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Groundwater Assessment for Sustainable Development in Al-Arish Area, Northern Sinai, Egypt

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Abstract: The al-Arish area occupies part of the northwest corner of the Sinai Peninsula, representing an important region for Egypt's development. Rapid population increase, economic activities, and climate change affect groundwater resources, which are considered the main resource used for drinking, domestic, and agricultural purposes in this region. This study evaluates the quality of groundwater for drinking and irrigation purposes. Fourteen groundwater samples were collected, analyzed for different physicochemical parameters, evaluated, and compared to WHO standards, and maps for their spatial distribution were constructed using ArcGIS 10.4.1 software. The Water Quality Index is calculated showing an average of 54.13 for the area representing poor water quality. The water quality is classified as good, poor, and very poor in 71%, 14.5%, and 14.5% of the samples.

SAR, Na%, and RSC measures were employed to assess the suitability of groundwater for irrigation purposes. According to SAR, 78.6 % of the samples are Good for irrigation. Na% classification indicates Suitable water for irrigation, except for one sample only. The results of RSC showed that all the groundwater samples are Suitable for irrigation.

The Piper and USSL analyses confirmed important mineralization and salinity hazards due to seawater intrusion due to the nearness of the study area to the Mediterranean Sea and the overexploitation of aquifers. The study highlighted the need for sustainable water management plans, advanced irrigation methods, and governmental efforts.

Keywords: Water Quality Index, Sodium Absorption Ratio, Sodium Percent, Residual Sodium Carbonate, Salinity Hazards, Piper Tri-linear Diagram, USSL Diagram.

1. INTRODUCTION

Sinai is an important area as Egypt's eastern boundary. Therefore, it is necessary to carry out different development activities, including socioeconomic, education, agriculture, industry, and other fields. Groundwater is the main source of water for agriculture, municipal, drinking, and industry. In addition to the population's rapid growth over the past ten years, Sinai's economy has grown, raising the region's water needs. In general, the Sinai Peninsula's groundwater supply cannot keep up with the expected rise in water needs. To fully utilize the surface and groundwater resources at reasonable costs, serious water development strategies have been established.

Groundwater chemistry is affected mainly by two factors: the mineral composition of the host rocks it interacts with, and the length of time of this interaction. Various chemical processes affect the characteristics of groundwater, such as acid-base reactions, mineral precipitation and dissolution, absorption and ion exchange, oxidation-reduction reactions, biological degradation, and the release and dissolution of gases [1] Assessing groundwater quality is essential, as it is as significant as quantity. To determine its suitability for various uses, chemical, physical, and bacteriological examinations are essential [2]. Field measurements of parameters like electrical conductivity (EC), hydrogen ion concentration (pH), and temperature should be taken on time upon sampling, as groundwater chemistry can change rapidly once exposed to light, temperature variations, air, or other environmental factors [3].

Unfortunately, pollution of groundwater has become a major socioeconomic issue across countries [4], made worse by the effects of global climate change, industrial and agricultural activities, and fast urbanization [5], [6]. It becomes essential to give planning authorities instructions to guarantee sustainable planning and the preservation of uncontaminated groundwater resources [7]. Monitoring the quality of water for domestic and drinking purposes is therefore an essential duty for every country, giving researchers and local authorities comprehensive information to help them make informed decisions [8]. The two main ways that well water can become contaminated are when the aquifer that the well draws water from is contaminated, and when surface water that contains contaminants enters the well through damaged well structures (Lapworth, et al., 2017; Thomas et al., 2020). For instance, the Dakahlia Governorate in Egypt had the most significant values for total dissolved solids in groundwater [12]. Therefore, when evaluating the water quality, the well's kind, age, and depth are very important.

Groundwater quality has been regularly assessed and monitored in recent years using the Geographic Information System (GIS) technique in conjunction with the inverse distance weighting (IDW) interpolation method. This technique is an effective tool for analyzing and assessing spatial data related to water resources and various groundwater quality parameters [13], [14], [15], [16], [17], [18], [19]. It is a time-efficient and economically feasible method for transforming large data sets to create various spatial distribution maps and projections that reveal trends, associations, and sources of contaminants.

The WQI was initially developed according to the weighted arithmetic computation of the groundwater parameters (Horton, 1965). Several researchers developed several WQI models based on the weighted arithmetic method's rating and weighing of different water quality criteria [21], [22], [23], [24], [25], [26]. With values ranging from 0 to 100, the WQI is a dimensionless number. Based on a variety of water quality factors, the WQI is a unique digital rating expression that expresses the overall state of the water quality at a specific location and time, such as excellent, good, poor, and very poor. As a result, the WQI is an important tool for comparing groundwater quality and management.

