhardt
Chlorides	NF ISO 9297V 2000 Silver nitrate titration with chromate as indicator (Mohr method)	–-
Sulphate	NF T90-040V 1986 Nephelometric method	Cary 60 UV–Vis spectrophotometer type Agilent Technologies
Calcium	NF T90-016V 1984 EDTA (Ethylenediaminetetra-acetic acid) Titrimetric Method	–
Hardness, Magnesium	NF T90-003V 1984 Water Tests: EDTA Titrimetric Method	–
Bicarbonate	NM ISO 9963-1V 2001	–
Metals: Fe, Na, K, Li, Mn, Sr, Al, Ni, Ca, Mg	NM ISO 11885V 2014 Determination of selected elements by spectroscopy Optical emission with high induced plasma frequency (ICP-AES)	Inductively Coupled Plasma Spectrometry

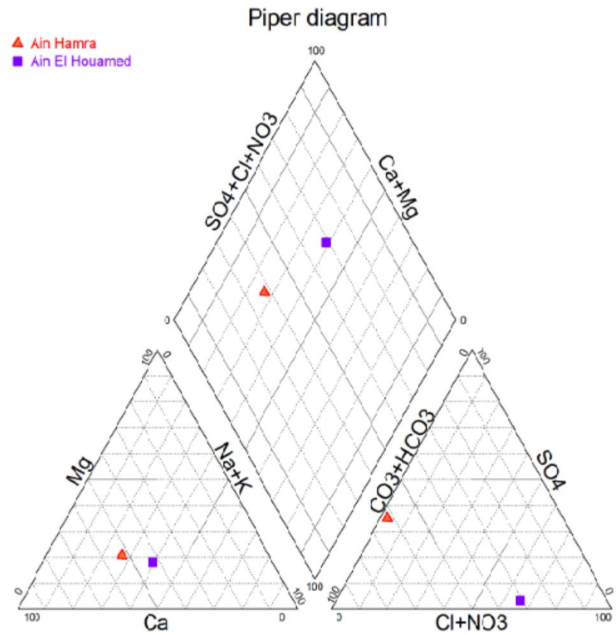

Fig. 5 Projection on the piper diagram of the waters studied analyses

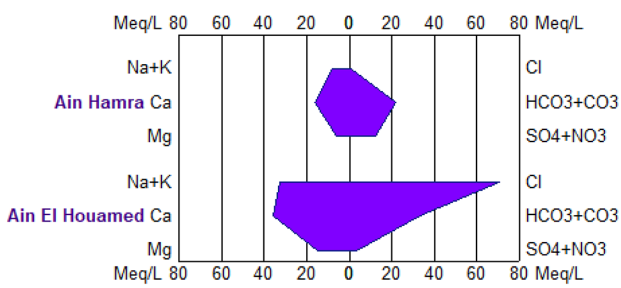

Fig. 6 Projection on the Stiff diagram of the waters studied analyses

the chemical evolution of water in an aquifer, as well as the mixtures of waters of different mineralization, and to predict the lithology from chemical analyses. The representation of the results of chemical analyzes in the Piper diagram (Fig. 5) makes it possible to identify two families of water: a chlorinated and sulphated calcium and magnesium water for the Ain El Haouamed source, and calcium and magnesium bicarbonate water for the Ain Hamra source.

To compare the chemical compositions of the studied spring waters, the results were also represented using the Stiff diagram. This diagram involves constructing a polygon for each water sample, and the geometric shape of the polygon is determined by the content of the considered chemical elements. On the Stiff diagram (Fig. 6), the analytical data for the major ions are plotted on horizontal axes located on either side of the original vertical axis. Cations, including Na^+, K^+, Ca^{2+} and Mg^{2+}, are represented on the left side, while anions, including Cl^-, HCO_3^-, and SO_4^{2-}, are represented on the right side. According to the results presented in the stiff diagram (Fig. 6), two distinct families of spring waters can be observed: the calcic bicarbonate family, which corresponds to the chemical composition of the Ain Hamra spring water, and the calcic chloride family, representing the chemical composition of the El Haouamed spring water. The stiff diagram effectively demonstrates the differentiation between these two water sources based on their chemical compositions, providing valuable insights into the distinct characteristics of each spring.

4.2 Physico-Chemical Parameters

Thermal water is groundwater, which is not always suitable for human consumption. Depending on the composition, treatment may be necessary to make the water safe for drinking or other specific uses [31]. It differs from surface water, either by the presence of gas or mineral salts, or by an abnormally high temperature. Concerning the classification of thermal sources, it has been taken into consideration: the geological origin, the temperature of the emerging water, and its chemical composition.

4.2.1 Temperature

The main physical property of thermal water is its temperature when it is emerged, it affects almost all physical, chemical and biological mechanisms, it is highly variable from one source to another one. According to the different degrees of temperature, the waters are distinguished [32, 33].

- Hyperthermal with a temperature above 50°C;
- Mesothermal or thermal when the temperature is between 35 and 50 °C;
- Hypothermal when the temperature is between 20 and 35 °C;
- Cold when the temperature is below 20 °C.

The emergence temperatures of the thermal waters in the Eastern Rif region are between 24 and 43 °C (Table 2). The higher temperature recorded is that of the Yadim and also of the Kariat Arekman.

