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Groundwater Quality Assessment in Siwa Oasis, Egypt, Using Different Indicators and GIS

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ABSTRACT

Groundwater plays a pivotal role as a natural resource for human existence due to its ability to provide a consistent water supply to the populace and its status as one of the primary sources of irrigation for enhancing agricultural productivity. The Siwa Oasis in Egypt is a popular tourist destination with agricultural and economic significance. This study integrates the geographic information system (GIS) technique with various hydrochemical indicators and statistical factor analysis to assess the groundwater quality for irrigation purposes. Thirty groundwater samples were sourced from the oasis's three main water resources: wells, springs, and lakes. The analysis took place at the Water and Soil Lab Unit of the Desert Research Centre in Cairo, Egypt, adhering to the standard protocols laid out by the American Society for Testing and Materials and the accepted techniques of the American Public Health Association (APHA). The suitability of groundwater for irrigation was assessed using FAO recommendations, focusing on parameters that proved more effective in the Siwa Oasis context. These parameters included the unsuitable for irrigation due to their extreme salinity and the presence of more dissolved solids than other water sources; these lakes serve as drainage for other resources within the percentage of sodium (Na %), sodium absorption rate (SAR), soil water permeability index (PI), and potential salinity (PS). According to the findings, the majority of wells and some springs are suitable for irrigating crops that can withstand high salinity levels. Lakes, on the other hand, were oasis.

1. Introduction

Groundwater in Egypt plays a crucial role in enhancing human health, economic growth, and ecological variety, serving as a vital resource for irrigation, drinking, and industrial use. Its wide availability, constant temperature, excellent quality, and low development costs make it an essential and dependable source in all climate zones, including urban and agricultural areas in both developed and developing nations [1, 2]. Despite the abundance of groundwater, it may remain unusable as its quality deteriorates significantly due to chemical and bacteriological pollution due to human activities in the social and industrial sectors [3].

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Moreover, groundwater is qualitatively dependent on the physical, chemical and bacteriological quality of the recharged water, internal runoff, and underground geochemical responses [4, 5]. Hydrological and human factors can also cause regular changes in groundwater. The quality of groundwater varies substantially depending on the kind of penetrated lithofacies [6]. Egypt's population increased by three times in the last fifty years, while renewable water supplies have stayed constant [7]. The current situation necessitates an immediate requirement for water. In order to address the escalating food demand, the agricultural utilizes almost 80% of the accessible water. This is why the Egyptian government is persistently exploring avenues to enhance and regulate its water resources [8].

Siwa Oasis is regarded as an exceptionally auspicious locale owing to its historical riches, medicinal significance, renowned handicrafts, and endearing natural features, which render it a coveted tourist destination that appeals to diverse global audiences, Also it is one of Egypt's agricultural supply areas [9]. Due of its high priority for extending agriculture in the future and reclaiming the desert, it was chosen for inquiry.

The agricultural production represents the principle activity of Siwa oasis inhabitants that count about 30000 capita [10]. The primary sources of revenue in Siwa comprise the cultivation of date palm and olive, owing to their capacity to endure saline conditions. Nonetheless, certain locations are occupied with the cultivation of citrus and fruit orchards, accompanied by the intercropping of lucerne as an intercropping [3, 11]. Elsaied [12], illuminated the distinctiveness of the vegetation in Siwa Oasis, which encompasses an agricultural system of historical significance, replete with a wealth of traditional cultivars that are integral to its cultural legacy. In October of 2016, the Food and Agriculture Organization of the United Nations (FAO) identified the Siwa Oasis as a Globally Important Agricultural Heritage System (GIAHS). Groundwater and springs are the only available water source in the oasis [4, 13].

Agriculture in the oasis is reliant on groundwater from wells and springs. Various serious environmental changes have arisen related to the environmental challenges of the invaluable groundwater resources that endanger human life, agriculture, and economic activities. These principle challenges are: first, the high level of salinity resulting from the high groundwater level is a major problem in Siwa Oasis because of the high rates of evaporation, especially in the summer [14, 15] and also the extravagance of the flood irrigation system, and the problem of agricultural drainage [12, 16]. Second, the mismanagement of drilling underground wells has led to desertification and the expansion of surface lakes [17].

