

Groundwater Chemistry on the Hasouna Wellfields in Man-Made  
River Project of Libya: A Case Study

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## Groundwater Chemistry on the Hasouna Wellfields in Man-Made River Project of Libya: A Case Study

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### Abstract

The Hasouna Wellfields of the Great Man-Made River Project (GMRP) in Libya constitute an important source of groundwater from the Cambro-Ordovician Hasouna aquifer. This study investigates the groundwater chemistry of the Hasouna Wellfields based on field measurements and laboratory analyses from 484 wells. The main objectives are to characterize the physicochemical properties and major dissolved constituents of the groundwater, evaluate its suitability for drinking and irrigation purposes, and assess the potential implications of groundwater chemistry for wells, pumping equipment, and water-conveyance infrastructure.

The results indicate that the groundwater is generally neutral to slightly alkaline, with a mean pH of 7.17. The mean electrical conductivity (EC) is 1609.08  $\mu\text{S}/\text{cm}$ , while the mean total dissolved solids (TDS) concentration is 1039.42 mg/L. The groundwater is hard to very hard, with a mean total hardness of 400.79 mg/L as  $\text{CaCO}_3$  and a mean total alkalinity of 139.81 mg/L as  $\text{CaCO}_3$ . The major cations include  $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ ,  $\text{Na}^+$ , and  $\text{K}^+$ , with mean concentrations of 114.57, 28.33, 188.27, and 8.44 mg/L, respectively. The principal anions include  $\text{HCO}_3^-$ ,  $\text{CO}_3^{2-}$ ,  $\text{Cl}^-$ ,  $\text{SO}_4^{2-}$ ,

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and  $\text{NO}_3^-$ , with mean concentrations of 169.17, 0.30, 297.35, 210.19, and 53.59 mg/L, respectively.

The results indicate relatively high mineralization, particularly reflected by TDS, EC, chloride, and sulphate concentrations. The mean nitrate concentration is also an important water-quality parameter that requires continued monitoring. Irrigation assessment indicates a significant salinity hazard, whereas the sodium-related indices indicate a comparatively lower sodium hazard. The calculated saturation and corrosion indices indicate that the groundwater is slightly undersaturated with respect to calcium carbonate and has potential corrosive characteristics. Overall, the findings highlight the importance of continued groundwater-quality monitoring and appropriate management of salinity, nitrate, calcium-carbonate saturation, and corrosion potential in the Hasouna Wellfields and the associated Great Man-Made River water-conveyance system.

**Keywords:** Groundwater; Hasouna Wellfields; Hasouna Aquifer; Great Man-Made River; Hydrochemistry; Groundwater Quality; Salinity; Irrigation Water; Corrosion.

## كيمياء المياه الجوفية في حقول آبار الحساونة بمشروع النهر الصناعي في ليبيا: دراسة حالة

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### الملخص:

تُعد حقول آبار الحساونة التابعة لمشروع النهر الصناعي في ليبيا مصدراً مهماً للمياه الجوفية المستخرجة من خزان الحساونة الجوفي من العصرين الكمبري والأوردوفيشي. تهدف هذه الدراسة إلى توصيف كيمياء المياه الجوفية في حقول آبار الحساونة، بالاعتماد على القياسات الحقلية والتحليل المختبرية لـ 484 بئرًا. وتتمثل الأهداف الرئيسة للدراسة في توصيف الخصائص الفيزيائية والكيميائية والمكونات الذائبة الرئيسة للمياه الجوفية، وتقييم مدى ملاءمتها لأغراض الشرب والري، وتقييم الآثار المحتملة لكيمياء المياه الجوفية على الآبار ومعدات الضخ ومنشآت نقل المياه.

أظهرت النتائج أن المياه الجوفية تتميز عمومًا بطبيعة متعادلة إلى قلوية قليلًا، حيث بلغ متوسط الرقم الهيدروجيني (pH) 7.17 وبلغ متوسط التوصيلية الكهربائية (EC) 1609.08 ميكروسيمنز/سم، بينما بلغ متوسط تركيز المواد الصلبة الذائبة الكلية 1039.42 (TDS) ملجم/لتر. وتتميز المياه بأنها عسرة إلى شديدة العسرة، حيث بلغ متوسط العسرة الكلية 400.79 ملجم/لتر محسوبة على أساس كربونات الكالسيوم (CaCO<sub>3</sub>)، في حين بلغ متوسط القلوية الكلية 139.81 ملجم/لتر محسوبة على أساس CaCO<sub>3</sub>. وشملت الكاتيونات الرئيسة Ca<sup>2+</sup> و Mg<sup>2+</sup> و Na<sup>+</sup> و K<sup>+</sup>، بمتوسطات تركيز بلغت 114.57 و 28.33 و 188.27 و 8.44 ملجم/لتر، على التوالي. أما الأنيونات الرئيسة فشملت HCO<sub>3</sub><sup>-</sup> و CO<sub>3</sub><sup>2-</sup> و Cl<sup>-</sup> و SO<sub>4</sub><sup>2-</sup> و NO<sub>3</sub><sup>-</sup>، بمتوسطات تركيز بلغت 169.17 و 0.30 و 297.35 و 210.19 و 53.59 ملجم/لتر، على التوالي.