Table 2 Temperature of thermal sources of oriental Rif [17]

Sources	Hajra Safra	Ain Chifa	Ain Haddou	Ain Hamam	Arekman	Puits Yadim
Temperature (°C)	26	32	29	38.5	42	43

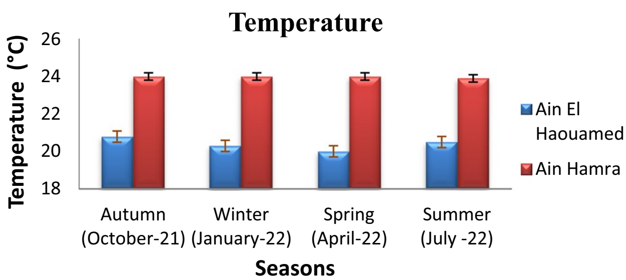

Fig. 7 Variation of temperature at different seasons

For our study, the evolution of the temperature is made according to the seasonal variability (Fig. 7) and we note that the temperature of Ain El Haouamed decreases slightly during the winter and the spring, and remains almost stable for the source Ain Hamra.

The average temperatures recorded for the sources Ain Hamra, and Ain El Haouamed are respectively 23.98 °C and 20.32 °C. So the studied sources are classified in the category of hypothermal waters.

4.3 Hydrogen Potential (pH)

Hydrogen potential (pH) measures the acidity of water. The determination of the pH value is based on measuring the potential difference of an electrochemical cell using a suitable pH meter. Hydrogen potential values are between 6 and 8.5 in natural waters [34]. This parameter characterizes a large number of physico-chemical balances and depends on multiple factors, including the water's origin [35]. For the waters studied, the average pH values are 6.8 for the Ain El Haouamed source and 6.48 for the Ain Hamra source. The acidity of these waters is primarily attributed to their high mineralization and elevated CO_2 concentration [36].

The pH values of the waters of the Ain El Haouamed source show a slight decrease from 7 in autumn to 6.65 in summer. The highest pH value of the waters of Ain Hamra is recorded in winter (Fig. 8).

The recorded pH values conform to the stringent standards established for potable water by the World Health Organization (WHO), falling within the range of 6.5–8.5. Furthermore, the pH values documented for the investigated sources exhibit similarities to those observed in multiple thermal springs of the Eastern Rif, ranging from 6.1 to 7.25 [17].

4.3.1 Electrical Conductivity

The electrical conductivity of water is the conductance of a column of water between two metal electrodes with a surface area of 1 cm^2 and separated from each other by 1 cm. It depends on the concentration of ions and measures the capacity of the water to conduct electricity. Since most of the dissolved matter in water is in the form of electrically charged ions [37], the electrical conductivity increases in parallel with the temperature, which explains its high value for thermal waters [38].

The average conductivity value is very high in Ain El Haouamed, reaching 9793 µS/cm far exceeding national and international drinking water standards. On the other hand, Ain Hamra has an average conductivity of 2700 µS/cm, which is an acceptable value according to the Moroccan standard (NM 03.7.001), but it greatly exceeds international standards, which are around 1500 µS/cm (WHO). The electrical conductivity values for the studied sources are higher than that of Moulay Yacoub, which is around 48,250 µS/cm, and Sidi Hrazem, which is equal to 1370 µS/cm [39]. They exhibit similarities to those observed in several thermal springs of the Eastern Rif [17].

The results obtained allow us to conclude that the waters of the two sources studied are highly mineralized. These strong mineralizations can be linked to the presence of geological formations containing evaporates [17]. As illustrated in Fig. 9, there is a limited degree of seasonal fluctuation in conductivity.

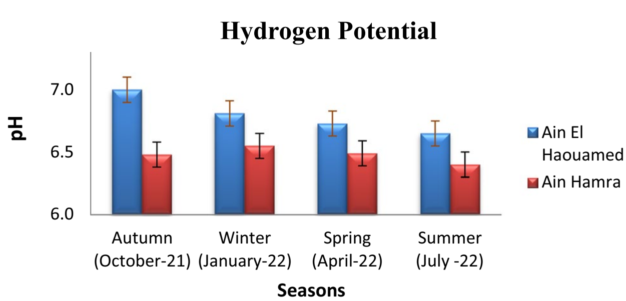

Fig. 8 Variation of hydrogen potential

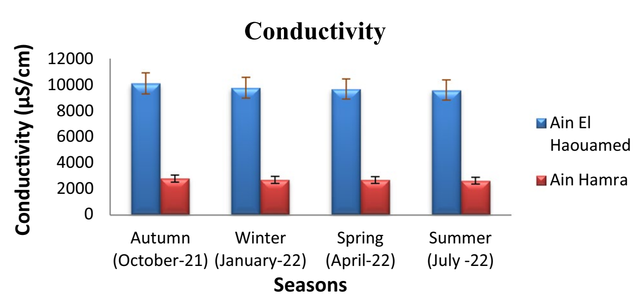

Fig. 9 Seasonal variation of electrical conductivity

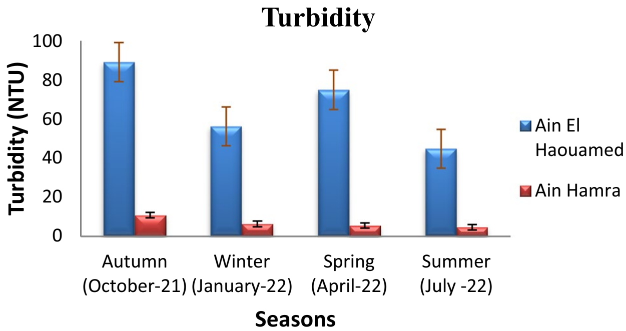

Fig. 10 Seasonal variation of turbidity

4.3.2 The Turbidity

The turbidity constitutes a very important physical parameter for water quality control; it refers to the amount of matter in a liquid that makes it cloudy due to solid and colloidal particles in suspension that absorb, diffuse, or reflect the light. High turbidity can allow micro-organisms to attach themselves to suspended particles.

