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# Hydrogeochemical Characterization of Groundwater Resources in the Northern Part of Amman-Zarqa Basin, North-East El Mafraq/Jordan

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## Abstract

In one of the world's most water-scarce regions, the Amman-Zarqa Basin, specifically North-East Mafraq, Jordan, is a crucial groundwater resource. In this regard, this study focuses on the hydrogeochemical properties of groundwater within this area and its suitability for drinking and domestic use. Careful collection and analysis of groundwater samples in terms of physicochemical parameters like pH, total dissolved solids (TDS), electrical conductivity (EC) and major ions of nitrate (NO3-), sulphate (SO42), bicarbonate (HCO3-), chloride (Cl-), magnesium (Mg2+), calcium (Ca2+), potassium (K +), and sodium (Na +) were done. Our results show that groundwater quality was highly variable across the study area, which is a function of both natural geologic formations and human activities. However, most of the samples meet the World Health Organization (WHO) and Water Authority of Jordan (WAJ) drinking water standards, while some are found to be high in TDS, chloride, and nitrate, and then require treatment before use. Historical data from 1998 indicate that, while overall water quality has not changed remarkably, there have been increases in some areas of salinity and nitrate, illustrating the ongoing effect of agricultural practices and groundwater extraction. An important implication from this study is the critical need for continuous monitoring and management of groundwater resources in Amman-Zarqa Basin, North-East El Mafraq area to support the sustainability of this resource. The insights provide valuable information to policymakers and stakeholders, enabling the development of a strategy for protecting and managing groundwater and ensuring its long-term availability to cater to the growing population and agricultural needs in the region.

**Keywords:** *Groundwater; Quality Index; Quality Assessment; Amman-Zarqa Basin; Hydrogeochemistry North-East EL-Mafraq*

## 1. Introduction

Jordan relies on groundwater to meet the water demands of households, businesses, and farms; the country is the world's second most water-scarce (UNICEF, 2020; Radaideh, 2022). According to Radded (2005), Jordan extracts around 520 million cubic meters (MCM) of groundwater total. The agricultural sector consumes about 54% of this water, followed by municipal use at 40% and industrial use at 6% (Radded, 2005). The majority of Jordan's water comes from underground basins, which vary in volume and quality. These basins cover nearly the entire nation and account for approximately 61% of the country's total accessible water supply. Of these twelve basins, two are being underutilised, four are near their equilibrium abstraction limit, and six are being overextracted (Odeh et al., 2019). The overexploitation of groundwater resources has led to a decline in water quality and a reduction in the amount available for use (Jordan, Geography and Population, 2001). According to the Ministry of Water and Irrigation (2017), groundwater basins are heavily pumped from both public and private wells. Reikat and Al Kharabsheh (2020) note that groundwater levels have dropped significantly over the last several decades due to pumping that surpasses the aquifers' safe yield.

Groundwater levels have been steadily declining since the 1980s, and this trend has accelerated in recent decades due to rising abstraction to meet the demands of an expanding human population, increased migration from neighboring countries, and intensified agricultural development (MWI and BGR, 2017). Jordan relies heavily on groundwater due to the country's scarce surface water resources. Water levels have dropped, total dissolved solids (TDS) have increased, and groundwater flows westward instead of eastward because of these restrictions (BGR 2013). Since then, it has become critically necessary to preserve the region's current water resources (MWI, 2017). The goal of this study was to catalogue the hydrogeochemical characteristics of the groundwater in Jordan's North East El Mafraq, which is part of the Amman-Zarqa Basin.

## 2. Description of the study area

The study area is situated in the northern part of the Amman Zarqa Basin, including 35.67°W, 36.82°E, 32.40°N, and 31.70°S, with a total area of 3860 km² (95% of the basin area is in Jordan and 5% is in southern Syria). (USAID, 2000). Located between an elevation of 1460 m above sea level at Salkhad city in Jebel Al Arab in Syria and Amman the South direction (Al Shibli et al., 2017). The four governorates of Amman, Zarqa, Mafraq, and Balqa, which are densely populated, consider this basin as a main source of water. A

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particularly north-eastern part of the EL Mafraq basin was selected, covering an area of approximately 965 km². The water divisions with the neighboring basins' boundary can be roughly determined by (Yarmouk, Azraq-Dulail). The elevation of this basin ranges from 700 to 1200 meters, characterized by undulating topography in the west and flat areas in the east and south. The area covered by this study was approximately 50 km² out of a total of 985 km², and the elevation of the wells in the study area falls within the specified. The elevation of wells in the study area is within the elevation rangepproximately 50 km² out of a total of 985 km². The elevation of the wells in the study area ranges from 500 to 1,000 m above sea level. (Fig. 1).A semi-arid climate is present in this place, which is characterized by hot, dry summers and mild, wet winters. It has varied topography, featuring both flat plains and hilly terrains. The Amman-Zarqa basin is a key element in the larger Jordan Rift Valley system, which is of great importance in terms of regional hydrogeology. Agricultural activities represent our study area of the basin, for which traditional irrigation practices have a significant impact on the groundwater resources.