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تشير النتائج إلى وجود تمعدن مرتفع نسبياً في المياه الجوفية، ويتضح ذلك بصورة خاصة من قيم TDS و EC وتركيزات الكلوريد والكبريتات. كما يمثل متوسط تركيز النترات أحد مؤشرات جودة المياه المهمة التي تتطلب استمرار المراقبة. وأظهر تقييم صلاحية المياه للري وجود خطر ملحوظ للملوحة، في حين أشارت المؤشرات المرتبطة بالصوديوم إلى انخفاض نسبي في خطر الصوديوم. كما أظهرت مؤشرات التشبع والتآكل المحسوبة أن المياه الجوفية في حالة عدم تشبع نسبياً بكاربونات الكالسيوم، مع وجود خصائص قد تشير إلى قابلية للتآكل. وبوجه عام، تؤكد النتائج أهمية الاستمرار في مراقبة جودة المياه الجوفية، والإدارة المناسبة للملوحة والنترات وحالة التشبع بكاربونات الكالسيوم وإمكانات التآكل في حقول آبار الحساونة ونظام نقل المياه المرتبط بمشروع النهر الصناعي.

**الكلمات المفتاحية:** المياه الجوفية؛ حقول آبار الحساونة؛ خزان الحساونة الجوفي؛ مشروع النهر الصناعي؛ الهيدروكيمياء؛ جودة المياه الجوفية؛ الملوحة؛ مياه الري؛ التآكل.

## 1- Introduction

The Man-Made River Project (MMRP) is one of Libya's major water-supply projects and was developed to transport groundwater from large desert Wellfields to the coastal regions. The project was launched in 1983 and was designed to supply approximately 6.5 million m<sup>3</sup> of water per day to support domestic, agricultural, and industrial water demands. The GMRP comprises several major groundwater systems and Wellfields, including the Sarir-Sirt and Tazerbo-Benghazi systems, the Kufra-Tazerbo system, the Sirt-Assdada link, the Hasouna-Jeffara system, and the Ghadamis-Zwara system (El-Mabrouk and Sahli, 2006).

Groundwater is an important component of water resources in arid and semi-arid regions, where surface-water resources are limited and groundwater provides a major source of water for domestic, agricultural, and other uses. The chemical composition of groundwater is controlled by interactions between groundwater and the geological formations through which it flows, as well as by recharge conditions, groundwater residence time, mineral dissolution and precipitation, and ion-exchange processes. Consequently, groundwater chemistry provides important

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information about water quality, mineralization, and suitability for different uses. (Hem, 1985; Appelo and Postma, 2005).

Groundwater quality is commonly evaluated using a combination of physicochemical parameters and dissolved chemical constituents. Important physicochemical parameters include temperature, pH, electrical conductivity (EC), total dissolved solids (TDS), dissolved oxygen (DO), oxidation-reduction potential (ORP), total hardness, and alkalinity. These parameters provide an overall indication of groundwater chemical conditions and are particularly useful for evaluating mineralization, hardness, salinity, redox conditions, and the potential interaction of groundwater with wells, pumping equipment, and water-transfer systems. (Hem, 1985; APHA, AWWA, and WEF, 2017).

The major dissolved constituents of groundwater include the principal cations calcium ( $\text{Ca}^{2+}$ ), magnesium ( $\text{Mg}^{2+}$ ), sodium ( $\text{Na}^{+}$ ), and potassium ( $\text{K}^{+}$ ), and the principal anions bicarbonate ( $\text{HCO}_3^{-}$ ), carbonate ( $\text{CO}_3^{2-}$ ), chloride ( $\text{Cl}^{-}$ ), sulphate ( $\text{SO}_4^{2-}$ ), and nitrate ( $\text{NO}_3^{-}$ ). The concentrations and relative proportions of these constituents are important indicators of groundwater chemistry. Calcium and magnesium contribute substantially to water hardness, whereas sodium, chloride, and sulphate contribute to dissolved mineral content and salinity. Bicarbonate and carbonate are important in controlling alkalinity and calcium-carbonate equilibria, while nitrate is an important water-quality parameter requiring continued monitoring when concentrations are elevated. (Hem, 1985; Appelo and Postma, 2005; World Health Organization, 2022). Groundwater chemistry is also important from an engineering perspective. Elevated concentrations of dissolved ions may increase TDS and EC and may affect the suitability of water for irrigation. High concentrations of calcium and magnesium may contribute to increased hardness and mineral deposition in wells, pumps, and pipelines. Conversely, groundwater that is undersaturated with respect to calcium carbonate may have a greater tendency to dissolve carbonate minerals and may contribute to aggressive conditions in contact with certain construction and pipeline materials. Therefore, groundwater chemistry should be evaluated not only in terms of its suitability for drinking and irrigation but also

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in relation to its potential effects on wells, pumping equipment, and water-conveyance infrastructure. (Stumm and Morgan, 1996; Langmuir, 1997; Sahli, 2006).