The presence of numerous sabkhas and salt marshes serves as an evident manifestation of the consequences arising from these problems, This is exemplified by the emergence of four salt lakes that characterize the Siwa Oasis: Al-Maraqi pond (9 km^2) and Birket Siwa (32 km^2) situated to the west of Siwa Oasis, while Birket Zaytun (16 km^2) and Birket Azmuri can be found on the eastern side [18]. According to [19], the annual loss of production for olive and date palm cultivation in Siwa Oasis is approximately 39% and 33%, respectively. If all these problems are not addressed, whether the rising groundwater level or the problem of agricultural drainage, this will negatively affect crops, especially dates and olives, as well as buildings and infrastructure networks, such as water, sewage and roads. The future of Siwa Oasis will be in danger, and it may face extinction within a few decades according to Desert Research Center and Groundwater Research Institute.

Groundwater has become an issue under enormous pressure all over the world. Thus, water quality assessment is of urgent importance recently [20]. The evaluation of water quality is a crucial instrument that contributes to the achievement of sustainable development and furnishes pivotal data for the purpose of water governance [21]. Groundwater is perceived to possess a greater degree of purity and freedom from contamination when compared to surface water. Nonetheless, the haphazard release of industrial wastewater, substandard agricultural drainage, and the depositing of solid waste contribute to the pollution of groundwater, culminating in deleterious health effects and harm to agricultural produce [22].

Numerous scientific papers have attempted to predict soil and water quality indicators due to the significant interest shown by different sovereign entities, leading researchers to develop new water quality prediction models using established scientific and practical applications. Various methods exist for evaluating water quality, including principal component analysis, neural network models, water pollution index methods, statistical analysis methods, and others, each with their own characteristics, scope, and limitations; among these methods, statistical analysis is particularly important for analyzing groundwater chemistry. Many powerful methods are available to assess the water quality such as the hydrochemical analysis, neural network model, water pollution index method, statistical analysis method and others. Each has its characteristics, applicable scope, and limitations.

A statistical analysis method is a vital tool in the analysis of groundwater chemistry. Traditional hydrogeological and hydrochemical analysis as well as statistical techniques to evaluate groundwater resources utilized in both [23] and [24]. while Ismail and M. El-Rawy [25] relied on chemical analysis of groundwater samples in West Sohag, and the results were used to evaluate the quality of water for drinking and irrigation purposes after comparing it with standard specifications. However, Abdelmawgoud et al. [26] addresses the hydrochemical characteristics of groundwater resources in Minya Governorate and their impact on the assessment of groundwater quality through the use of hydrochemical analysis and Geographic Information Systems (GIS). Merrikhpour and Jalali [27] displays the concentration of hydrochemicals and heavy metals in soil and water resources in the Iranian province of Hamedan was studied. Qishlaqi et al. [28] evaluated the physical and chemical properties of 14 sampling stations according to the WHO standard, and almost all the samples had suitable drinking conditions according to them, and while comparing the agricultural standard, they were also suitable for irrigation purposes. El-Rawy et al. [29] reveals that inadequate wastewater treatment facilities and uncontrolled agricultural chemical application in the Nile Valley contribute to microbial contamination and water composition changes at disposal sites.

Furthermore, the integration of GIS in groundwater quality analysis is crucial for informed decision making and improved water management, as GIS has been instrumental in determining groundwater quality [28] and [29], so many researchers have cited several studies related to groundwater assessment and management, including studies on the use of GIS for groundwater modeling, estimation of recharge, and integrated management of surface and groundwater resources as in [30]. Using GIS can also help in creating thematic maps through the IDW (Inverse Distance Weightage) interpolation tool in a GIS environment as displayed in [33], and in [26], the hydrochemical characteristics of groundwater resources in El-Minia Governorate were examined and evaluated through the use of hydrochemistry and GIS analysis.

Climate data was gathered in [34] in order to evaluate the effects of global climate change on the water quality indices of the Nile River upstream of Cairo drinking water treatment plants (WTPs). The study conducted by [35] has demonstrated the utility of factor analysis in discerning the distinct signatures of uncontaminated groundwater, agricultural activities, mining activities, and sewage effects. The research [36] utilizes multivariate statistical analysis to compute the water quality index (WQI) and explores the associations between the physicochemical parameters, proposing a two-factor model that accounts for more than 74% of the overall groundwater quality variation. factor analysis was applied in [38] to explore pollution indices and set thresholds for seawater salinity and arsenic contamination in a Taiwanese region affected by Blackfoot disease. A variety of ANN algorithms have been effectively employed in the areas of civil engineering and water resources in recent years., as described in [36, 37], and [38].