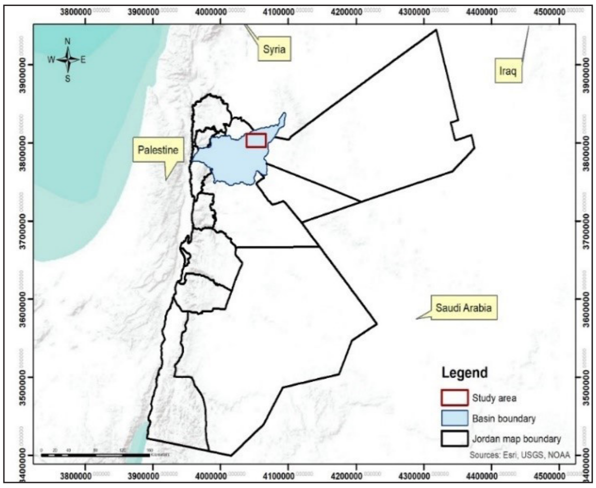

**Figure 1.** Location map of the study area

## 3. Hydrogeology of Northern Amman-Zarqa Basin

The Amman–Zarqa basin is one of the primary sources of fresh groundwater in Jordan. The basin is divided into three main aquifers (BGR 2013): basalt aquifer, limestone aquifer (the generally most important aquifer of the basin), comprised as Amman Wadi Es Sir Aquifer, and sandstone (Kurnub) aquifer (Figure 2). The later is a regional aquifer recharges from limited outcrop areas of Baqa and Jerash and leakage from the upper carbonate aquifers. It is estimated that the total recharge for this aquifer in the basin is about 8 MCM/year (MWI, 2000). The aquifer is isolated from the upper Zarqa aquifer by the bluish green shale and marls of the upper Zarqa formation and capped by the Nau'r marls.

The Amman–Wadi Es Sir Aquifer (B2/A7) is a semi-confined aquifer with parts of it unconfined (Al-Momani et al. 2007). It has high permeability and storage capacity, and is rechargeable annually over a wide geographic area, particularly in densely populated areas. The aquifer comprises three formations, Amman Formation (B1), Ghudran Formation (B2), and Wadi Sir Formation (A7). The three formations are hydraulically connected and so are considered one aquifer. The B2/A7 unit has a varying thickness, ranging from approximately 100 m in the north of Amman to about 500 m in the south (Al-Momani et al. 2007). The depth of the water table cannot be determined, and it varies depending on the location as well as the hydrogeological conditions. The water table in some areas near the Zarqa River ranges from less than 50 m to greater than 150 m (AlMomani et al., 2007). The unconfined part of the aquifer with an effective porosity of 10−30 % and the confined part is characterized by a storage coefficient (Al-Mamani et al. 2007) of about $5x10^{-5}$. BS is the top formation of the B2/A7 sequence of formations in the Amman-Zarqa Basin. Basaltic lava flows have been extruded onto an eroded surface of older rocks, forming it. This unit varies in thickness from less than 10 meters to more than 100 meters. However, six lava flows were determined to extend from North to South to Al Hashmyiha area (MWI, .2000). The estimated recharge to the whole Basalt aquifer in Jordan is about 45 MCM/y of fresh water suitable for all types of usages. From that amount, 28 MCM/y is available within the Amman-Zarqa Basin in Jordan; the rest is discharged from this basin into the Azraq Basin. Transmissivity: 2-113,000 $m^2/d$, Storage Coefficient: 0.0001-0.003 (MWI,.2000).

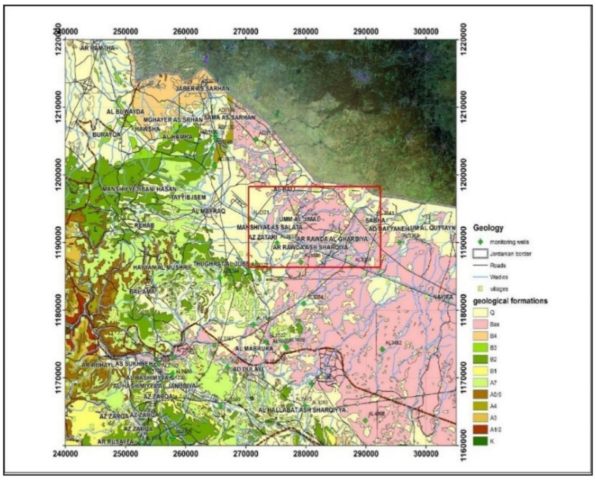

**Figure 2.** Geological map of the study area ( Margane et al.,2015). The basin is divided into three main aquifers: basalts aquifer (at the top); limestone aquifer (in the middle, comprised of as Amman Wadi Es Sir Aquifer), and sandstone aquifer (Kurnub Aquifer (K), at the bottom).

## 4. Materials and Methods

During March and April 2023, eight water samples were collected from different wells in the study area and underwent laboratory analysis at the Jordanian Ministry of Water and Irrigation for physicochemical parameters, including major and minor elements pH, TDS, and EC, at a temperature of 25 °C (Tables 1 and 2). Concentrations of cations ($Ca^{+2}$, $Mg^{+2}$, $Na^{+}$, $K^{+}$), anions ($HCO_3^-$, $SO_4^{-2,}$ $Cl^-$), and nitrate ($NO_3^-$), in addition to pH, TDS, and EC are also determined. Figure 3 shows the locations of the wells where these samples were collected in addition to four samples investigated by the ministry of water and irrigation (MWI) during the same period.