As shown in Fig. 10, the average turbidity content recorded in Ain El Haouamed is 66 NTU (Nephelometric Turbidity Unit), higher than the value recorded for Ain Hamra, which is 6.8 NTU. According to the standards, the turbidity values recorded in Ain El Haouamed located in the turbid water range (> 50 NTU), while Ain Hamra has an average value located in the slightly turbid water range (between 5 and 30 NTU). The values obtained are greater than 5 NTU, so the two sources are not acceptable according to the Moroccan standard (NM 03.7.001).

The seasonal variations of turbidity for the two sources show two different episodes: an autumn period characterized by high values and a summer period characterized by relatively low values.

4.3.3 Hardness

Water hardness is the amount of calcium and magnesium dissolved in water. This is a volumetric titration of calcium and magnesium ions using an EDTA solution at a pH of 10. The hardness values found are 265 °F (French Degree) in Ain El Haouamed and 121.7 °F in Ain Hamra (Fig. 11). Therefore, the waters of the two sources are hard (because Hardness > 30 °F). This is attributed to the limestone nature of the geological terrains through which water passes, corresponding to the presence of a high concentration of calcium and magnesium [40]. These findings align with the results obtained by Taybi [18]. Regarding seasonal variations, they are not significant for the two sources.

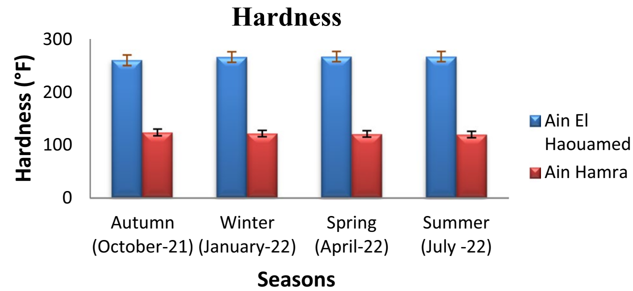

Fig. 11 Seasonal variation of hardness

4.3.4 Nutritional Elements

The concentrations of orthophosphate and nitrates in the two sources are insignificant.

The average nitrite concentrations, depicted in Fig. 12, measure 0.4 mg/L in Ain El Haouamed, surpassing the recorded value of 0.1 mg/L in Ain Hamra. This parameter exhibits high concentrations in autumn and summer and low concentrations in winter and spring.

The average ammonium concentration in Ain El Haouamed is 1.97 mg/L, which is higher than the recorded 0.45 mg/L in Ain Hamra. Regarding seasonal variations, they are not significant for the two sources.

The average total nitrogen value is 3.9 mg/L in Ain El Haouamed, higher than the recorded 0.49 mg/L in Ain Hamra. The seasonal variations of total nitrogen do not show any notable variations.

Nutrient levels based on nitrogen (nitrites, nitrates and ammonium) and phosphorus (orthophosphate and total phosphorus) are generally very low in the waters of the two sources studied. They are lower than the maximum values admissible by the drinking water standards. These low values indicate the absence of any source of pollution in Ain El Haouamed and Ain Hamra, justifying the very deep origins of their waters.

4.3.5 Silicas (SiO_2)

The average concentrations of silica are very high in the two sources; the recorded values are 25.75 mg/L in Ain El Haouamed and 32.50 mg/L in Ain Hamra (Fig. 13). These values significantly exceed the recorded levels for the most well-known sources in Morocco, Moulay Yacoub (14 mg/L), and Sidi Hrazem (4.5 mg/L) [39]. The formations surrounding the source are composed of clays, marls, and limestones and the main component of clay and marls is silica. This indicates significant interaction of water with the clayey Triassic and Marly formations of the Miocene during its passage.