The purpose of this study is to analyze and assess groundwater quality for the Al-Arish area in the Sinai Peninsula for sustainable development. In this study, groundwater samples taken from wells had their physicochemical characteristics assessed and compared to WHO international requirements for drinking and domestic uses based on the Water Quality Index (WQI). Because of the intense agricultural activity in the study area, a thorough evaluation of the groundwater's suitability for irrigation is provided in this study including some indices like Sodium Absorption Ratio (SAR), Sodium Percent (Na%), and Residual Sodium Carbonate (RSC).

2. Materials and Methods

2.1 Al-Arish Area, Sinai, Egypt

As shown in Figure 1, the Sinai Peninsula occupies roughly 6% of Egypt's overall land area, with a total size of 61,000 km². Water is the primary constraint on Sinai's natural resources, and its growth potential is minimal [27].

The al-Arish area is a promising area for agricultural and industrial projects, but the sustainable development of the area is slowed due to the pollution hazards and increasing salinity due to over-exploitation of the limited water resources.

Its boundaries are latitudes 33°44′16.7”– 33°53′24.1” and longitudes 31°02′11.6”–31°10′18.5”. Its base is north, stretching about 210 kilometers between Port Said and Rafah Cities along the Mediterranean coast. Near the town of Al-Arish, the huge Wadi Al-Arish empties into the Mediterranean Sea, collecting drainage from a sizable northern plateau area. Al-Arish city is 344 km away from Cairo the capital of Egypt.

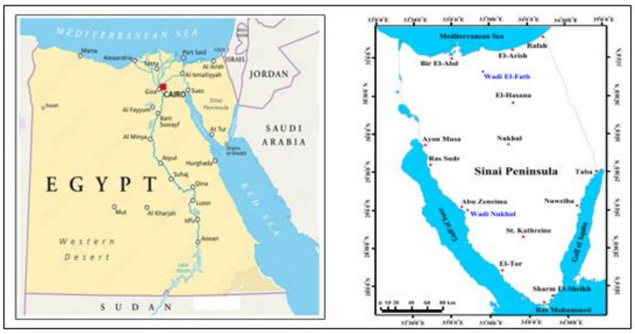

Fig 1. Al-Arish Area, Sinai Peninsula, Egypt

2.2 Sampling and Methods

Fourteen samples were collected during January and February 2024 from municipal groundwater pumping stations and private wells in the Al-Arish area, as shown in Figure 2. Groundwater samples were collected in aped polyethylene bottles, prewashed with detergent, and rinsed thrice with water. The samples were collected after allowing the water to run for at least 20 minutes to stabilize the variation in electric conductivity (EC) and Temperature [28]. Each sample was collected in two bottles: one was sent to be analyzed on the same day, while the other was subsequently preserved using one drop of concentrated nitric acid for each 100 ml sample before analysis to minimize changes in the physiochemical characteristics of the water [29].

The groundwater samples were analyzed for hydrogen ion concentration (pH), electrical conductivity (EC), total dissolved solids (TDS), major cations (Na^+, K^+, Ca^{2+}, Mg^{2+}), major anions (Cl^-, SO_4^{2-}, NO_3^-, CO_3^{2-}, HCO_3^-), alkalinity (Alk), iron (Fe), manganese (Mn), copper (Cu), zinc (Zn), and barium (Ba).

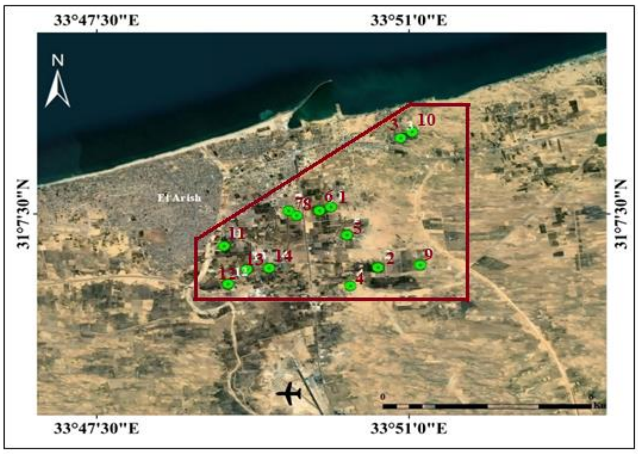

Fig 2. Wells for Groundwater Samples in the Al-Arish Area

Electrical conductivity (EC) was determined in situ using a digitally combined electrode (HANNA HI 991300). Samples were filtered in the laboratory using a 45-µm filter and analyzed for chemical constituents according to [30]. Whole water analysis was performed 1 day after sampling and storage at 4°C. A flame photometer was used to determine Na and K. Volumetric methods were used to measure Ca, Mg, CO_3, HCO_3, and Cl.