**Table 1**. The coordination of wells in the study area (WGS84 coordinate system)

| NO | ID | Latitude (N) | Longitude (E) | Elevation m (A.S.L) | Aquifer type |
|---|---|---|---|---|---|
| 1 | AL1453 | 32.306073 | 36.410086 | 727 | B2/A7 |
| 2 | AL1558 | 32.287751 | 36.391879 | 693 | BS |
| 3 | AL1482 | 32.271608 | 36.365288 | 674 | B2/A7 |
| 4 | AL1480 | 32.277561 | 36.400323 | 706 | BS |
| 5 | AL1481 | 32.238237 | 36.362903 | 615 | B2/A7 |
| 6 | AL3027 | 32.330888 | 36.390543 | 672 | B2/A7 |
| 7 | AL3018 | 32.304439 | 36.442042 | 747 | B2/A7 |
| 8 | AL2447 | 32.255617 | 36.369586 | 648 | B2/A7 |
| Data from MWI | | | | | |
| 9 | AL3467 | 32.345616 | 36.236409 | 681 | B2/A7 |
| 10 | AL2457 | 32.299714 | 36.481346 | 757 | BS |
| 11 | AL3007 | 32.329178 | 36.508418 | 849 | B2/A7 |
| 12 | AL3087 | 32.287376 | 36.510215 | 825 | B2/A7 |

**Table 2**. Physicochemical characteristics of groundwater samples in the study area in the years 1998-2023.

| | | | | | **2023** | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| ID | No$_3^-$ | SO$_4^{-2}$ | HCO$_3^-$ | CL$^-$ | Mg$^{+2}$ | Ca$^{+2}$ | K$^+$ | Na$^+$ | TDS | PH | EC |
| AL2447 | 48.83 | 31.26 | 157.37 | 120.72 | 18.32 | 23.71 | 5.39 | 93.78 | 546.49 | 7.91 | 858 |
| AL2457 | 60.17 | 136.75 | 133.47 | 128 | 27.35 | 18.6 | 8.75 | 133.47 | 654.21 | 8.34 | 1032.74 |
| AL3007 | 11.26 | 181.26 | 105.11 | 95.46 | 22.52 | 53.63 | 9.65 | 90.09 | 622.08 | 8.16 | 971.74 |
| AL3018 | 26.84 | 98.5 | 114.74 | 134.22 | 22.73 | 19.48 | 7.58 | 130.98 | 568.29 | 8.42 | 900.6 |
| AL3027 | 35.34 | 152.75 | 139.07 | 304.37 | 70.68 | 54.72 | 17.1 | 153.89 | 1016.84 | 8.25 | 1607.34 |
| AL3087 | 34.6 | 167.58 | 66.38 | 127.32 | 22.85 | 20.68 | 5.44 | 121.88 | 617.01 | 8.13 | 950 |
| AL1482 | 165.99 | 228.87 | 306.83 | 1026.12 | 148.39 | 192.4 | 18.86 | 428.81 | 2540.16 | 8 | 3968.68 |
| AL1480 | 68.69 | 111.9 | 189.46 | 237.1 | 31.02 | 33.24 | 13.3 | 189.46 | 839.83 | 7.53 | 1311.82 |
| AL1481 | 31.39 | 193.95 | 163.68 | 338.57 | 48.21 | 39.24 | 13.45 | 225.34 | 1127.81 | 7.63 | 1597.54 |
| AL3467 | 30.49 | 115.41 | 239.53 | 139.36 | 47.91 | 60.97 | 7.62 | 103.43 | 745.8 | 7.64 | 1197.63 |
| AL1558 | 32.73 | 115.63 | 119.99 | 217.08 | 57.81 | 43.63 | 8.73 | 103.63 | 752.68 | 8.11 | 1172.65 |
| AL1453 | 56.83 | 236.7 | 183.97 | 508.56 | 132.41 | 70.31 | 9.37 | 205.06 | 1412.01 | 8.38 | 2167.81 |
| | | | | | **1998** | | | | | | |
| ID | No$_3^-$ | SO$_4^{-2}$ | HCO$_3^-$ | CL$^-$ | Mg$^{+2}$ | Ca$^{+2}$ | K$^+$ | Na$^+$ | TDS | PH | EC |
| AL2447 | 45.3 | 29 | 146 | 112 | 17 | 22 | 5 | 87 | 507 | 7.68 | 796 |
| AL2457 | 55 | 125 | 122 | 117 | 25 | 17 | 8 | 122 | 598 | 8.1 | 944 |
| AL3007 | 10.5 | 169 | 98 | 89 | 21 | 50 | 9 | 84 | 580 | 7.92 | 906 |
| AL3018 | 24.8 | 91 | 106 | 124 | 21 | 18 | 7 | 121 | 525 | 8.17 | 832 |
| AL3027 | 31 | 134 | 122 | 267 | 62 | 48 | 15 | 135 | 892 | 8.01 | 1410 |
| AL3087 | 31.8 | 154 | 61 | 117 | 21 | 19 | 5 | 112 | 567 | 7.89 | 873 |
| AL1482 | 132 | 182 | 244 | 816 | 118 | 153 | 15 | 341 | 2020 | 7.77 | 3156 |
| AL1480 | 62 | 101 | 171 | 214 | 28 | 30 | 12 | 171 | 758 | 7.31 | 1184 |
| AL1481 | 28 | 173 | 146 | 302 | 43 | 35 | 12 | 201 | 1006 | 7.41 | 1425 |
| AL3467 | 28 | 106 | 220 | 128 | 44 | 56 | 7 | 95 | 685 | 7.42 | 1100 |
| AL1558 | 30 | 106 | 110 | 199 | 53 | 40 | 8 | 95 | 690 | 7.87 | 1075 |
| AL1453 | 48.5 | 202 | 157 | 434 | 113 | 60 | 8 | 175 | 1205 | 8.14 | 1850 |