The Hasouna Wellfields constitute an important groundwater source within the MMRP. The Wellfields are associated with Jabal Al Hasouna, also known as Jabal Fazzan, and are located in the west-central part of Libya on the northern margin of the Murzuq Basin. The Wellfields include the North East Jabal Hasouna North (NEJH(N)), North East Jabal Hasouna South (NEJH(S)), East Jabal Hasouna East (EJH(E)), and East Jabal Hasouna West (EJH(W)) Wellfields. Groundwater is primarily abstracted from the Cambro-Ordovician Hasouna Formation, which constitutes the main producing aquifer in the area. The overlying Zimam Formation forms an upper aquifer in parts of the study area.

The Cambro-Ordovician aquifer is essentially unconfined in the main part of the Hasouna Wellfields and becomes confined toward the north and east. Its saturated thickness varies from approximately 179 to 710 m, while transmissivity values range from about 1,500 to 2,000 m<sup>2</sup>/day. Regional groundwater flow in the Hasouna area is mainly directed toward the north and northeast (Sahli, 2006).

Because groundwater abstracted from the Hasouna Wellfields is transferred through the GMRP water-conveyance system to the coastal regions, its chemical composition is of particular importance. Changes in groundwater chemistry may affect water quality, irrigation suitability, scaling and corrosion processes, and the long-term performance of wells, pumping equipment, and pipelines. A comprehensive assessment of the groundwater chemistry is therefore important for evaluating the present condition of the resource and for supporting appropriate groundwater-management practices. (Sahli, 2006; Appelo and Postma, 2005).

The present study uses field measurements and chemical analyses from 484 wells in the Hasouna Wellfields to characterize the statistical distribution of the principal physicochemical parameters and dissolved chemical constituents. Particular attention is given to temperature, pH, dissolved oxygen, dissolved carbon dioxide, hydrogen sulphide, TDS, EC, oxidation-reduction potential, total hardness, alkalinity, and the major dissolved cations and anions. The

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groundwater chemistry is evaluated in relation to drinking-water quality, irrigation suitability, and indicators of calcium-carbonate saturation and corrosion potential. (Sahli, 2006; World Health Organization, 2022).

The main objective of this study is to characterize the groundwater chemistry of the Hasouna Wellfields, evaluate the distribution of the principal physicochemical parameters and dissolved ions, assess the suitability of the groundwater for drinking and irrigation purposes, and examine chemical indicators associated with calcium-carbonate saturation and corrosion potential. The study also identifies groundwater-quality parameters that require continued monitoring and appropriate management within the Hasouna Wellfields and the associated Man-Made River water-conveyance system.



Fig. 1.: Layout of the Major Systems of the Great Man-Made river Project, showing the Hasouna Wellfields. (after MMRP, 2004)

### Location:

The Hasouna Wellfields are located in the west-central part of Libya and are known as Jabal Al Hasouna (Jabal Fazzan), as Figure 1. The layout of the Hasouna Wellfields, which are located east and northeast of Jabal al Hasouna, is fourfold, Figure 2. The northern Wellfields are named North East Jabal Hasouna North (NEJH(N)) and South (NEJH(S)), respectively, and contain 158 wells. The East Jabal Hasouna East (EJH(E)) and West (EJH(W)) Wellfields are

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located southeast and south of the northern Wellfields, respectively and have 326 wells. The study area is located between longitudes  $14^{\circ} 13' 00''$  and  $15^{\circ} 30' 00''$  and latitudes  $29^{\circ} 42' 00''$  and  $27^{\circ} 50' 00''$ , as show in Figure 2. Sahli, N. I. M. (2006).

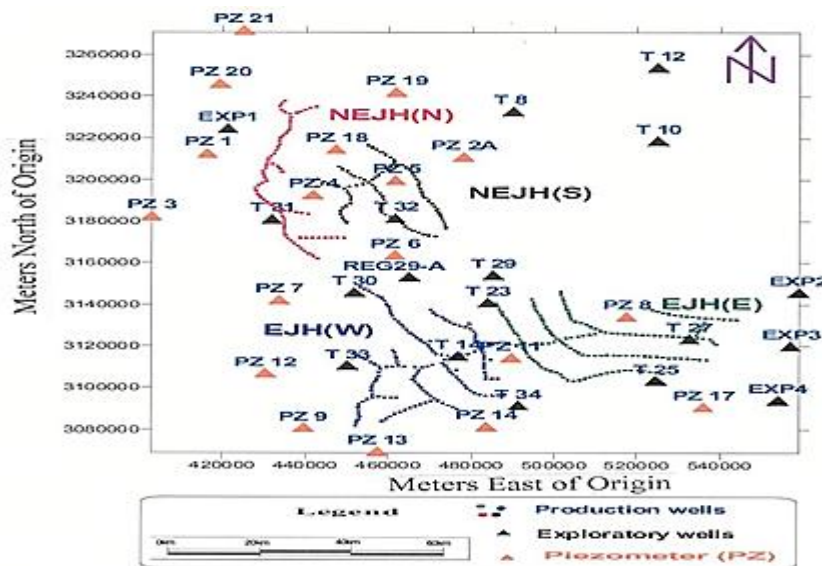


Fig.2.: Layout of All Hasouna Wellfields.