3. Groundwater Quality Parameters

The results of the groundwater analyses used to get the WQI are presented in Table 1. From Table 1, concerning Min values of the groundwater quality parameters, it was found that Min pH is in well S7, Min TDS, EC, Na, and Cl are in well S11, Min Ca and SO_4 are in well S5, Min K and HCO_3 are in well S9, and finally Min Mg is in well S4. Also, it was found that Max pH is in wells S11 and S12, Max TDS, EC, Na, Mg, HCO_3, Cl, and SO_4 are in well S7, Max Ca is in well S4, and Max K is in well S3.

Table 1. Groundwater Quality Parameters Analysis

Sample No.	PH	TDS (mg/L)	EC (µS/cm)	Na (mg/L)	Ca (mg/L)	Mg (mg/L)	K (mg/L)	HCO_3 (mg/L)	Cl (mg/L)	SO_4 (mg/L)
S1	7.92	4320	6750	980	312.78	147.20	11.0	163	1884.0	585.0
S2	7.46	4640	7250	1020	319.59	182.90	29.0	148	2011.0	641.0
S3	7.91	4947	7730	1060	425.06	219.67	32.0	126	2964.0	578.2
S4	7.66	8947	13980	1600	914.20	130.73	20.0	213	3736.0	1331.5
S5	7.88	4300	6720	970	289.50	171.07	15.0	146	1789.0	553.5
S6	7.83	5677	8870	1100	353.20	238.30	25.0	243	2366.0	892.0
S7	7.03	9190	14360	2100	906.26	507.80	18.0	283	4353.4	2384.1
S8	7.30	6960	10870	1850	641.60	352.35	12.0	248	3099.9	2321.8
S9	7.47	5030	7860	1135	396.99	223.56	8.8	107	2558.5	660.5
S10	7.80	4260	6660	960	376.79	191.97	10.0	120	2081.3	610.9
S11	8.02	4110	6420	800	525.31	225.99	29.0	156	1577.6	1286.4
S12	8.02	6140	9600	1125	882.20	330.48	24.0	234	2962.6	1733.3
S13	7.88	5720	8930	1100	834.08	296.46	24.0	219	2609.8	1721.9
S14	7.61	7060	11030	1370	850.12	371.79	30.0	204	3613.8	1687.3

Sample No.	PH	TDS (mg/L)	EC (µS/cm)	Na (mg/L)	Ca (mg/L)	Mg (mg/L)	K (mg/L)	HCO_3 (mg/L)	Cl (mg/L)	SO_4 (mg/L)
Mean	7.83	5816	9073.6	1221.3	559.29	253.39	21.5	181.9	2685.9	1176.9
Median	7.82	5353.5	8365	1100	475.19	224.78	22.0	183.5	2584.2	1089.2
SD	0.62	1566.7	2532.9	348.1	240.67	97.64	348.1	54.07	761.2	86.4
Min	7.03	4110	6420	800	289.50	130.73	8.8	107	1577.6	553.5
Max	8.02	9190	14360	2100	914.20	507.80	32.0	283	4353.4	2384.1

It was noticed that well S3 has Max K; well S4 has Max Ca and Min Mg; well S5 has Min Ca and SO_4, well S7 has Min pH and Max TDS, EC, Na, Mg, HCO_3, Cl, and SO_4; and well S9 has Min K and HCO_3. Well S11 has Max pH and Min TDS, EC, Na, and Cl; and well S12 has Max pH too.

The pH of the water under study ranged from 7.03 to 8.02 averaging 7.83 making it slightly alkaline. All the groundwater samples are within the preferred limit, 6.5-8.5, [31].