In this research, multivariate statistical analysis and GIS are used to examine the evaluation of groundwater quality in Siwa Oasis, Egypt. The spatial distribution of groundwater quality will be displayed. The factors controlling groundwater quality will be determined based on World Health Organization (WHO) [39] and Egyptian standards for drinking and domestic water [40], while for the assessment of water quality for irrigation, it will be based on the database of Food and agricultural Organization and Groundwater Hydrology [41]. In this study, the objectives are:

- Determining the hydrochemical characteristics of 30 selected samples from various water resources in the study area
- Evaluating groundwater resources in the study area for drinking and irrigation purposes
- Assisting in the sustainable management of the water resources in the oasis

2. Study Area

2.1. Topography and Climate

Siwa Oasis was designated for examination because it will be extremely important for extending agriculture and reclaiming the desert [11]. It is a geographical depression in the Matrouh Governorate, situated in the northwest of the Western Desert Egypt, spanning approximately 1200 km^2 (or 285,714 acres) [42]. The site is located in the northern Mediterranean coastal zone, approximately 330 km from Matrouh City, 560 km from Cairo, and 70 km from the Libyan-Egyptian borders [6]. It is located between longitudes 25° 15' 33" to 26o 8′ 3" E and latitudes 29° 5′ 0.3" to 29o 25' 20" N [43]. **Figure 1** shows the location map of Siwa Oasis, Western Desert, Egypt.

The desert climate is a defining feature of Siwa Oasis. It is relatively dry and humid, with average temperatures ranging from 5 to 40°C. The oasis experiences low rates of evaporation (5–15 mm), precipitation (0–3 mm), and wind speeds (6.8–12.5 km/h). This information was gathered from the meteorological stations of the Egyptian Meteorological Authority for Siwa Oasis [12]. The Siwa oasis in Egypt has access to various water resources, namely the Nubian sandstone aquifer system (NSSAS), the Tertiary carbonate aquifer system (TCAS), as well as springs and lakes [6].

2.2. Surface and Subsurface Geology

Oasis region has been the subject of intense research by many scientists in the field of geology (e.g., [44], [45] and [46]) . It is necessary to take these investigations into account and build on their findings to expand knowledge and understanding of the nature of this region. The insights gained from these studies can prove invaluable in the quest to discover the mysteries of the oasis and its geological formations. It is situated in a uniform basin within the Marmarica plateau, which is composed of Miocene-era limestone containing decomposing marine rocks with carbonates and marl interferences; the evaporates in Siwa Oasis are primarily composed of halite salts and gypsum, along with other salts, and the soil is loam and sandy loam [47]. Geological maps indicate that carbonate rocks from the middle and upper Miocene eras are located north of the Qattara Depression and the Siwa Oasis [48].

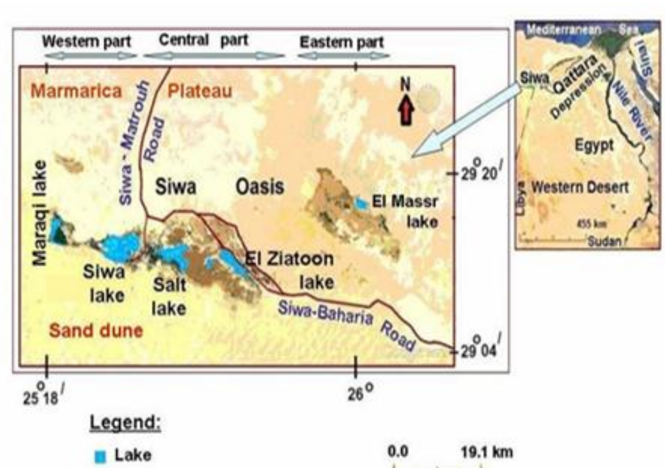


Figure 1: shows location map of Siwa oasis, Western Desert, Egypt showing sample location