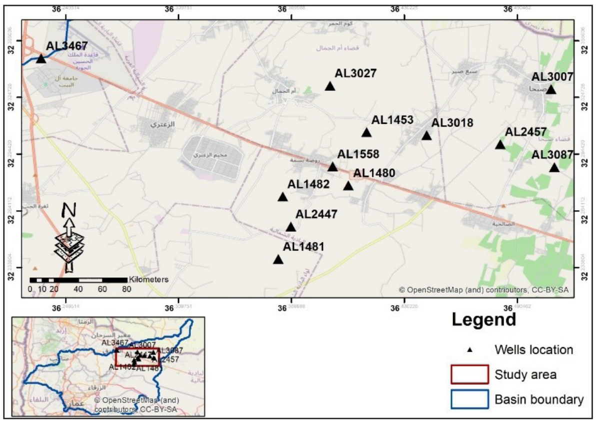

**Figure 3.** Wells locations map used in this

The pH value of the somewhat alkaline groundwater ranged from 7.53 to 8.42, with an average of 8.04. According to Detay, the groundwater type in the Za'atri area is highly mineralised water, as shown by the EC value. Based on the total dissolved solids (TDS) readings, which ranged from 546.49 to 2540.16 mg/L on average (Table 3), the groundwater samples were classified as either fresh or brackish. Based on this classification, 33.3 percent of the groundwater samples in the research region were brackish water from the Za'atri and Umm Al-Jamal areas, which is within the permitted range for TDS according to the Jordanian norm, which is 300 to 1000 mg/L, and according to the WHO guideline, which is less than 1000 mg/L. Because there are approximately 1,600 water wells in our study area, which leads to higher salt levels, groundwater is moving from east to west, especially in the Al Ba'ej area.

**Table 3**. Classification of samples based on TDS and EC Concentrations

| ID | TDS (mg/L) | EC (µS/cm) | WHO Classification | Jordan Classification |
|---|---|---|---|---|
| **AL2447** | 546.49 | 858 | Freshwater | Freshwater |
| **AL2457** | 654.21 | 1032.74 | Freshwater | Freshwater |
| **AL3007** | 622.08 | 971.74 | Freshwater | Freshwater |
| **AL3018** | 568.29 | 900.6 | Freshwater | Freshwater |
| **AL3027** | 1016.84 | 1607.34 | Brackish | Brackish |
| **AL3087** | 617.01 | 950 | Freshwater | Freshwater |
| **AL1482** | 2540.16 | 3968.68 | Brackish | Brackish |
| **AL1480** | 839.83 | 1311.82 | Freshwater | Freshwater |
| **AL1481** | 1127.81 | 1597.54 | Brackish | Brackish |
| **AL3467** | 745.8 | 1197.63 | Freshwater | Freshwater |
| **AL1558** | 752.68 | 1172.65 | Freshwater | Freshwater |
| **AL1453** | 1412.01 | 2167.8 | Brackish | Brackish |

## 5. Spatial Distribution of Major Ions

The concentrations of nitrate, sulfate, bicarbonate, chloride, magnesium, calcium, potassium, and sodium in the water samples indicate the sources and types of dissolved salts in the groundwater. Nitrate in groundwater originates from both natural sources, such as soil organic matter and plant residues, and anthropogenic sources, including fertilizers, animal manure, sewage, and industrial effluents. The nitrate concentration in the groundwater samples in the study area ranged from 11 to 166 mg/L, with an average of 50.3 mg/L. The acceptable limit for nitrate, according to the Jordanian standard, is 50 mg/L as $NO_3^-$, and according to the WHO standards, it is also 50 mg/L as $NO_3^-$ (Figure 4-a).

Sulfate is a naturally occurring anion in groundwater that can originate from the weathering of rocks and minerals containing sulfur compounds, or from anthropogenic sources such as industrial waste, mining activities, and combustion of fossil fuels. The sulfate concentration in the groundwater samples in the study area ranged from 31.26 to 236.7 mg/L, with an average of 147.55 mg/L. The acceptable limit for sulfate according to both the Jordanian standard and the WHO standard is 250 mg/L as $SO_4^{-2}$ (Figure 4-b).

Bicarbonate is a naturally occurring anion in groundwater that can originate from the dissolution of carbonate rocks such as limestone and dolomite, or from biological processes, such as photosynthesis and respiration. Bicarbonate is the main component of alkalinity, which is the capacity of water to neutralize acids.

Bicarbonate can affect the pH, hardness, and corrosion potential of water. The bicarbonate concentration in the groundwater samples in the study area ranged from 66.4 to 236.7 mg/L, with an average of 159.97 mg/L (Figure 4-c). There is no specific limit for bicarbonate in drinking water according to the Jordanian standard or the WHO standard, but it is generally recommended to keep it below 500 mg/L to avoid scaling and corrosion problems.