## GEOLOGY and HYDROGEOLOGY

Regionally the Hasouna Wellfields are situated on the northern edge of the Murzuq Basin and comprises rock formations ranging in age from Pre-Cambrian to Upper Cretaceous. The area is mainly formed by the Gargaf Plain, which is bordered in the west by the Jabal Hasouna Mountain. The Jabal Hasouna Mountain is elongated in a north-south direction, and its elevation is more than 1000 m above sea level in the central part (Jurak, 1978). It is constituted by outcrops of the sandstones of the Hasouna Formation, of Cambro-Ordovician (CO) age and volcanic rocks. The Hasouna Formation is overlain by the Zimam Formation of Upper Cretaceous age, which consists of limestone and sandy limestone with interbedded marl and clay layers. There are two aquifers in the Hasouna Wellfields area: Hasouna (Cambro-Ordovician) and Zimam (Upper Cretaceous). The Cambro-Ordovician (CO) is the main and lower

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aquifer in the Hasouna Wellfields. The Zimam aquifer is the upper aquifer in the Hasouna Wellfields.

The Cambro-Ordovician Aquifer in the study area is essentially unconfined, changing in the north and east to a confined aquifer. Its saturated thickness varies from 179 to 710 meters. The transmissivity ranges from 1,500 to 2,000 m<sup>2</sup>/day, the regional groundwater flow direction in the Hasouna area is mainly to the north and northeast (Sahli, N. I. M., 2006).

## WATER QUALITY IN THE HASOUNA WELLFIELDS

### Field measurements

Field measurements have been conducted, including temperature, pH, dissolved oxygen; dissolved carbon dioxide and dissolved hydrogen sulphide. Table 1 presents the statistical analysis of field measurements conducted on water samples collected from 484 wells across the Hasouna Wellfields.

**Table 1. Statistical Analysis of Field Measurements, Hasouna Wellfields**

| Statistical parameter | Temp °C | pH   | D.O. mg/l | CO <sub>2</sub> mg/l | H <sub>2</sub> S mg/l |
|-----------------------|---------|------|-----------|----------------------|-----------------------|
| Max                   | 36.80   | 7.96 | 8.55      | 97.00                | 0.12000               |
| Min                   | 24.50   | 6.32 | 0.10      | 3.70                 | 0.00000               |
| Mean                  | 30.57   | 7.17 | 4.92      | 15.92                | 0.00083               |
| Median                | 30.18   | 7.20 | 5.20      | 12.60                | 0.00000               |
| SD                    | 2.28    | 0.24 | 1.53      | 10.63                | 0.00730               |
| % CV                  | 7.46    | 3.32 | 31.18     | 66.77                | 877.86572             |

**SD = Standard Deviation, %CV = Percentage Coefficient of Variation.**

Generally, water temperature distribution in Hasouna Wellfields is not very marked, with a slight decrease in the west. Regionally, water temperatures increase to over 60°C in the vicinity of the igneous intrusive which form the Al Haruj Al Aswad mountain some 200 kilometers east of the Hasouna Wellfields. A noticeable variation in the pH values of Hasouna Wellfields water was observed, showing a slight increase from East to West. Generally, the average pH value is 7.17 which is within the acceptable limits (5.5 – 9.5) of WHO guidelines (GL) for drinking water.

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The Hasouna Wellfields water is well oxygenated with an overall average dissolved oxygen concentration of about 4.92 mg/l, which is sufficient to maintain an oxidizing chemical environment. The Hasouna Wellfields water shows variation in the concentration of CO<sub>2</sub>, with a general increase from north to east EJH(E) and from east to west. The CO<sub>2</sub> in the Hasouna Wellfields water should be monitored on a regular basis to avoid operational problems in the GMRP pipeline. Dissolved hydrogen sulphide (H<sub>2</sub>S) in the Hasouna Wellfields water showed very low concentrations, ranging from less than detectable to 0.004 mg/l and averaging 0.0004 mg/l (Sahli, 2006).

### Physical and General Parameters

Physical and general parameters which have been analyzed for the Hasouna Wellfields are: Total Dissolved Solids (TDS); Electrical Conductivity (EC); Redox Potential (ORP); Eh; Total Hardness, and Total Alkalinity. Table 2 represents the statistical analysis of the physical and general parameters for all the Hasouna Wellfields (Sahli, 2006).

**Table 2 Statistical Analysis of Physical and General Parameters,  
Hasouna Wellfields**

| Well No | TDS<br>mg/l | EC $\mu$ S/cm | ORP<br>mv | Calculated<br>Eh | Total<br>Hardness<br>mg/l as<br>CaCO <sub>3</sub> | Total<br>Alkalinity<br>mg/l as CaCO <sub>3</sub> |
|---------|-------------|---------------|-----------|------------------|---------------------------------------------------|--------------------------------------------------|
| Max     | 1973        | 2721          | 360       | 560.067          | 725                                               | 422                                              |
| Min     | 563         | 788           | 20        | 106.42           | 133                                               | 83                                               |
| Mean    | 1039.42     | 1609.08       | 154.93    | 353.58           | 400.79                                            | 139.81                                           |
| Median  | 1005.78     | 1553.00       | 143.00    | 341.85           | 393.00                                            | 139.50                                           |
| SD      | 226.00      | 343.78        | 64.01     | 65.77            | 67.66                                             | 24.00                                            |
| % CV    | 21.74       | 21.37         | 41.31     | 18.60            | 16.88                                             | 17.16                                            |
| n       | 484         | 484           | 484       | 484              | 484                                               | 484                                              |

SD = Standard Deviation, %CV = Percentage Coefficient of Variation and n = number.