There exist supplementary slabs of limestone, sandstone, pebbles, and flint from the Pleistocene era in the northern region of the Siwa Oasis. Additionally, there are geological formations from the Holocene era comprising fine grains of quartz and sabkha sediments consisting of silt and clay with hydrogeologic cross section along the Siwa oasis. Surface saline deposits are a distinctive feature of Siwa. These deposits are formed in a heterogeneous geological unit consisting of dolomite, black clay, anhydrite salts, halite, and other salts. These rock components are considered to be among the weakest, and the salts crystallize after being deposited in an exceptionally arid environment and in the presence of shallow lakes [50]. Table 1 displays a comprehensive overview of the Siwa area. The stratigraphic sequence of the subsurface is comprised of a sedimentary series from the uppermost stratum to the lowermost stratum in the following order.

2.3. Water Bearing Formations

Water-bearing formations represent a crucial resource that must be valued and utilized to their fullest potential. Through an analysis of lithological and hydrological attributes, it is possible to identify two primary regional aquifer systems: the Nubian sandstone aquifer system (NSSAS), which has a depth of approximately 2600 m, and the overlying Tertiary fractured carbonate aquifer system (TCAS), which has a depth of evaporated sediments [49]. Figure 2 represents the approximately 600 m [51]. Additionally, the region of Siwa is characterized by other significant bodies of water, including large lakes and springs, which will be examined in this investigation. The Nubian Sandstone Aquifer System is situated between the Upper Cretaceous shale and marl layers and the Pre-Cambrian basement rocks and is composed of continental sandstones that are intermixed with small deltaic and shallow marine clays and shales [52]. The aquifer displays elevated hydraulic parameters and restrictive conditions and is recharged by local precipitation. The overlying carbonate aquifer receives natural discharge via fault planes as well as artificial discharge through excavated boreholes. The TCAS consists of interbedded carbonate materials such as shale, siltstone, sandstone, and evaporate deposits. It is accessible through both manually-dug and mechanically-drilled wells and recharged via upward leakage of groundwater from the NSSAS. The discharge rate reaches an impressive 44, 2000 m3/day. The variability of groundwater quality is contingent on the type of lithofacies penetrated in distinct locations. The variability of groundwater quality is contingent on the type of lithofacies penetrated in distinct locations [6].

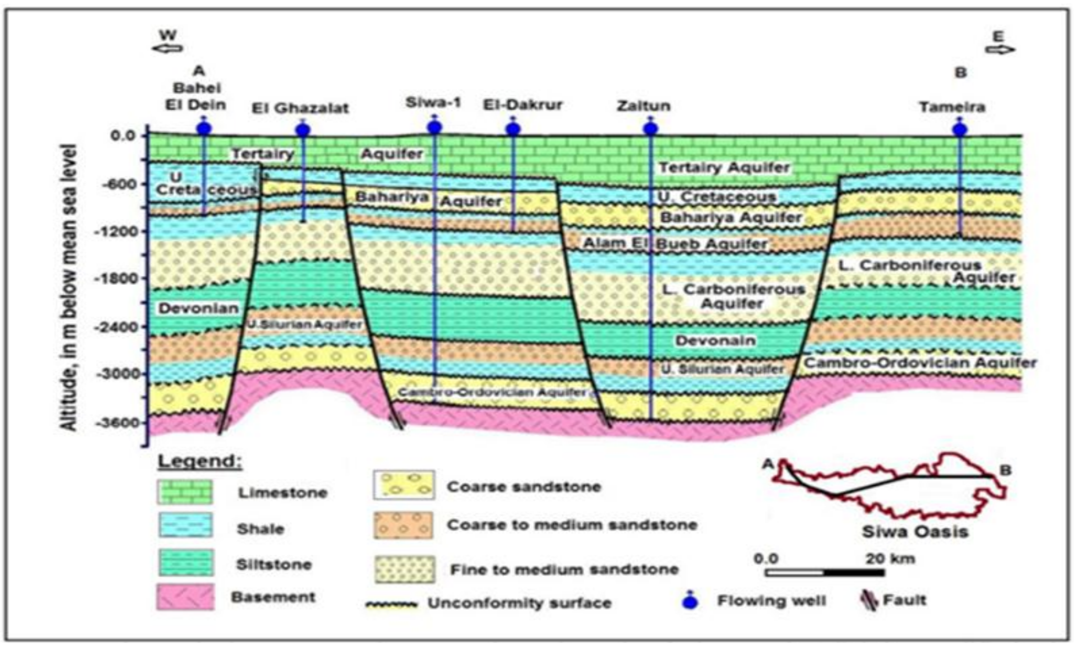
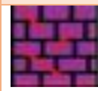
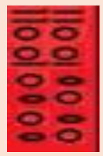
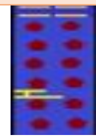
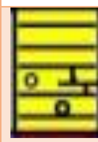