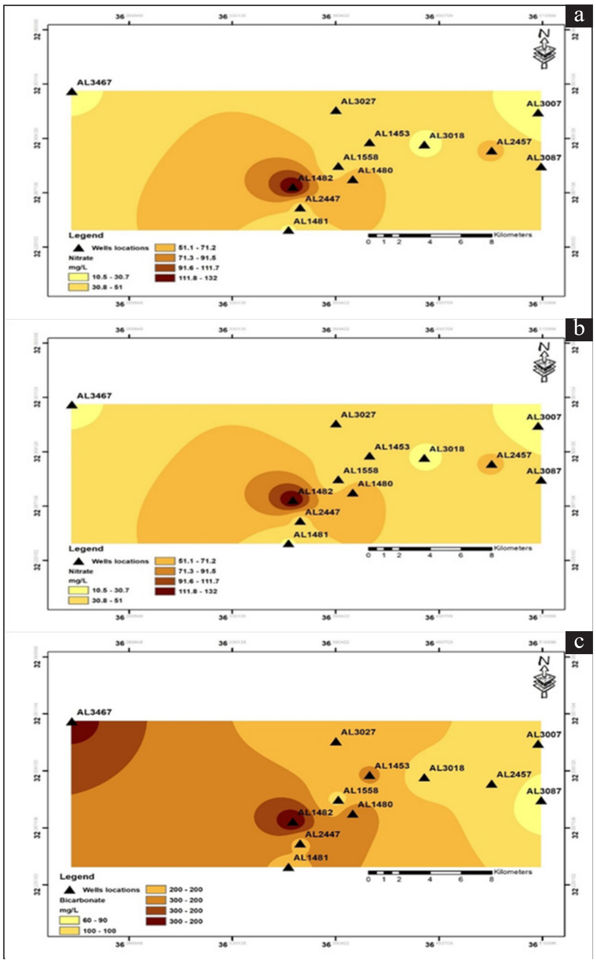

**Figure 4.** Spatial distribution maps of (a) Nitrate ($NO_3^-$), ( b) Sulphate ($SO_4^{-2}$), and (c) Bicarbonate ($HCO_3^-$) generated using the Inverse Distance Weighted (IDW) method in ArcGIS 10.6.1.

Chloride is a naturally occurring anion in groundwater that can originate from the dissolution of halite and other salt minerals, as well as from anthropogenic sources such as seawater intrusion, irrigation return flows, sewage, and industrial effluents. The chloride concentration in the groundwater samples in the study area ranged from 95.46 to 1026.12 mg/L, with an average of 281.41 mg/L. The acceptable limit for chloride, according to the Jordanian standard, is 250 mg/L as $Cl^-$, and according to the WHO standard, is 250 mg/L as $Cl^-$ or 600 mg/L as NaCl (Figure 5-a).

Magnesium is a naturally occurring cation in groundwater that can originate from the dissolution of dolomite and other magnesium-bearing minerals, or from anthropogenic sources such as fertilizers, detergents, and industrial wastes. The magnesium concentration in the groundwater samples in the study area ranged from 18.32 to 148.4 mg/L, with an average of 54.2mg/L. There is no specific limit for magnesium in drinking water according to the Jordanian standard or the WHO guideline, but it is generally recommended to keep it below 150 mg/L to avoid adverse effects (Figure 5-b).

Calcium is a naturally occurring cation in groundwater that can originate from the dissolution of calcite and other calcium-bearing minerals, as well as from anthropogenic sources such as fertilizers, lime, and cement. The calcium concentration in the groundwater samples in the study area ranged from 18.60 to 192.4 mg/L, with an average of 54.2 mg/L. There is no specific limit for calcium in drinking water according to the Jordanian standard or the WHO guideline. Still, it is generally recommended to keep it below 200 mg/L to avoid adverse effects. Potassium is a naturally occurring cation in groundwater that can originate from weathering of feldspar and other potassium-bearing minerals, or from anthropogenic sources such as fertilizers, detergents, and industrial wastes (Figure 5-c).

The potassium concentration in the groundwater samples in the study area ranged from 5.39 to 18.9 mg/L, with an average of 10.44 mg/L. There is no specific limit for potassium in drinking water according to the Jordanian standard or the WHO guideline, but it is generally recommended to keep it below 50 mg/L (Figure 5-d). Sodium is a naturally occurring cation in groundwater that can originate from the dissolution of halite and other sodium-bearing minerals, or anthropogenic sources such as seawater intrusion, irrigation return flows, sewage, and industrial effluents. The sodium concentration in the groundwater samples in the study area ranged from 84 to 341 mg/L, with an average of 144.92 mg/L. The acceptable limit for sodium according to the Jordanian standard is 200 mg/L as $Na^+$, and according to the WHO guideline is 200 mg/L as $Na^+$ or 500 mg/L as NaCl (Figure 5-e).