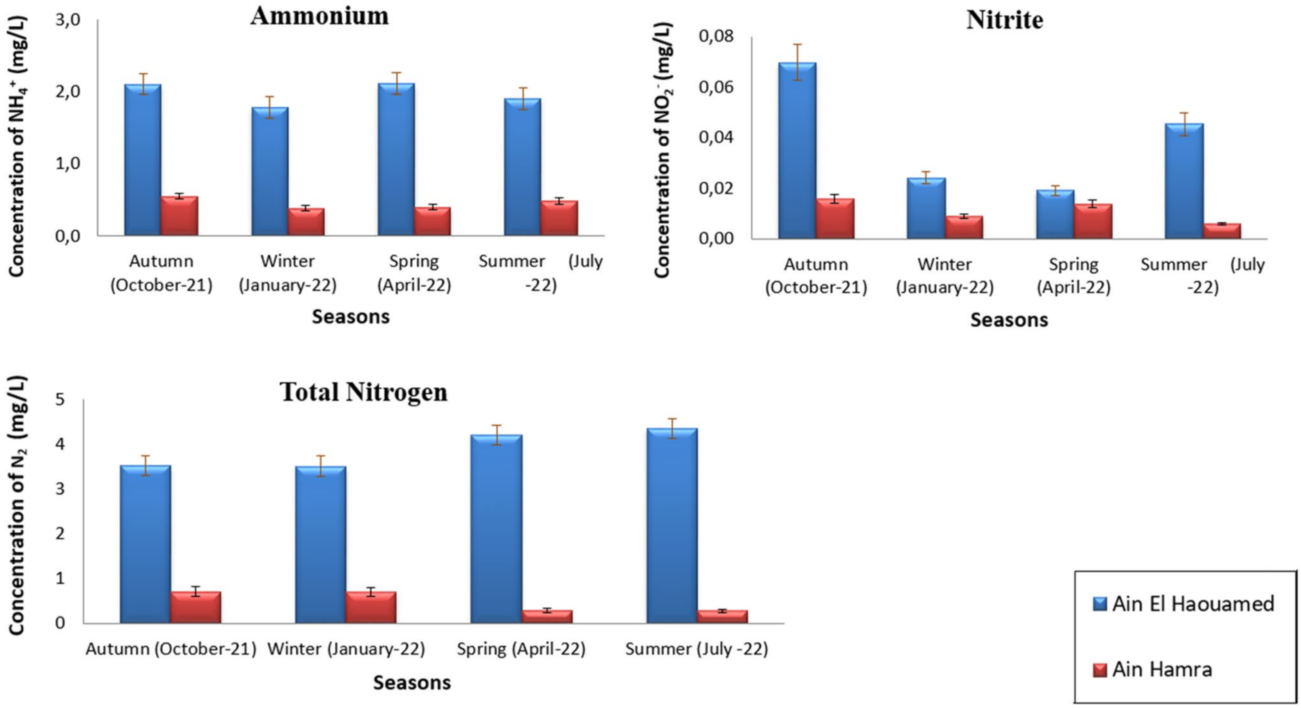

Fig. 12 Nitrogen-based nutrient variations

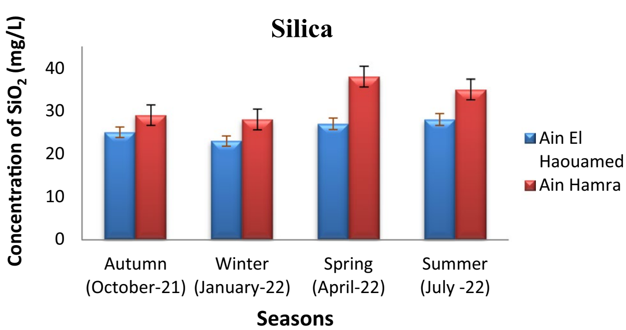

Fig. 13 Seasonal variations in silica content

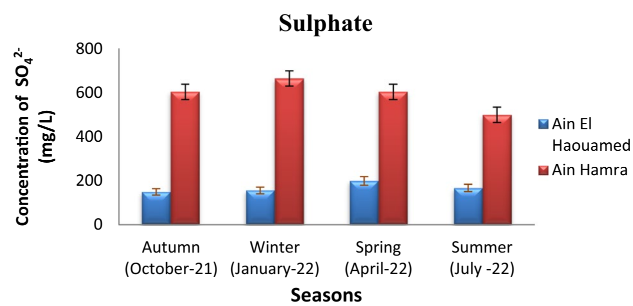

Fig. 14 Sulfate content variations

The silica content remains below the maximum value acceptable by Moroccan standards for drinking water. For both sources, the values recorded in spring and summer are higher than those recorded in autumn and winter.

4.3.6 The Sulphates

They are encountered either in magnesium sulphates form or calcium form in hard water. In general, the presence of sulphate in natural waters indicates the presence of gypsum or pyrite [41].

As represented in Fig. 14, the quantity of sulphate in the Ain El Haouamed source is equal to 167.75 mg/L, while Ain Hamra has an average value equal to 593.75 mg/L. The concentration recorded in sulphates in the waters of Ain Hamra greatly exceeds the acceptable limit values for water intended for human consumption. However, the concentration recorded in the water of Ain El Haouamed remains within the standards (Fig. 14). The obtained results fall within the range of sulfate concentrations observed in the thermal springs of the Eastern Rif, typically ranging between 28.2 and 709.10 mg/L [17].

The sulfate-rich water is known for its healing properties [42, 43], used for the treatment of kidney ailments and metabolic disorders. It is recommended for the treatment of eczema, scars and sequelae of burns, disorders of the digestive tract, disease of the hepatic tract, and also for the treatment of venous affections and rheumatism, as well as for intestinal problems.

4.3.7 Chlorides

The chloride content of natural waters is associated with that of sodium. The chloride concentration should not exceed 750 mg/L according to Moroccan standards and 250 mg/L according to the WHO.

The average chloride content is assembled in Fig. 15. In Ain El Haouamed, the average chloride content is extremely high: 2512.73 mg/L, while Ain Hamra contains a value not exceeding 30.93 mg/L. The chloride concentrations in thermal springs in Morocco vary significantly from one station to another [39]. Seasonal variations in chloride are not significant for the two sources (Fig. 15). The evolution of chlorides over the study period is similar to that of conductivity (the more the conductivity increases, the more the concentration of chlorides increases). This could be due to the regional geological nature [44]. Chlorinated waters have growth-stimulating effects, used for treatments of neurological conditions and developmental disorders.

4.3.8 Bicarbonates

Sodium bicarbonate, calcium bicarbonate, and mixed bicarbonate waters are of deep origin (volcanic region) [45], naturally carbonated if the concentration of carbon dioxide is greater than 250 mg/L.

For the waters studied, the variation of bicarbonate concentrations at different season are presented in Fig. 16. The bicarbonate concentrations are very high in the waters of both Ain El Haouamed (2032.83 mg/L) and Ain Hamra (1338.95 mg/L). This indicates that the waters of the studied sources are bicarbonate waters and have a great therapeutic effect on certain diseases [46]. Regarding seasonal variations, they do not affect the bicarbonate parameter of the two sources.

The bicarbonate concentration is higher than that recorded for several thermal waters in Morocco [39].