The average value of the total dissolved solids concentration for Hasouna Wellfields is 1039.42 mg/l with a range from 563 mg/l to 1973 mg/l. The distribution of TDS in the Wellfields area is high in the south-central margin of the NEJH(N) Wellfield and between the

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NEJH(S) and NEJH(N) Wellfields. These anomalies of high TDS are located on the perimeter coinciding with the southern rim (platform) of the Gargaf Uplift, due the mixing processes between the upper and lower Aquifers.

Hasouna Wellfields water generally has high to very high electrical conductivity (EC) values. Thus, the Wellfields' overall EC mean value was found to be 1,610  $\mu\text{S}/\text{cm}$ , with an upper limit of 2,721  $\mu\text{S}/\text{cm}$  and a lower limit of 925  $\mu\text{S}/\text{cm}$ . The distribution of EC in the Hasouna Wellfields correlates very well with the distribution of TDS in the Hasouna Wellfields. The average electrical conductivity for all Hasouna Wellfields water is 1,609.08  $\mu\text{S}/\text{cm}$  and fails the 1,500  $\mu\text{S}/\text{cm}$  Standard (WHO) GL.

Hasouna Wellfields water is characterized by oxidizing conditions with all wells having a positive oxidation-reduction potential (ORP). The average value of ORP for Hasouna Wellfields is 155 mV, ranging from 20 mV to 360 mV. The majority of the wells in the Wellfields show a relatively highly oxidizing environment. The distribution of ORP in the Hasouna Wellfields area increases from west to east. The calculated values for Eh correlate very well with ORP.

Generally, the Hasouna wellfields groundwater is extremely hard with an average total hardness of 400 mg/l as  $\text{CaCO}_3$  (minimum value is 133 mg/l as  $\text{CaCO}_3$ , whereas the maximum value is 725 mg/l as  $\text{CaCO}_3$ ). This is above the upper limit of 500 mg/l as  $\text{CaCO}_3$  suggested by the WHO Criteria. 71% of the total hardness is given by the calcium content, averaging 114.5 mg/l, and the balance by magnesium, averaging 28.3 mg/l. Since there is no water-softening treatment available in the Hasouna Wellfields, it is possible that the high total hardness will eventually cause problems in supply. The total alkalinity, which is the measure of carbonate, bicarbonate and hydroxide ions along with other bases, for Hasouna Wellfields has an indicated average value of 139.81 mg/l as  $\text{CaCO}_3$ , ranging from 83 mg/l as  $\text{CaCO}_3$  to 422 mg/l as  $\text{CaCO}_3$ .

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### Major Cations and Anions

The major chemical constituents are considered to be the cations and the anions. The cations are: Calcium; Magnesium; Sodium and Potassium. The anions are: Bicarbonate; Carbonate; Chloride; Sulphate; Nitrate and Silicate. Table 3 represents the statistical analysis of major cations and anions for all the Hasouna Wellfields.

**Table 3. Statistical Analysis of the Cations and Anions, Hasouna Wellfields**

| Statistical Parameter | Ca mg/l | Mg mg/l | Na mg/l | K mg/l | HCO <sub>3</sub> mg/l | CO <sub>3</sub> mg/l | Cl mg/l | SO <sub>4</sub> mg/l | NO <sub>3</sub> mg/l | SiO <sub>2</sub> mg/l |
|-----------------------|---------|---------|---------|--------|-----------------------|----------------------|---------|----------------------|----------------------|-----------------------|
| Max                   | 195.59  | 68.81   | 429.89  | 56.00  | 301.34                | 0.89                 | 600.14  | 589.82               | 133.00               | 27.75                 |
| Min                   | 49.00   | 7.30    | 78.16   | 0.00   | 98.94                 | 0.04                 | 97.00   | 72.53                | 0.00                 | 2.30                  |
| Mean                  | 114.57  | 28.33   | 188.27  | 8.44   | 169.17                | 0.30                 | 297.35  | 210.19               | 53.59                | 14.22                 |
| Median                | 116.00  | 26.32   | 189.43  | 6.65   | 170.84                | 0.28                 | 291.52  | 201.00               | 55.42                | 14.10                 |
| SD                    | 20.25   | 9.60    | 48.68   | 5.44   | 22.67                 | 0.15                 | 92.16   | 69.28                | 17.30                | 2.79                  |
| % CV                  | 17.68   | 33.87   | 25.86   | 64.41  | 13.40                 | 48.91                | 30.99   | 32.96                | 32.27                | 19.65                 |
| N                     | 484     | 484     | 484     | 484    | 484                   | 484.00               | 484     | 484                  | 484                  | 484                   |

**SD = Standard Deviation, %CV = Percentage Coefficient of Variation, and N = number.**

The cation concentrations are within the limits expected for groundwater in the region. The calcium concentration averages 114.57 mg/l and ranges between 49 mg/l and 195.59 mg/l. The median value is 116 mg/l, reflecting an approximately normal distribution of calcium concentrations. The average magnesium (28.3 mg/l) and potassium (8.45 mg/l) concentrations are within the acceptable WHO GL of 50 and 12 mg/l respectively. The level of sodium however, is extremely high, ranging from 78.16 mg/l to 429.89 mg/l. The total average sodium composition for the Hasouna Wellfields water is 188.27 mg/l. This average composition is within the acceptable WHO GL of 200 mg/l. These sodium concentrations may be a problem for those people who are on low-sodium diets because of high blood pressure. Sodium is virtually impossible to remove by normal treatment processes, but could be ameliorated by dilution with a low-sodium source.