Figure 2: Hydrogeologic cross section A-B along the axis of Siwa oasis [6]

Table 1: A comprehensive segment pertaining to the geological formations present

in Siwa Oasis, Egypt.

Era	Age		Avg. Thickness	Log	Lithic description	Depositional environment
Cenozoic	Tertiary	Miocene	250 m		Limestone with marl.	Shallow marine
		Eocene	350 m		Sandstone, siltstone and shale	Fluvio-Marine
Mesozoic	Cretaceous		600 m		Composed of sandstone with shale and carbonate intercalations overlain by impermeable layer of carbonaceous shale and argillaceous limestone.	Shallow marine Near shore
Paleozoic	Carboniferous		912 m		sandstone intercalated with shale and siltstone	Near shore, Continental
	Devonian		347 m		Mudstone, siltstone, Carbonaceous sandstone, limestone & dolomite	Fluviatile, Continental, Shallow marine
	Silurian		626 m		Mudstone and siltstone	Fluviatile, Marine
	Ordovician/ Cambrian		315 m		Sandstone intercalated with shale and siltstone beds	Continental

3. Materials and Methods

To accomplish the study's goals, a sampling program and laboratory analysis were conducted in Siwa Oasis during the year 2020 in order to evaluate the suitability of water for drinking and irrigation practices. Thirty representative groundwater samples were collected from various locations in the central and western parts of Siwa Oasis for analysis in order to derive diverse physical and chemical variables, as well as groundwater samples, across three distinct water body categories: wells (21 samples from TCAS and 2 samples from NSSAS), springs (5 samples), and lakes (2 samples). The sampling points' position coordinates are recorded using a Global Positioning System (GPS) to delineate the precise latitudinal and longitudinal coordinates of the designated sampling locations as shown in **Figure 1**. The portable Manta 2, Water-Quality Multiprobe (Model Sub 3, USA) was utilized to measure the inverse logarithm to base 10 of hydrogen ion concentration (PH) and total dissolved solids (TDS) in this study.

Two separated laboratories were utilized for the purpose of carrying out the essential chemical examination. The Water and Soil Laboratory Unit, situated at the Desert Research Center in Cairo, Egypt, executed the process of ascertaining the presence of dissolved major ions and heavy metals. They followed the standard protocol set by the American Society for Testing and Materials and in accordance to the standard methods adopted by the American Public Health Association (APHA) [53]. Golden Software Surfer 12 software was used to build 3D maps of the TCAS that were accessible by the bulk of producing wells. These maps show the spatial distributions of dissolved components at different depths. The geochemical processes that arise from the interactions between water and sediments and how they influence the distribution and concentration of various chemical constituents were investigated. XLSTAT software was used to calculate the factor analysis and statistics summaries.

The methodologies used for the estimation of water quality parameters are summarized in **Table 2**. The chemical classification of water is carried out using GWW software. Water samples were obtained using new, pre-sanitized containers made of polyethylene, capable of holding up to 1 L of fluid. These samples were then taken to the laboratory for further analysis, utilizing an ice box. The Ultrameter SM101 instrument was utilized in the field to obtain measurements of thirty groundwater samples for pH, total dissolved solids (TDS), and electrical conductivity (EC) immediately, major cations (Ca^{+2}, Mg^{+2}, Na^{+}, K^{+}), and major anions (HCO_3^{-}, Cl^{-}, SO_4^{-2}, CO_3^{-2}) as shown in **Table 3**. The values of the descriptive statistics (minimum, maximum, average, and standard deviation) in the groundwater samples of the study area were calculated and tabulated in Table 4. The assessment of outcomes is conducted in accordance with the drinking water quality criteria established by the World Health WHO [39] and the applicable Egyptian regulations concerning drinking water [40] obtained also in **Table 4**. However, Irrigation quality parameters such as TDS, TH, Sodium Percentage (Na %), Sodium Adsorption Ratio (SAR), Permeability Index (PI), Magnesium Hazard (MH), Potential salinity (PS) and Kelley's Ratio (KR) were computed in **Table 8** based on the physicochemical analyses of groundwater samples, following the standards set by the Food and Agricultural Organization were used.