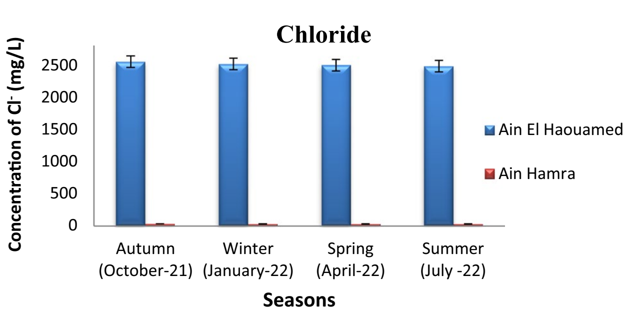

Fig. 15 Seasonal variations in chloride content

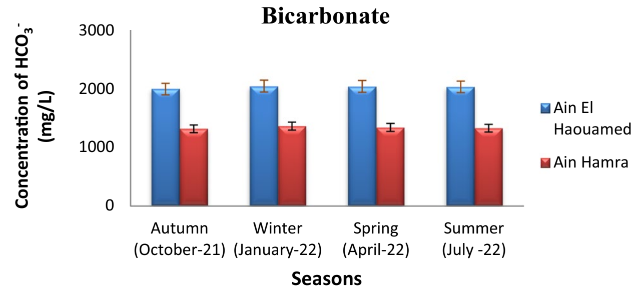

Fig. 16 Bicarbonates content variation at different seasons

4.3.9 Carbon Dioxide (CO_2)

The sources of Ain El Haouamed and Ain Hamra are rich in carbon dioxide, the average contents are respectively 935.83 mg/L and 803.28 mg/L (Fig. 17). The results are similar to those of certain sources in the eastern Rif region, which are characterized by their high carbon dioxide content [17].

These values indicate that these sources are naturally gaseous and can dissolve the rocks with which they come into contact, resulting in strong mineralization (magnesium, calcium, iron…), which explains the therapeutic quality of these two sources [46].

For both sources, the values recorded in spring and summer are higher than those recorded in autumn and winter. This leads to the conclusion that seasonal variations are insignificant due to disruptions in climatic conditions.

These carbonaceous waters can be rich in sodium, derived from the hydrolysis of plagioclases, as well as in calcium and magnesium resulting from the hydrolysis of ferromagnesian silicate minerals (olivine, micas, etc.) in the rocks [47].

4.3.10 Metals

The average concentration of iron presents a very high value in Ain El Haouamed and in Ain Hamra, as shown in Fig. 18, with concentrations of 5.10 mg/L and 1.75 mg/L respectively. This explains the red color of their waters.

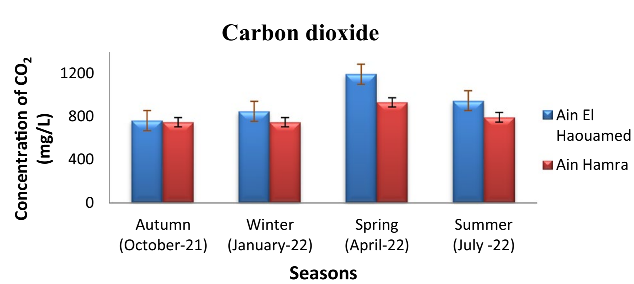

Fig. 17 Variations in carbon dioxide content

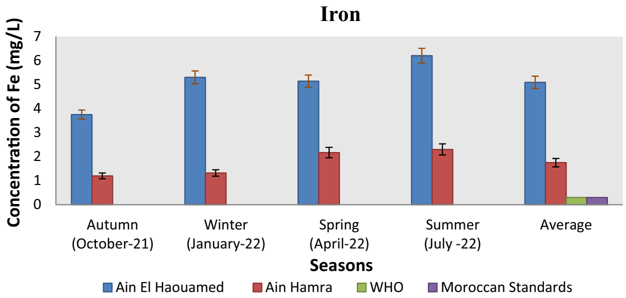

Fig. 18 Iron concentration at Ain El Haouamed, Ain Hamra compared with WHO and Moroccan standards

The latter are Ferruginous because the iron content is greater than 1 mg/L. Generally, the average concentration values measured in the two sources exceed the concentrations recommended by Moroccan and international standards (WHO) (Fig. 18). Concerning Ain Hamra source water, the results obtained agree with the values found by Taybi et al. [18].

The presence of iron in groundwater originates from various sources, and iron is generally associated with sedimentary rocks deposited in reducing environments (marls, clays) and with metamorphic rocks because it is often found in high concentrations in the waters of the cuirasses. basement alteration [48].

The average calcium content is very high in Ain El Haouamed (721.44 mg/L) comparing it with those of Ain Hamra (339.68 mg/L), this concentration is mainly due to water contact with carbonate rocks also with some igneous rocks [49]. The high calcium values explain the high mineralization of the waters of the sources studied (Fig. 19). Regarding the average concentration of magnesium found in Ain El Haouamed which is around 186.76 mg/L is very higher than that recorded in the waters of the Ain Hamra source (81.03 mg/L) (Fig. 19). The dissolution of carbonate rocks and magnesium minerals can be the origin of magnesium in the waters from two sources [49]. For the average sodium concentration, it is very higher in the water of Ain El Haouamed (720.45 mg/L) than in the water of Ain Hamra (195.09 mg/L) (Fig. 19). We notice that the source with the highest sodium value, Ain El Haouamed, also has a high