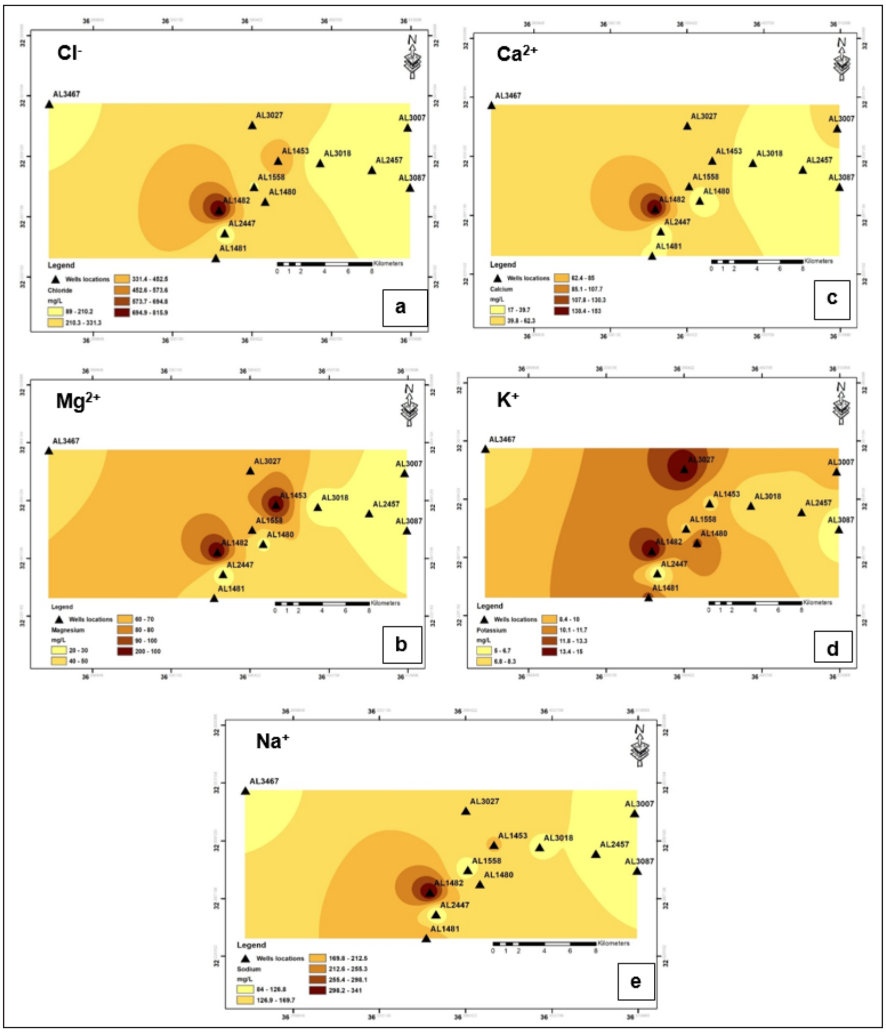

**Figure 5.** Spatial distribution maps of (a) Chloride), ( b) Magnesium, (c) Calcium , (d) Potassium, and (e) Sodium generated using the Inverse Distance Weighted (IDW) method in ArcGIS 10.6.1.

Groundwater samples exhibit a wide range of values, indicating high variability in their hydrogeochemical characteristics. These samples can be categorized into three primary groups based on their dominant anions and cations: the Chloride Group ($Cl^-$ dominant), the Bicarbonate Group ($HCO_3^-$ Dominant), and Sodium Group ($Na^+$ Dominant). The Chloride group is the most prevalent, with six samples having Classicism, the dominant anion, and the sodium group is the most common among the cations, with nine samples showing $Na^+$ as the dominant cation. The Chloride group has the highest salinity, with an average TDS of 810 mg/L. The Bicarbonate group has the highest alkalinity, with an average $HCO_3^-$ concentration of 153 mg/L. The Magnesium group is noted for its hardness, with an average $Mg^{+2}$ concentration of 44 mg/L. The groundwater can be classified into three types based on the combination of dominant anions and cations: Saline Water ($Cl^-$ and $Na^+$), Carbonate Water ($HCO_3^-$ and $Ca^{+2}$), and Sulfate Water ($SO_4^{-2}$ and $Mg^{+2}$).

## 6. Statistical analysis

Through statistical analysis, we can sift through vast amounts of data and draw conclusions about broader patterns. This analysis aims to determine the relationship between the water quality measures. All eleven of the observed parameters have their calculated correlation matrices presented in Table 4. We measured eleven parameters: NO, SO, HCO, Cl, Mg, Ca, K, Na, TDS, pH, and EC. Almost all of the parameters exhibit unidirectional variation, except for pH, which exhibits bidirectional variation, as shown in Table 4. Overall, there are strong positive correlations ($r > 0.9$) between all the parameters, except for pH, which exhibits a slight negative correlation ($r < -0.3$) with the other parameters. The strongest relationships are observed when there is a relationship between total dissolved solids (TDS) and electrical conductivity (EC), between chloride ($Cl^-$) and TDS, between $Cl^-$ and EC, between calcium ($Ca^{+2}$) and $Cl^-$, between $Ca^{+2}$ and TDS, between $Ca^{+2}$ and EC, between magnesium ($Mg^{+2}$) and $Cl^-$, between $Mg^{+2}$ and TDS, between $Mg^{+2}$ and EC, between sodium ($Na^+$) and $Cl^-$, between $Na^+$ and TDS, and between $Na^+$ and EC. The evaporite minerals halite (NaCl) and gypsum ($CaSO_4$) have the and most significant impact on these parameters because their concentration in groundwater increases, as seen in these correlations. The weakest correlations were observed between pH and nitrate ($NO_3^-$), sulphate ($SO_4^{-2}$), and magnesium ($Mg^{+2}$), among others. These metrics appear to be loosely associated according to the correlations, and their content in water samples may originate from several sources or be the result of distinct processes. To illustrate, pH is primarily controlled by the carbonate equilibrium and the partial pressure of carbon dioxide; $NO_3^-$ is primarily produced by organic matter decomposition and agricultural fertilisers; $SO_4^{-2}$ is obtained mainly from the dissolution of gypsum and the oxidation of sulphide minerals; and $Mg^{+2}$ is primarily derived from the dissolution of dolomite. Parameters such as $K^+$ and $Cl^-$, $K^+$ and $Ca^{+2}$, $NO^-$ and $SO_4^{-2}$, $SO_4^{-2}$ and bicarbonate ($HCO_3^-$), and so on exhibit moderate correlations with each other ($0.7 < r < 0.9$). A closer examination of the correlations between these factors and their concentrations in water samples reveals that they are relatively interconnected and share a common source of influence. So, $K^+$ and Cl are produced by silicate weathering and halite dissolution; dolomite dissolution and ion exchange by fertilisers and organic matter oxidation; $NO_3^-$ and $SO_4^{-2}$ by gypsum dissolution and sulphide oxidation; and so on.