The total dissolved solids (TDS) values ranged from 4110 to 9190 mg/L. The high values of TDS can be explained by seawater intrusion and upconing from the underlying mineralized tertiary aquifer due to excessive extraction from the quaternary aquifer in all the study area. The groundwater in the study area is classified as brackish water at wells 1, 2, 3, 5, 10, and 11; and is classified as salt water at wells 4, 6, 7, 8, 9, 12, 13, and 14 [32]

The electrical conductivity (EC) values ranged from 6420 to 14360, averaging 9073.57 µS/cm. EC reflects the amount of total dissolved solids and serves as an indirect indicator of salinity. The high concentration of TDS and the mineralization of organic materials caused the high EC level. Also, the conductivity of water increases by approximately 2% for each 1°C rise in temperature [33].

Figures 3 and 4 show spatial distribution maps of the groundwater quality parameters in the study area. These maps were created using ArcGIS 10.4.1 applying the inverse distance weighting (IDW). These maps help with environmental monitoring, understanding, and foreseeing the spread of pollutants.

From Figure 3, the north and west of the study area have a very high pH distribution (high alkalinity) because of increased human activities and salt production. TDS and EC are characterized by irregular distribution reaching their minimum concentrations in the northeast and then increasing gradually to reach their maximum concentrations at the central north and south parts of the study area. It is found that the maximum concentration of Na is in the central north part.