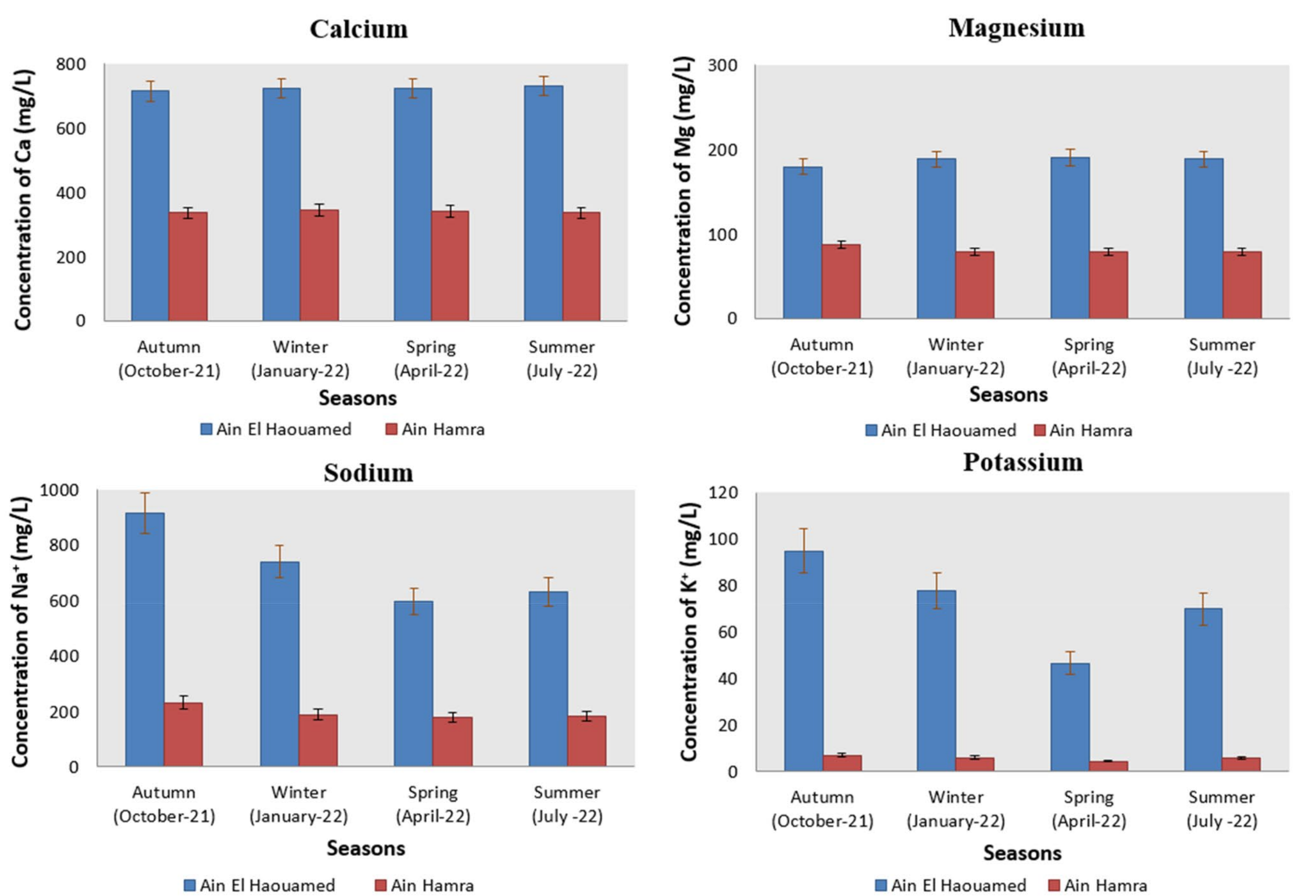

Fig. 19 Variations in metals content

chloride content. This phenomenon is due to the capture of water by the NaCl contained in the salt diapirs of the Triassic clay. The average concentration of potassium has a value of 72.23 mg/L high in Ain El Haouamed whereas for Ain Hamra, the average value is lower, around 5.89 mg/L (Fig. 19). Potassium is an element mainly found in igneous rocks and clays.

Strontium concentrations are found in the order of 9.80 mg/L and 16.15 mg/L in Ain El Haouamed and Ain Hamra.

The concentrations of lithium and manganese present very high values in Ain El Haouamed (2.39 mg/L of Li and 0.72 mg/L of Mn), compared with those of Ain Hamra (0.15 mg/L of Li and 0.08 mg/L of Mn).

The waters of the two sources generally have very low concentrations (less than 0.01 mg/L) of certain metals Cr; Cu; Ni; Al.

5 Conclusion

The present study focuses on two thermal water sources, namely Ain El Haouamed and Ain Hamra, emphasizing the diversity of factors that impart uniqueness to the studied waters. According to the obtained results, it is observed that the studied thermal waters are hypothermal, with an acidic pH and distinctive physicochemical characteristics. They are hard, and have high electrical conductivity, with reduced levels of silica, nitrogen, and phosphorus. Both sources provide ferruginous waters, with iron concentrations exceeding national and international drinking water standards. The high concentrations of carbon dioxide classify them as carbonated waters, conferring therapeutic properties, especially for the treatment of anemia, digestive disorders, and skin issues, and they may be used for the prevention and treatment of cardiovascular diseases.

The high concentration of chlorides, sodium, and sulfates in the thermal waters of the Ain El Haouamed source can be attributed to contact with the saliferous terrigenous formations and through base exchange with Triassic red clay (Diapir) at the contact zone between the eastern Rif and its front-country. On the other hand, the Ain Hamra source is a thermal spring rich in bicarbonates, calcic, and manganese metals. The variation in hydrogeochemical facies is primarily attributed to the geological nature of the traversed terrain and the emergence of water through faults. The waters of both studied sources exhibit considerable levels of metallic elements, indicating a deep crystalline circulation. The Seasonal variations are not significant due to the disturbance of meteorological conditions in Morocco.