The anion concentrations are also within the limits expected for groundwater in the region. Bicarbonate concentration in the Hasouna Wellfields water ranges from 99mg/l to 301 mg/l with an

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overall mean concentration 169mg/l. The carbonate concentration in the Hasouna Wellfields is very low averaging 0.3 mg/l and the reasons for this concentration are the low pH and high CO<sub>2</sub> content. The average chloride concentration is 297.35 mg/l, ranging from 97 mg/l to 600.14 mg/l, which is high but complies with the 400 mg/l Standard (WHO GL). The distribution of chloride in the Hasouna Wellfields shows high concentration in the centre of the Wellfields area, decreasing to the north. The ratio of sodium to chloride is 1.576, which is very close to the stoichiometric value of 1.542. It is possible that this concentration of sodium chloride will be tasted by the consumer. The average sulphate concentration is 210.19 mg/l, and this complies with the 250 mg/l Standard. 21% of the sulphate ion is associated with the calcium and magnesium ion pairs giving rise to permanent hardness, and the sodium and potassium single negative ions.

### Chemical Indicators of Corrosion and Water Aggressivity (Saturation Indices and Corrosion Indices)

Several indexes were used to indicate the potential of Hasouna Wellfields water to cause corrosion or to precipitate incrusting deposits on wells pumps and pipelines. The calculated indices are presented in Table 4 as a statistical summary.

**Table 4. Statistical Analysis of the Chemical Indicators of Corrosion and Water Aggressivity**

| Statistical Parameter | pH   | pHs  | Langelier Index LI | Ryznar Index RI | CCPP mg/l | Corrosivity Index | Chloride Corrosion Index |
|-----------------------|------|------|--------------------|-----------------|-----------|-------------------|--------------------------|
| Max                   | 7.96 | 8.64 | 0.54               | 10.27           | 15.80     | 17.94             | 3.87                     |
| Min                   | 6.32 | 6.74 | -1.63              | 6.83            | -129.00   | 0.00              | 2.33                     |
| Mean                  | 7.17 | 7.48 | -0.31              | 7.80            | -11.71    | 3.77              | 3.03                     |
| Median                | 7.20 | 7.48 | -0.26              | 7.73            | -6.05     | 3.66              | 3.00                     |
| SD                    | 0.25 | 0.26 | 0.26               | 0.46            | 18.44     | 1.38              | 0.25                     |
| % CV                  | 3.47 | 3.50 | -84.33             | 5.95            | -157.52   | 36.52             | 8.37                     |
| n                     | 484  | 484  | 484                | 484             | 470       | 484               | 484                      |

SD = Standard Deviation, %CV = Percentage Coefficient of Variation and n is number. (Specialized technical terms, e.g. pHs, LI, RI, CCPP etc are defined in the Appendix).

The mean pH of the groundwater was 7.17, whereas the mean saturation pH (pHs) was 7.48. The mean Langelier Saturation Index was -0.31, indicating slight undersaturation with respect to calcium

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carbonate ( $\text{CaCO}_3$ ). The mean Ryznar Index was 7.80, which is consistent with water that has limited calcium-carbonate scale-forming potential. The mean CCPP was  $-11.71 \text{ mg/L as CaCO}_3$ , further indicating a tendency toward calcium-carbonate undersaturation.

The negative LSI and CCPP values indicate that the groundwater is not saturated with respect to  $\text{CaCO}_3$  under the prevailing chemical conditions. Although the groundwater has a neutral to slightly alkaline pH, calcium-carbonate saturation is not controlled by pH alone. It also depends on the concentrations and activities of calcium and carbonate species, alkalinity, temperature, and ionic strength. Therefore, a relatively high pH does not necessarily mean that groundwater will be saturated with  $\text{CaCO}_3$ . In the Hasouna Wellfields, the relatively limited availability of dissolved calcium and carbonate species, together with the other chemical conditions of the groundwater, can contribute to the observed undersaturation.

The mean Corrosivity Index (CI) was 3.77, while the mean Chloride Corrosion Index (CCI) was 3.03. These indices provide additional information about the potential aggressiveness of groundwater toward materials used in wells, pumping equipment, and water-conveyance infrastructure. However, corrosion is a complex process that depends not only on groundwater chemistry but also on temperature, dissolved gases, flow conditions, material type, surface condition, and exposure time. Therefore, the calculated indices should be considered indicators of potential corrosive conditions rather than direct measurements of actual corrosion rates.

Overall, the saturation and corrosion indices indicate that groundwater in the Hasouna Wellfields has a slight tendency toward  $\text{CaCO}_3$  undersaturation and may present conditions conducive to corrosive interactions with susceptible materials. These findings highlight the importance of continued monitoring of groundwater chemistry and of further evaluation of corrosion processes in wells, pumping equipment, and the associated water-conveyance system.