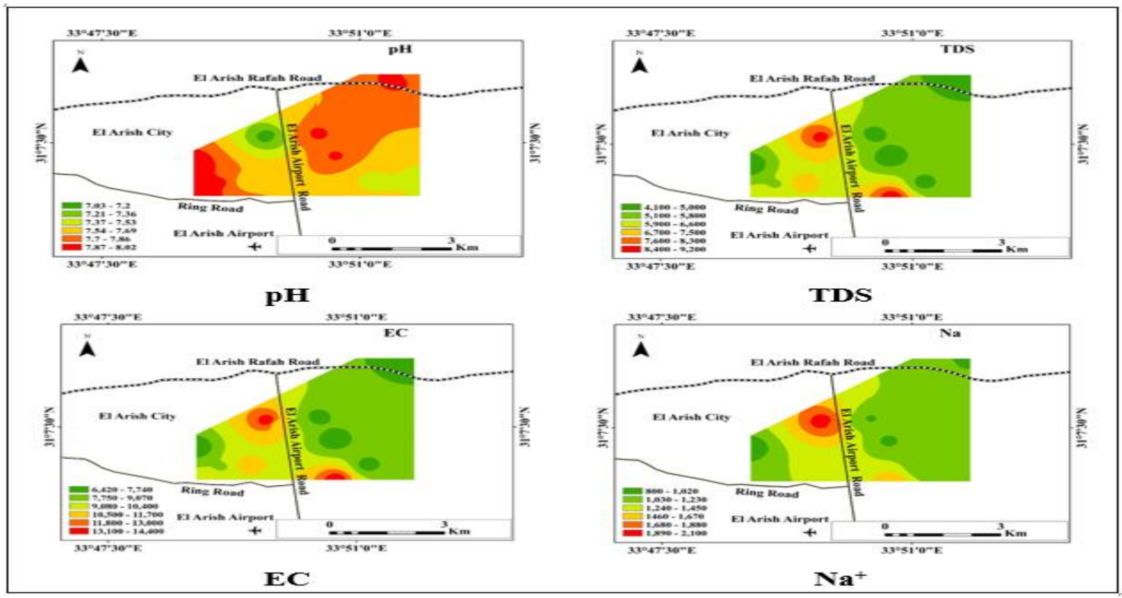

Fig 3. Spatial Distribution Maps for pH, TDS, EC, and Na in Al-Arish Area

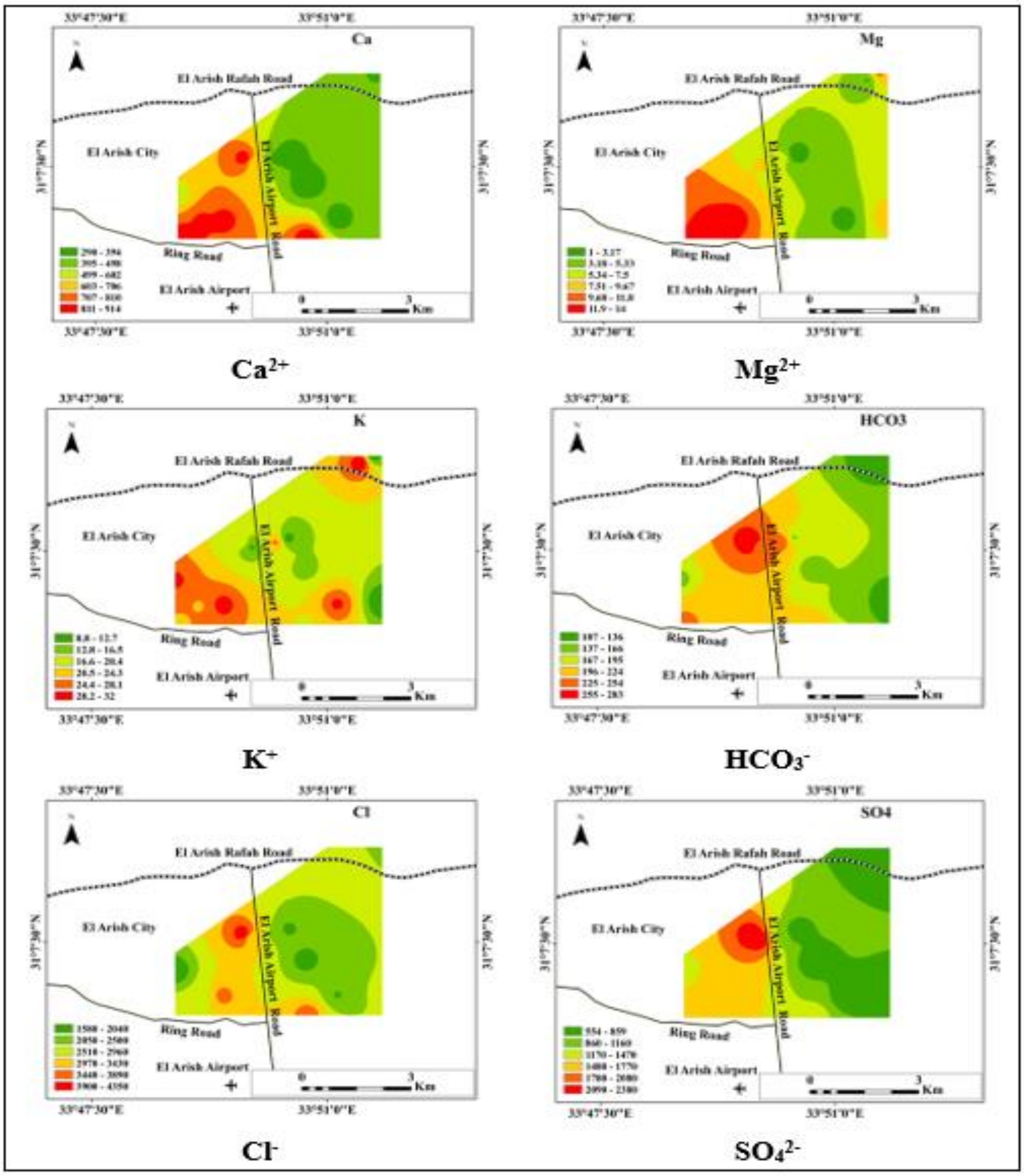

Fig 4. Spatial Distribution Maps for Ca, Mg, K, HCO_3, Cl, and SO_4 in Al-Arish Area

From Figure 4, the maximum concentrations of Ca were in the western half of the study area. The maximum concentrations of Mg were in the western parts, and the maximum concentrations of K were in the western parts and small parts in the north and south. The maximum concentrations of HCO_3, SO_4, and Cl are mainly in the central north parts.

4. Water Quality Index (WQI)

The WQI has been determined using the drinking water quality standard recommended by the World Health Organization [34]. The Water Quality Index has been calculated using the weighted arithmetic method, which was originally proposed by [35] and developed by [36].

The weighted arithmetic water quality index (WQI) is represented by:

$$WQI = \sum_{i=1}^{n} WiQi / \sum_{i=1}^{n} Wi \quad (1)$$

where: n = number of parameters, Wi = unit weight for the i^{th} parameter, and Qi = quality rating (sub-index) of the i^{th} water quality parameter.

The unit weight (Wi) of the water parameters is inversely proportional to the recommended standards for the corresponding parameters.

$$Wi = K/Sn \quad (2)$$

where: K = proportional constant and Sn = standard value for i^{th} parameters

The value of K was considered '1'.

$$K=1/\sum\left(\frac{1}{Sn}\right) \quad (3)$$

$$Qi=100\,[(V_0-V_i)\,/\,(S_n-V_i)] \quad (4)$$

where: Vo = observed value of i^{th} parameter at a given sampling site, Vi = ideal value of i^{th} parameter in pure water. All the ideal values (Vi) are taken as zero for drinking water except pH and dissolved oxygen [37]. 7.0 is the ideal value of pH (for natural/ pure water), while the permissible value is 8.5 (for polluted water). Concerning dissolved oxygen, the ideal value is 14.6 mg/L while the standard permissible value for drinking water is 5 mg/L.