The results obtained indicate the crucial importance of these two springs, fully justifying the need to deepen scientific research to reveal their benefits both therapeutically and economically. This is in line with other countries, such as France, which strategically utilize thermal springs for individual well-being, economic and tourism gains. Renowned thermal stations like Vichy, Avène and La Roche, exemplify this integrated approach. The recognition of this value emphasizes the necessity to persist in research for a deeper understanding and for the exploitation of the therapeutic and economic potentials inherent in these precious resources.

In order to prevent any health risks associated with the consumption of untreated water from these two sources, we have planned to incorporate a microbiological study into our perspectives.

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Declarations

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

References

1. Farhat N, Hussain S, Faisal F, Batool I, Noreen M (2021) Physico-chemical characteristics and therapeutic potential of Chutrun thermal springs in Shigar Valley, Gilgit-Baltistan (Pakistan). Appl Water Sci 11:19
2. Juncosa Rivera R, MeijideFailde R, Delgado Martin J (2019) Therapeutic characteristics of Galician mineral and thermal waters (NW-Spain) ascribed to their local/regional geological setting. Sustain Water Resour Manag 5:83–99
3. Gebretsadik A, Taddesse F, Melaku N, Haji Y (2021) Balneotherapy for musculoskeletal pain management of hot spring water in Southern Ethiopia: perceived improvements. Inquiry 58:00469580211049063
4. Najar IN, Sharma P, Das S, Sherpa MT, Kumar S, Thakur N (2022) Bacterial diversity, physicochemical and geothermometry of South Asian hot springs. Curr Res Microb Sci 3:100125
5. Zhang F-Q, Liu J, Chen X-J (2023) Comparative analysis of bacterial diversity in two hot springs in Hefei China. Sci Rep 13:5832
6. Duangjit S, Somsuwan B, Inpeng S, Buddhisa S, Bumrungthai S (2022) The specific properties of phusang hot spring water: safety and benefits. Cosmetics 9:89
7. Dogliotti G, Galliera E, Iorio E, De Bernardi-Di-Valserra M, Solimene U, Corsi MM (2011) Effect of immersion in CO2-enriched water on free radical release and total antioxidant status in peripheral arterial occlusive disease. Int Angiol 30:12
8. Cacciapuoti S, Luciano MA, Megna M, Annunziata MC, Napolitano M, Patruno C, Scala E, Colicchio R, Pagliuca C, Salvatore P (2020) The role of thermal water in chronic skin diseases management: a review of the literature. J Clin Med 9:3047