### Drinking Water

Water from all the Hasouna Wellfields will be mixed in the GMRA pipe line and will then comprise a single water type by the

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time it reaches the main cities; Therefore, in this section it will be described on the basis of an average composition. Table 5 summarizes the average chemical composition of all Hasouna Wellfields water. These values are compared with the drinking water standards set by the World Health Organization (WHO).

Table 5 shows that the average chemical composition of the Wellfields water meets WHO guidelines for drinking water standards, except TDS, CO<sub>2</sub> and NO<sub>3</sub>. The CO<sub>2</sub> concentration is not limited by WHO but it does have an effect on the GMRA pipeline.

The mean total dissolved solids (TDS) concentration for the Hasouna Wellfields exceeds the WHO-recommended guideline value for drinking water by approximately 40 mg/L. This represents a relatively small exceedance and indicates that the overall TDS level is not particularly high, especially when compared with TDS concentrations reported for previous water-supply sources in the western regions of Libya. However, nitrate concentrations are of greater concern from a public-health perspective and therefore require particular attention when assessing the suitability of the groundwater for drinking purposes.

**Table 5. Average Composition, Hasouna Wellfields Water and Safe Drinking Water Standards (WHO, 1997)**

| Constituent                            | Concentration (mg/l)                         |                  |
|----------------------------------------|----------------------------------------------|------------------|
|                                        | Average Composition Hasouna Wellfields Water | (WHO) guidelines |
| PH value                               | 7.17                                         | 6.5-9.5          |
| TDS                                    | 1039.42                                      | 1000             |
| CO <sub>2</sub>                        | 15                                           | -                |
| Calcium (Ca)                           | 117.8                                        | 250              |
| Magnesium (Mg)                         | 28.33                                        | 50               |
| Sodium (Na)                            | 188.27                                       | 200              |
| Chloride (Cl)                          | 299.16                                       | 400              |
| Sulphate (So <sub>4</sub> )            | 210.74                                       | 400              |
| Potassium K                            | 8.44                                         | 12               |
| Nitrate No <sub>3</sub>                | 53.23                                        | 50               |
| Total Hardness (As CaCO <sub>3</sub> ) | 400.79                                       | 500              |

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| Constituent           | Concentration (mg/l)                         |                  |
|-----------------------|----------------------------------------------|------------------|
|                       | Average Composition Hasouna Wellfields Water | (WHO) guidelines |
| <b>Iron (Fe)</b>      | 0.09                                         | <b>0.3</b>       |
| <b>Boron (B)</b>      | 0.35                                         | <b>0.5</b>       |
| <b>Fluoride (F)</b>   | 0.78                                         | <b>1.5</b>       |
| <b>Copper (Cu)</b>    | 0.01                                         | <b>2</b>         |
| <b>Manganese (Mn)</b> | 0.01                                         | <b>0.4</b>       |
| <b>Zinc (Zn)</b>      | 0.02                                         | <b>0.03</b>      |
| <b>Lead (Pb)</b>      | 0                                            | <b>0.01</b>      |
| <b>Cadmium (Cd)</b>   | 0                                            | <b>0.003</b>     |
| <b>Chromium (Cr)</b>  | 0.01                                         | <b>0.05</b>      |
| <b>Arsenic (As)</b>   | 0                                            | <b>0.01</b>      |
| <b>Mercury (Hg)</b>   | 0                                            | <b>0.001</b>     |

**WHO Guidelines: Drinking Water Standards Developed by the World Health Organization. Concentrations: mg/l or as stated in the Table**

### Water Quality for Irrigation

The principal usage of water provided by the GMRA will be for irrigation, with 87% allocated to agriculture, 11% to domestic use and 2% to industry. The suitability of water for irrigation purposes is governed by a series of values based on the total dissolved solids content (salinity) and the sodium content, more specifically the ratio of sodium ions to calcium and magnesium ions, a characteristic referred to as the sodium adsorption ratio (SAR). The quantity of free sodium bicarbonate is also important.

Several criteria have been used to test the suitability of water from all Hasouna Wellfields for irrigation. These criteria include the Alkali Hazard, which is based on the estimation of the Residual Sodium Carbonate (RSC), the Soluble Sodium Percentage (SSP) and the Sodium Hazard, described by the Sodium Adsorption Ratio (SAR). The Wilcox diagram, Figure 3, is a graphical means of describing the salinity hazard of irrigation water, as is the Magnesium Hazard Percentage (MHP), Table 6. Figure 3 shows that there is high salinity hazard but the alkali hazard (sodium) is low.