$Qi = 0$ (absence of contaminants), $0 < Qi < 100$ (contaminants are within the prescribed standard), and $Qi > 100$ (contaminants are above the standards).

In this study, WQI has been considered as illustrated in Table 2 [36], [38], [39]. The calculated WQI for the Al-Arish area is presented in Table 3, and the WQI distribution in the Al-Arish area is shown in Figure 5.

Table 2. Weighted Arithmetic WQI Classification of Water Quality

WQI	Classification
0–25	Excellent
26–50	Good
51–75	Poor
76–100	Very Poor
>100	Unsuitable

Table 3. WQI for the Al-Arish Area

Sample No.	Well	WQI	Classification
S1	N1	49.36	Good
S2	N2	87.34	Very Poor
S3	N9	54.82	Poor
S4	N12	72.60	Poor
S5	R18	48.51	Good
S6	R26	91.74	Very Poor
S7	Private	42.93	Good
S8	Private	44.68	Good
S9	Private	45.53	Good
S10	Private	45.45	Good
S11	Private	42.75	Good
S12	Private	42.93	Good
S13	Private	43.31	Good
S14	Private	45.86	Good
Average WQI		54.13	Poor

The average WQI for the area is 54.13 representing poor water quality. It is concluded that the water quality is good, poor, and very poor in 71%, 14.5%, and 14.5% of the studied samples, as shown in Figure 6.

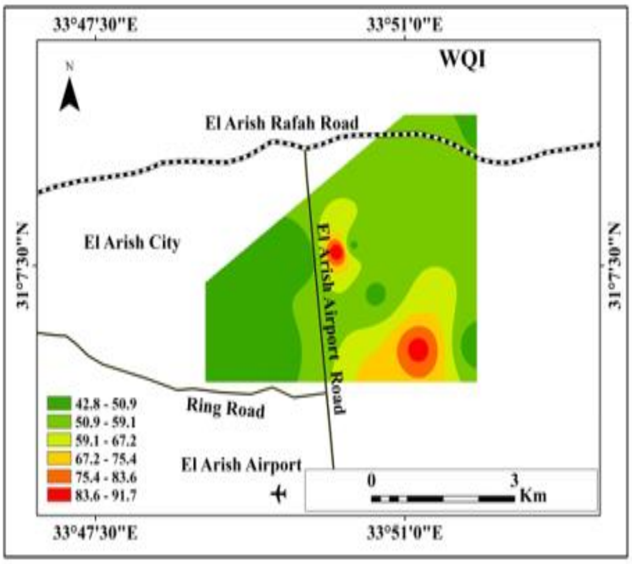

Fig 5. WQI Distribution in Al-Arish Area

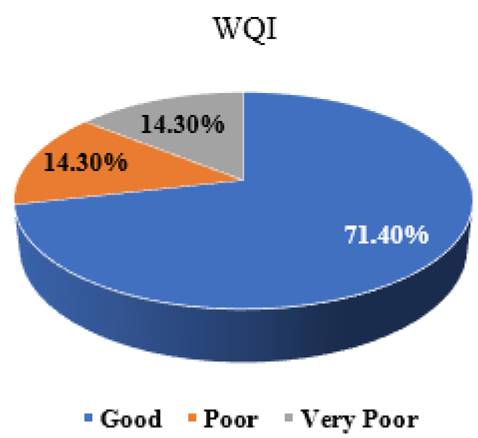

Fig 6. WQI Percentage Ratios in Al-Arish Area

5. Evaluating Groundwater Quality for Irrigation

Groundwater quality was evaluated to examine its suitability for irrigation purposes by investigating the measures of SAR, Na%, and RSC. Classification of water quality according to these measures is shown in Table 4. The obtained results are presented in Table 5.