9. Gabriela D, Alexandru R (2015) Therapeutic effects of carbonated mineral waters in cardiovascular rehabilitation. Balneo Res J 6:39–43
10. Mourelle ML, Gómez CP, Legido JL (2023) Hydrobiome of thermal waters: potential use in dermocosmetics. Cosmetics 10:94
11. Benziada M (2022) The hot springs of central northern Algeria hydro geochemical and therapeutic aspects: direct applications and therapeutic value. Geothermal energy. InTech, London, pp 1–4
12. Mao S, Xiao K, Zhou W, Xu H, Zhang S (2023) The impact of hot spring hydrotherapy on pain perception and dysfunction severity in patients with chronic low back pain: a systematic review and meta-analysis. J Pain Res 16:3925–3944
13. Barnich N, Rodrigues M, Sauvanet P, Chevarin C, Denis S, Le Goff O, Faure-Imbert D, Hanh T, Roques CF, Chassaing B, Alric M (2021) Beneficial effects of natural mineral waters on intestinal inflammation and the mucosa-associated microbiota. Int J Mol Sci 22:4336
14. Mohim M, Kachkoul R, El Habbani R, Lahrichi A, SqalliHoussaini T (2022) In vitro effect of Sidi Hrazem mineral water on the dissolution of calcium oxalate monohydrate calculi (Whewellite). Sci Afr 16:e01187
15. Gaignot C (2006) Le thermalisme en question. Dossier de presse thermalisme-Thermalies, pp 1–11
16. Rimi A (2001) Gradient géothermique au Maroc. Bulletin de.l'Institut scientifique section Sciences de la Terre, pp 1–6
17. Benmakhlouf M (2001) Sources thermales du Maroc: relation entre le thermalisme et la tectonique. Thèse d'Etat
18. Taybi H, Bargach K, Boulfia M, Lamchouri F (2019) Etude géologique et qualités physico-chimique et bactériologique des eaux thermales de la source "Ain Hamra" de la Province de Taza (Rif Oriental-Maroc). J Water Environ Technol 4(1):443–451
19. El Morabiti K (2000) Contribution à la connaissance géologique, hydrochimique et isotopique des eaux thermales du Maroc septentrional
20 Mouchane M, Taybi H, Bargach K, Elmniai A (2023) Study of physico-chemical and bacteriological quality of water from Ain Mkbrta source in Morocco. E3S Web Conf 412:01033
21. Aitsi S, Ettaki J, Doumi K, Chabli A, Belghyti D (2022) Hydrogeochemical study of the Hamma My Yacoube, Sidi Slimane–Morocco. Lect Notes Netw Syst 393:657–670
22. Bignon Y-J (2022) COMMENT L'HISTOIRE DE LA MÉDECINE THERMALE A VICHY A CONDUIT À SON INSCRIPTION AU PATRIMOINE MONDIAL DE L'UNESCO. Presse Therm Clim 159:11–30
23. Jilali A, Chamrar A, El Haddar A (2018) Hydrochemistry and geothermometry of thermal water in northeastern Morocco. Geotherm Energy 6:1–16
24. Barkaoui AE, Zarhloule Y, Rimi A, Verdoya M, Bouri S (2014) Hydrogeochemical investigations of thermal waters in the northeastern part of Morocco. Environ Earth Sci 71:1767–1780
25. Marcais J, Van Leckwyck W (1936) Sur la géologie et les gisements de lignite de la plaine de Guercif. C.R.7ème Congr. Int. Mines, Méttal. et Géol. Appl., Paris,t.1, , pp 289–300
26. Frizon-de-Lamotte D, Nzaghloul M, Haissen F, Mohn G, Leprêtre R, Gimeno-Vives O, Atouabat A, El Mourabet M, Abassi A (2017) Rif externe: comment comprendre et expliquer le chaos apparent ? Géologues 194:13
27. Frizon De Lamotte D (1985) La structure du Rif Oriental (Maroc), [unpublished Ph. D. thesis] (Université Pierre et Marie Curie, Paris
28. Benyaich A (1991) Evolution tectono-sédimentaire du Rif externe centro-occidental (régions de M'sila et Ouezzane, Maroc): La marge africaine du Jurassique au Crétacé: Les bassins néogènes d'avant-fosse. Thèse d'Etat, Université de Pau et des Pays de l'Adour
29. Colo G (1961) Contribution a l'étude du Jurassique du Moyen Atlas septentrional: Atlas de planches hors texte. Éd. de la Division de la géologie, Direction, Ministère, Royaume du Maroc, Rabat
30. ISO 5667-3 version 2016: Water quality—sampling—part 3: preservation and handling of water samples
31. Duru CE, Enedoh MC, Duru IA (2019) Physicochemical assessment of borehole water in a reclaimed section of Nekede Mechanic Village, Imo State, Nigeria. Chemistry Africa 2:689–698
32. Richard C (1996) Collection option bio: Les eaux, les bactéries, les hommes et les animaux. Sc. & Méd. Paris: Elsevier
33. Roques CF (2007) Le thermalisme, la médecine que la Terre nous a donnée. Géosciences 5:74–79
34. Chapman D, Chapman DV (1996) Water quality assessments: a guide to the use of biota, sediments and water environmental monitoring, 2nd edn. E & FN Spon, London
35. Haddad H, Ghoualem H (2014) Caractérisation physico-chimique des eaux du bassin hydrographique côtier algérois. LARHYSS Journal 155–167
36. Lei Y, Zhao Z, Zhang B, Tang X, Luo Y, Wang G, Gao J, Zhang D (2022) Genesis of significance of carbonated thermal water springs in Xining Basin. China Water 14:4058
37. Derwich E, Benaabidate L, Zian A, Sadki O, Belghity D (2010) Caractérisation physico-chimique des eaux de la nappe alluviale du haut Sebou en aval de sa confluence avec oued Fès. LARHYSS Journal, pp 101–112.
38. Rodier J (1984) L'analyse de l'eau; Eaux naturelles, eaux résiduaires, eau de mer, 7ème Edition, Ed. Dunod, Paris
39. Fikri-Benbrahim K, Houti A, El Ouali LA, Flouchi R, El Hachlafi N, Houti M, Rachiq S (2021) Main therapeutic uses of some Moroccan hot springs' waters. Evid-Based Complement Altern Med 2021:e5599269
40. Boughrous AA (2007) Biodiversité, écologie et qualité des eaux souterraines de deux régions arides du Maroc: le Tafilalet et la région de Marrakech. Université Cadi Ayyad Faculté Des Sciences Semlalia Marrakech, Marrakech
41. Ghazali D, Zaid A (2013) Étude de la qualité physico-chimique et bactériologique des eaux de la source Ain Salama-jerri (Région de Meknès-Maroc). LARHYSS J, pp 25–36
42. Costantino M, Izzo V, Conti V, Manzo V, Guida A, Filippelli A (2020) Sulphate mineral waters: a medical resource in several disorders. J Tradit Complement Med 10:320–326
43. Fraioli A, Mennuni G, Petraccia L, Fontana M, Nocchi S, Grassi M (2010) Sulphate-bicarbonate mineral waters in the treatment of biliary and digestive tract diseases. Clin Ter 161:163–168
44. Salah A, Douae E, Touria I, Khadija EK, Mohammed T, Driss B (2020) Study of the quality of the thermal spring moulay yacoube hamma and its impact on the Hamma River, Sidi Slimane–Morocco. Int J Civ Eng Technol 11:02
45. Gizaw B (1996) The origin of high bicarbonate and fluoride concentrations in waters of the Main Ethiopian Rift Valley, East African Rift system. J Afr Earth Sc 22:391–402
46. Gáti T, Tefner IK, Kovács L, Hodosi K, Bender T (2018) The effects of the calcium-magnesium-bicarbonate content in thermal mineral water on chronic low back pain: a randomized, controlled follow-up study. Int J Biometeorol 62:897–905
47. Canellas J, Blavoux B (1995) Relations entre les structures géologiques, la composition chimique des eaux minérales et leurs orientations thérapeutiques. La Houille Blanche, pp 81–86
48. Chaouki M, Zeddouri A (2015) Etude de la Vulnérabilité à la Pollution Chimique des Eaux Souterraines (ZNS) de la Région d'Ouargla. Sud-Est Algérien 7:79–89

49. Parizot M (2008) Contrôle de surveillance de la qualité des masses d'eau souterraine de la Guyane conformément à la Directive Cadre Européenne sur l'Eau : saison des pluies 2008. Rapport final|Bio-plateaux