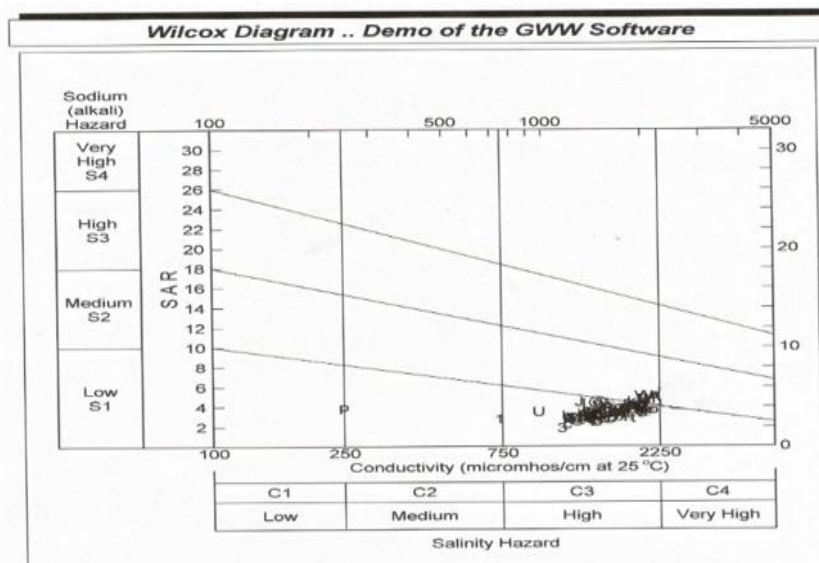
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**Table 6. Statistical Analysis of Suitability of Hasouna Water for Irrigation**

| Statistical Parameter | RSC    | SSP     | MHP    |
|-----------------------|--------|---------|--------|
| Max                   | -0.141 | 111.942 | 43.938 |
| Min                   | -9.382 | 22.680  | 17.654 |
| Mean                  | -4.84  | 49.44   | 33.08  |
| Median                | -4.86  | 50.07   | 32.45  |
| SD                    | 1.60   | 8.48    | 5.30   |
| % CV                  | -33.14 | 17.15   | 16.03  |
| N                     | 484    | 484     | 484    |

SD = Standard Deviation, %CV = Percentage Coefficient of Variation and n is number.



**Fig 3. Wilcox diagram showing the classification of groundwater sample from the Hasouna Wellfields based on electrical conductivity (EC) and sodium adsorption ratio (SAR).**

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## CONCLUSIONS

The groundwater chemistry of the Hasouna Wellfields was evaluated using field measurements and chemical analyses from 484 production wells. The study focused on the principal physicochemical parameters, major dissolved ions, drinking-water quality, irrigation suitability, calcium-carbonate saturation, and potential corrosion characteristics.

The groundwater is generally neutral to slightly alkaline, with a mean pH of 7.17. The mean groundwater temperature was 30.57 °C, while the mean dissolved oxygen and dissolved carbon dioxide concentrations were 4.92 and 15.92 mg/L, respectively. The groundwater is characterized by relatively high mineralization, with mean EC and TDS values of 1,609.08 µS/cm and 1,039.42 mg/L, respectively.

The groundwater is hard to very hard, with a mean total hardness of 400.79 mg/L as CaCO<sub>3</sub>. The mean total alkalinity was 139.81 mg/L as CaCO<sub>3</sub>. The major dissolved cations were Ca<sup>2+</sup>, Mg<sup>2+</sup>, Na<sup>+</sup>, and K<sup>+</sup>, with mean concentrations of 114.57, 28.33, 188.27, and 8.44 mg/L, respectively. The principal anions were HCO<sub>3</sub><sup>-</sup>, CO<sub>3</sub><sup>2-</sup>, Cl<sup>-</sup>, SO<sub>4</sub><sup>2-</sup>, and NO<sub>3</sub><sup>-</sup>, with mean concentrations of 169.17, 0.30, 297.35, 210.19, and 53.59 mg/L, respectively.

The relatively high concentrations of TDS, EC, chloride, and sulphate indicate relatively high groundwater mineralization. These characteristics are important for both drinking-water management and irrigation use. The mean nitrate concentration is also an important water-quality parameter requiring continued monitoring, particularly because concentrations vary considerably among individual wells.

The assessment of irrigation-water quality indicates that salinity is an important factor affecting groundwater suitability for agricultural use. The negative mean RSC value indicates a low residual carbonate hazard, while the sodium-related indices indicate variability in the potential sodium hazard among individual wells. Therefore, irrigation management should consider the combined effects of salinity and sodium rather than relying on a single irrigation index.

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The calcium-carbonate saturation assessment indicates slight undersaturation of the groundwater with respect to  $\text{CaCO}_3$ . The mean LSI was  $-0.31$  and the mean CCPP was  $-11.71$  mg/L as  $\text{CaCO}_3$ , while the mean RI was  $7.80$ . The observed undersaturation is not inconsistent with the relatively high groundwater pH because  $\text{CaCO}_3$  saturation depends on several interacting factors, including pH, calcium concentration, carbonate and bicarbonate availability, temperature, and ionic strength.

The calculated corrosion-related indices indicate potential corrosive conditions that require consideration in the management of wells, pumping equipment, and water-conveyance infrastructure. However, the calculated indices should be regarded as indicators of potential water aggressivity rather than direct measurements of corrosion rates. Further investigations of actual corrosion processes and material performance are recommended.

Overall, the results demonstrate that groundwater from the Hasouna Wellfields is an important water resource but requires continued quality monitoring and appropriate management. Particular attention should be given to salinity, nitrate concentrations, calcium-carbonate saturation, and potential corrosion. Monitoring individual wells, rather than relying only on field-wide mean values, is recommended to identify localized changes in groundwater quality and to support sustainable management of the Hasouna Wellfields and the associated Great Man-Made River water-conveyance system.

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