5.1 Sodium Absorption Ratio (SAR)

According to [40]: $SAR = Na^{+}/[(Ca^{2+} + Mg^{2+})/2]^{1/2}$

Table 4. Classification of Water Quality for Irrigation Purposes

Measure	Range	Water Quality for Irrigation
SAR	< 10	Excellent
	10-18	Good
	18-26	Fair
	> 26	Unsuitable
Na %	< 20	Excellent
	20-40	Good
	40-60	Permissible
	60-80	Doubtful
	> 80	Unsuitable
RSC	< 1.25	Safe
	1.25-2.5	Marginal
	> 2.5	Unsuitable

Table 5. Results of Water Quality for Irrigation Purposes

<table>
<tr><th>Sample</th><th colspan="2">SAR</th><th colspan="2">Na %</th><th colspan="2">RSC</th></tr>
<tr><td>S1</td><td>16.13</td><td rowspan="3">Good</td><td>60.58</td><td>Doubtful</td><td>-25.23</td><td rowspan="14">Safe</td></tr>
<tr><td>S2</td><td>15.87</td><td>59.09</td><td rowspan="13">Permissible</td><td>-28.79</td></tr>
<tr><td>S3</td><td>14.66</td><td>54.25</td><td>-37.49</td></tr>
<tr><td>S4</td><td>18.49</td><td>Fair</td><td>55.32</td><td>-53.11</td></tr>
<tr><td>S5</td><td>15.74</td><td rowspan="3">Good</td><td>59.70</td><td>-26.34</td></tr>
<tr><td>S6</td><td>16.75</td><td>58.81</td><td>-33.68</td></tr>
<tr><td>S7</td><td>15.62</td><td>56.37</td><td>-33.53</td></tr>
<tr><td>S8</td><td>19.51</td><td rowspan="2">Fair</td><td>51.15</td><td>-82.99</td></tr>
<tr><td>S9</td><td>20.52</td><td>56.79</td><td>-57.38</td></tr>
<tr><td>S10</td><td>15.91</td><td rowspan="5">Good</td><td>56.30</td><td>-36.73</td></tr>
<tr><td>S11</td><td>10.36</td><td>44.06</td><td>-42.54</td></tr>
<tr><td>S12</td><td>11.56</td><td>40.87</td><td>-67.81</td></tr>
<tr><td>S13</td><td>11.74</td><td>42.18</td><td>-62.82</td></tr>
<tr><td>S14</td><td>13.90</td><td>45.09</td><td>-70.14</td></tr>
</table>

5.2 Sodium Percent (Na%)

According to [41]:

$Na\% = ((Na^{+}+K^{+})/(Na^{2+}+Ca^{2+}+Mg^{2+}+K^{+})) * 100$.

The allowable sodium level in water typically ranges from 0 to 40 meq/L. High sodium groundwater will enhance the soil-water exchange response, changing the permeability and texture of the soil and making it unsuitable for plant growth and difficult to farm [42].

5.3 Residual Sodium Carbonate (RSC)

[43] proposed an empirical measure to forecast the increased alkalinity danger associated with $CaCO_3$ and $MgCO_3$.

$RSC = (CO_3^{2-}+HCO_3^{-}) - (Ca^{2+}+Mg^{2+})$

According to SAR, 78.6 % of the samples were Good for irrigation (11 wells from 14) and 21.4 % were Fair. Na % measurements indicated that the water quality is Permissible for irrigation, except for one sample only (S1) that exhibits slightly Doubtful quality. The results of RSC showed that all the groundwater samples are Suitable for irrigation.

6. Hydrochemical Facies

The chemical characteristics of water solutions within hydrologic systems have been analyzed using the concept of hydrochemical facies, which allows for the categorization of water compositions into distinct groups. This classification reflects the chemical interactions between minerals in subsurface rock formations and groundwater. The Piper tri-linear diagram [44] is a widely used tool for examining hydrochemistry, as well as identifying similarities and differences in water samples based on the predominant cations and anions [45]. Additionally, it helps in identifying and classifying rock-water interactions, solution kinetics, geology, and sources of groundwater contamination [46].

The groundwater samples from the study area, as shown in Fig 7, predominantly fall into two categories, fields I and II. The first group of samples (samples S1-S10) is classified under field I (Ca-Mg-Cl-SO_4 type), which indicates a higher concentration of alkaline earth elements (Ca & Mg) compared to alkalies (Na & K), and a predominance of stronger acidic anions (Cl & SO_4) over weaker ones (CO_3 & HCO_3). The second group (samples 11-14) falls under field II (Na-K-Cl-SO_4 type), indicating a higher concentration of alkalies (Na & K) compared to alkaline earth elements (Ca & Mg), along with a dominance of stronger acidic anions. This categorization suggests the influence of halite weathering [46] and the infiltration of surface salts into the groundwater, likely due to irrigation practices in the area. The prevalence of sodium in the groundwater samples could be attributed to seawater intrusion and extraction from the underlying mineral-rich aquifer throughout the study area.