**Table 4**. Correlation coefficient matrix of water quality parameters

| parameters | No$_3^-$ | SO$_4^{-2}$ | HCO$_3^-$ | CL$^-$ | Mg$^{+2}$ | Ca$^{+2}$ | K$^+$ | Na$^+$ | TDS | PH | EC |
|---|---|---|---|---|---|---|---|---|---|---|---|
| No$_3^-$<br>SO$_4^{-2}$<br>HCO$_3^-$ | 1 | | | | | | | | | | |
| CL$^-$ | 0.20056 | 1 | | | | | | | | | |
| Mg$^{+2}$ | 0.67233 | 0.07215 | 1 | | | | | | | | |
| Ca$^{+2}$ | 0.83488 | 0.54906 | 0.6469 | 1 | | | | | | | |
| | 0.61947 | 0.61045 | 0.5774 | 0.8927 | 1 | | | | | | |
| K$^+$ | 0.75784 | 0.49082 | 0.7166 | 0.8989 | 0.80784 | 1 | | | | | |
| Na$^+$ | 0.47752 | 0.41648 | 0.4337 | 0.6516 | 0.50863 | 0.59075 | 1 | | | | |
| TDS | 0.85207 | 0.52422 | 0.6288 | 0.9424 | 0.72589 | 0.7979 | 0.69522 | 1 | | | |
| | 0.81689 | 0.59469 | 0.6761 | 0.9936 | 0.88853 | 0.91859 | 0.67591 | 0.9431 | 1 | | |
| PH | -0.1021 | 0.20099 | -0.4894 | -0.017 | 0.15615 | -0.0681 | -0.1905 | -0.153 | -0.058 | 1 | |
| EC | 0.83349 | 0.57229 | 0.6879 | 0.9925 | 0.89231 | 0.93353 | 0.67067 | 0.9333 | 0.998 | -0.0381 | 1 |

## 7. Groundwater quality assessment

The data obtained by hydrogeochemical analyses of 12 groundwater samples of the study area were evaluated in terms of their suitability for drinking and domestic uses.

### *7.1 Portability of groundwater for drinking and domestic uses*

The physical and chemical parameters of the analytical results of groundwater were compared with the standard guideline values recommended by the World Health Organisation (WHO 2011) and the Water Authority of Jordan (WAJ 2002). for drinking and domestic purposes (Table 5).

**Table 5**. Guidelines of the WHO and WAJ standards of water for drinking and domestic purposes

| | | WHO (2011) | | WAJ (2002) | |
|---|---|---|---|---|---|
| **Parameters** | **Unit** | **Guideline value (the maximum desirable limit for drinking purposes** | **Highest permissible limit (highest permissible limit for domestic purposes** | **Maximum desirable limit (Maximum desirable limit for drinking purposes** | **Maximum permissible limit (the highest permissible limit for domestic purpose** |
| $SO_4^{-2}$ | mg/L | 250 | 400 | 250 | 400 |
| $HCO_3^-$ | mg/L | N/A | N/A | N/A | N/A |
| $Cl^-$ | mg/L | 250 | 600 | 250 | 600 |
| $NO_3^-$ | mg/L | 50 | 50 | 50 | 50 |
| $Mg^{+2}$ | mg/L | N/A | N/A | N/A | 150 |
| $Ca^{+2}$ | mg/L | N/A | N/A | N/A | 200 |
| $Na^+$ | m g/L | 200 | 200 | 200 | 200 |
| $K^+$ | m g/L | N/A | N/A | N/A | N/A |
| TDS | m g/L | 1000 | N/A | 1000 | 1500 |
| EC | µS/cm | N/A | N/A | N/A | N/A |
| PH | Unitless | 6.5-9.5 | 7.0-8.5 | 6.5-9.5 | 7.0-8.5 |

The groundwater quality in the study area varies according to different parameters and standards. While the pH is within the safe range of 6.5–8.5 for both WHO and WAJ standards, some samples have high concentrations of TDS, $SO_4^{-2}$, $Cl^-$, $NO_3^-$, $Na^+$ , $Ca^{+2}$ , and $Mg^{+2}$ that exceed the desirable or permissible limits for drinking water quality. The most common parameters that exceed both standards are TDS, $Cl^-$, and $Na^+$ , affecting more than a third of the samples. $NO_3^-$ is another parameter that exceeds both standards, affecting about a quarter of the samples, and poses serious health risks such as methemoglobinemia, gastric cancer, goiter, birth malformations, and hypertension.

Evaluation of water quality index WQI is a critical way to assess the quality of water because it helps to understand water quality issues by integrating complex data. For computing WQI, each of the 11 parameters (pH, TDS, $Cl^-$, $NO_3^-$ , $SO_4^{2-}$, $HCO_3^-$ , $Ca^{+2}$, $Mg^{+2}$, $Na^{+,}$ $K^+$ ,and EC ) is assigned a weight (wi) according to its relative importance in the overall quality of water for drinking purposes.

The relative weight (Wi) for each parameter is computed according to Tiwari & Mishra (1985). The calculated relative weight value of each parameter is presented (Table 6).