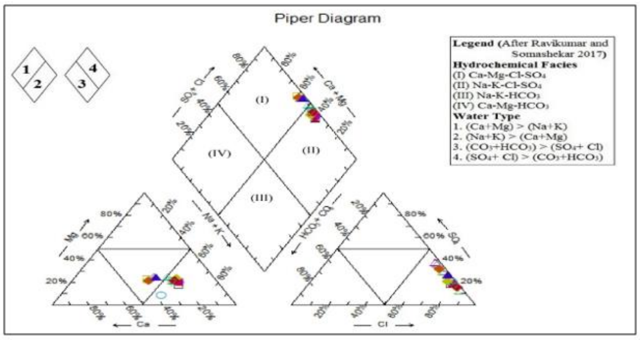

Fig 7. Piper Diagram showing Groundwater Facies according to [44]

The USSL [40] diagram merges EC vs SAR into a single plot due to their critical role in irrigation, categorizing irrigation water into 16 distinct classes. As shown in Fig 8, according to the USSL Diagram, Al-Arish groundwater is positioned at C4-S4 class indicating that all wells are Salinity and Sodium Hazards. Such high salinity conditions can be detrimental to most crops unless they are salt-tolerant. Effective strategies are essential to manage this salinity hazard, including advanced irrigation techniques, cultivating suitable crops, and implementing adequate leaching and drainage systems.

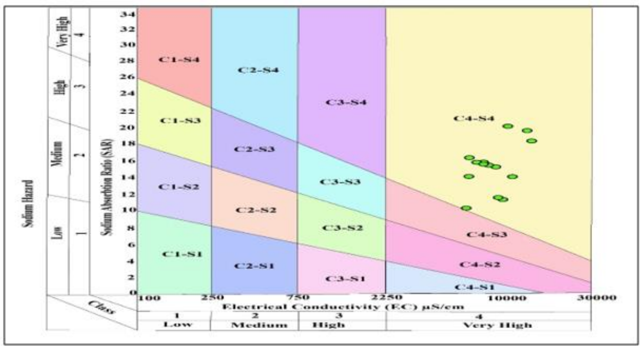

Fig 8. USSL Diagram for the Suitability of Water for Irrigation

7. Conclusions

Fourteen groundwater samples were collected from the Al-Arish area and analyzed for different water quality parameters including pH, EC, TDS, major cations (Na^+, K^+, Ca^{2+}, Mg^{2+}), and major anions (Cl^-, SO_4^{2-}, NO_3^-, CO_3^{2-}, HCO_3^-).

The water quality index was determined, showing an average of 54.13 for the area representing poor water quality. It is concluded that the water quality is good, poor, and very poor in 71%, 14.5%, and 14.5% of the studied samples. Spatial distribution maps of the groundwater quality parameters and WQI in the study area were created to help monitor, understand, and foresee the spread of water parameters.

SAR, Na%, and RSC measures were employed to assess the suitability of groundwater for irrigation purposes. According to SAR, 78.6 % of the samples were Good for irrigation and 21.4 % were Fair. The Na% measurements indicated that the water quality is Permissible for irrigation, except for one sample only (S1) that exhibits slightly Doubtful quality. The results of RSC showed that all the groundwater samples are Suitable for irrigation.

To examine the chemical interactions between minerals in subsurface rock formations and groundwater, hydrochemical analyses were performed.

Applying the Piper tri-linear diagram, the groundwater samples from the study area fall into two categories, fields I and II. The first group of samples (S1-S10) is classified under field I indicating a higher concentration of alkaline earth elements (Ca & Mg) and a predominance of stronger acidic anions (Cl & SO_4). The second group of samples (11-14) falls under field II indicating a higher concentration of alkalies (Na & K) along with a dominance of stronger acidic anions.

According to the USSL Diagram, Al-Arish groundwater is positioned at C4-S4 class indicating that all wells are Salinity and Sodium Hazards.

8. Recommendations

The study highlights attention to the poor state of groundwater in the northwest Sinai Peninsula, which is caused by both natural and man-made stresses. Urgent comprehensive water management plans are needed to address over-extraction, pollution, and salinity rise. It is suggested to apply strategies such as using salt-tolerant crops, constructing counters in the Al-Arish area to manage groundwater extraction to achieve groundwater equation balance, and improving irrigation systems. Sustainable groundwater use can also be greatly aided by raising local awareness and constructing infrastructure for pollution monitoring and treatment.

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