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

**Table 6**. Relative weights of chemical parameters

| Parameter | Weight (wi) | Standards (WHO, JS286) | Relative weight (Wi) |
|---|---|---|---|
| $K^+$ | 1 | 6.5-8.5 | 0.022 |
| $Na^+$ | 2 | 1000 | 0.044 |
| $Ca^{2+}$ | 3 | 250 | 0.067 |
| $Mg^{2+}$ | 3 | 50 | 0.067 |
| $SO_4^{-2}$ | 4 | 250 | 0.089 |
| Ph | 4 | 200 | 0.089 |
| TDS | 5 | 150 | 0.111 |
| $Cl^-$ | 5 | 200 | 0.111 |
| $NO_3^-$ | 5 | 200 | 0.111 |
| $HCO_3^-$ | 5 | 50 | 0.111 |

The maximum weight of 4 is assigned to pH due to its major importance in quality assessment. The minimum weight of 1 is given to $K^+$ as it plays an insignificant role in the water quality assessment. Other parameters are assigned weights between 2 and 5 depending on their importance in water quality determination.

The quality rating scale (qi) for each parameter was obtained by using the following equation

$$qi = \frac{ci}{si} * 100 \tag{2}$$

where qi is the quality rating, Ci is the concentration of each chemical parameter in each water sample in mg/L, and JISM standard for each chemical parameter is in mg/L. Finally, the calculated water quality index determined the SI for each chemical parameter

$$SI = wi * qi \tag{3}$$

$$WQI = \sum SIi \tag{4}$$

Where SIi is the sub-index of the ith parameter; qi is the rating based on the concentration of the ith parameter. The WQI for each sample is shown in Table 7.

**Table 7**. Water Quality Index (WQI) value of groundwater in the study area

| ID | WQI |
|---|---|
| AL1453 | **66.67** |
| AL1480 | **39.72** |
| AL1481 | **53.33** |
| AL1482 | **119.64** |
| AL1558 | **35.63** |
| AL2447 | **25.81** |
| AL2457 | **30.94** |
| AL3007 | **36.42** |
| AL3018 | **26.89** |
| AL3027 | **48.12** |
| AL3087 | **38.1** |
| AL3467 | **35.28** |

WQI classifies the waters into five categories (Excellent, Good, Poor, etc.) as shown in Table 8.

**Table 8**. Classification of WQI range and category of water

| WQI Range | Category of water |
|---|---|
| 0-50 | Excellent |
| 51-100 | Good |
| 101-175 | Fair |
| 176-300 | Poor |
| <300 | Very poor |

The average WQI of 46.38 for all samples indicates that the groundwater quality in the research area is excellent. But the fact that water quality varies geographically means that this average can be misleading. Water quality index (WQI) values ranging from 119.64 for the sample taken at Al 1482 indicate that the water quality is fair and might require substantial treatment prior to use. The high quantity of TDS in this sample is primarily responsible for the high WQI result (Table 9). According to the statistics, 75% of the samples scored an Excellent on the Water Quality Index (WQI), meaning they don't need any treatment to be suitable for consumption or other uses. Water quality that is satisfactory but may benefit from treatment is indicated by 16.67% of the samples classified as Good. The water may require substantial treatment before consumption, as just 8.33% of the samples are classified as fair, suggesting slight contamination. The samples are not usable because they are not in the poor or very poor categories, which means they are not highly or seriously polluted.

**Table 9.** Water Quality Index (WQI) Classification of the study area

| ID | Category |
|---|---|
| AL1453 | Good |
| AL1480 | Excellent |
| AL1481 | Good |
| AL1482 | Fair |
| AL1558 | Excellent |
| AL2447 | Excellent |
| AL2457 | Excellent |
| AL3007 | Excellent |
| AL3018 | Excellent |
| AL3027 | Excellent |
| AL3087 | Excellent |
| AL3467 | Excellent |

## 8. Conclusion

The Amman-Zarqa Basin can be a great source of fascination, considering that it is characterized by many diverse geological formations, which primarily affect groundwater quality. Groundwater in this region is highly varied in its chemical composition, reflecting the diverse rock types and human activities present. The water quality in general complies with the standards for drinking and domestic use as defined by the World Health Organization (WHO) and the Water Authority of Jordan (WAJ). Yet, in certain areas, some elevated concentrations of total dissolved solids (TDS), chloride ($Cl^-$), and nitrate ($NO_3^-$) can be observed, which may potentially occur as a result of agricultural activity and groundwater overabstraction. Salinity variation between different points is notable. With high agricultural activities in Za'atri and Umm Al-Jamal, the salinity is high.

' 'It's probably related to growers using fertilizers and overpumping the water table, concentrating salt in the water. The hydrochemical facies of the groundwater samples are observed to be different, with bicarbonate–calcium and chloride–sodium varieties. Such an outcome indicates that both natural geological formations and human activities influence water chemistry. Overall, the current groundwater quality remains relatively stable compared to data from 1998. Nevertheless, a few increases in TDS and nitrate levels in certain parts of the basin show continuing effects from agricultural practices and groundwater pumping. The sustainability of groundwater resources in the Amman-Zarqa Basin must be ensured through continuous monitoring and good management.

This study provides policymakers and stakeholders with valuable insights for planning effective groundwater management and protection strategies. In essence, the groundwater in the Amman Zarqa Basin is suitable for use, but management is required to address areas with a higher level of contamination, as well as to ensure the future sustainability of this valuable natural resource.

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