Table 2: The methodologies used for the estimation of water quality parameters

Parameter	Methodology
pH	**pH meter**
EC	**EC meter**
TDS	**TDS meter**
Na^{+}, K^{+}	**Flame Photometer**
Ca^{+2}, Mg^{+2}	**EDTA Titration**
CO_3^{-2}, HCO_3^{-}	**Acid-base Titration**
Cl^{-}	**AgNO3 Titration**
SO_4^{-2}	**Spectrophotometer**

4. Results and Discussion

The results of this study will be presented and discussed in the parts below:

4.1. Hydrogeochemical characteristics of groundwater

The analytical results of the major cations and anions in the water samples are shown in **Table 5**. The concentration levels of both cations and anions in the entirety of the groundwater samples examined in the designated location are deemed to be within the acceptable parameters established by the World Health Organization. The hydrochemical classification of groundwater reveals four water types (NaCl 80%, $NaHCO_3$ 10%, $NaSO_4$ 7%, and $MgCl_2$ 3%). The prevalence of sodium chloride and magnesium chloride as the primary water types is indicative of the dissolution of evaporates and the extensive utilization of fertilizers, while the appearance of sodium bicarbonate water type signifies the replenishment of subsurface water from surface water bodies. The phenomenon of recharge is observed as a result of the return flow from the irrigation process. This process plays a dual role in not only leaching the soil, but also enriching the groundwater with the ions that are present in the soil profile as is evidenced in **Table 1**.

4.1.1. Nubian Sandstone Aquifer System (NSSAS)

The significance of the pH factor lies in its ability to effectively classify a wide range of geochemical equilibriums. As it is known, positive ions have an alkaline tendency, in contrast to negative ions, which have acidic and neutral to very moderate acidity inclinations. Groundwater released from deep wells tapped into the NSSAS is alkaline (pH greater than 7 standard units). It ranges between 6.7 and 9.1, with an average of 7.9 that indicates all the water samples are within the preferred limit of 6.5–8.5 for drinking and irrigation [53], [54], and fresh, with total dissolved solids (TDS) ranging between 242 and 287 mg/l. The examined aquifer system exhibits a remarkable and consistent inclination towards diminished concentrations of major anions and cations in comparison to the remaining water resources that were analyzed in the designated region.

The hydrochemical composition analysis indicates that bicarbonate and sodium ions have the highest concentration levels among the other ions, thereby dominating the major ion concentrations. The relative abundance of major ions, in the order of their concentration (first more abundant in millequivalents per liter, meq/l) is as follows: rNa^{+}, rMg^{+2}, rCa^{+2}, rK^{+} - $rHCO_3^{-}$, rCl^{-}, rSO_4^{-2}.

4.1.2. Tertiary Carbonate Aquifer System (TCAS)

The chemical characteristics of groundwater recovered from shallow wells that pierce the Tertiary Coastal Aquifer System differ greatly from those of the NSSAS. The pH level of the groundwater is greater than 7, indicating its alkaline nature. The salinity of the groundwater varies from brackish to salty, with a total dissolved solids (TDS) range of 1903.2 to 10,124.9 mg/l. Most of the groundwater samples exhibit noteworthy concentrations of main components that are dissolved. The anionic and cationic compositions commonly contain elevated levels of the sodium and chloride ionic constituents. The principal ions' relative abundances in water samples, from most abundant to least abundant, are as follows: Na^{+}, Mg^{+2}, Ca^{+2}, K^{+}, Cl^{-}, SO_4^{-2}, and HCO_3^{-}. Deviations in the cationic and anionic configurations have been identified for samples 25, 13, and 24. **Figure 3** denoting the spatial distribution of TDS and dissolved major constituents.

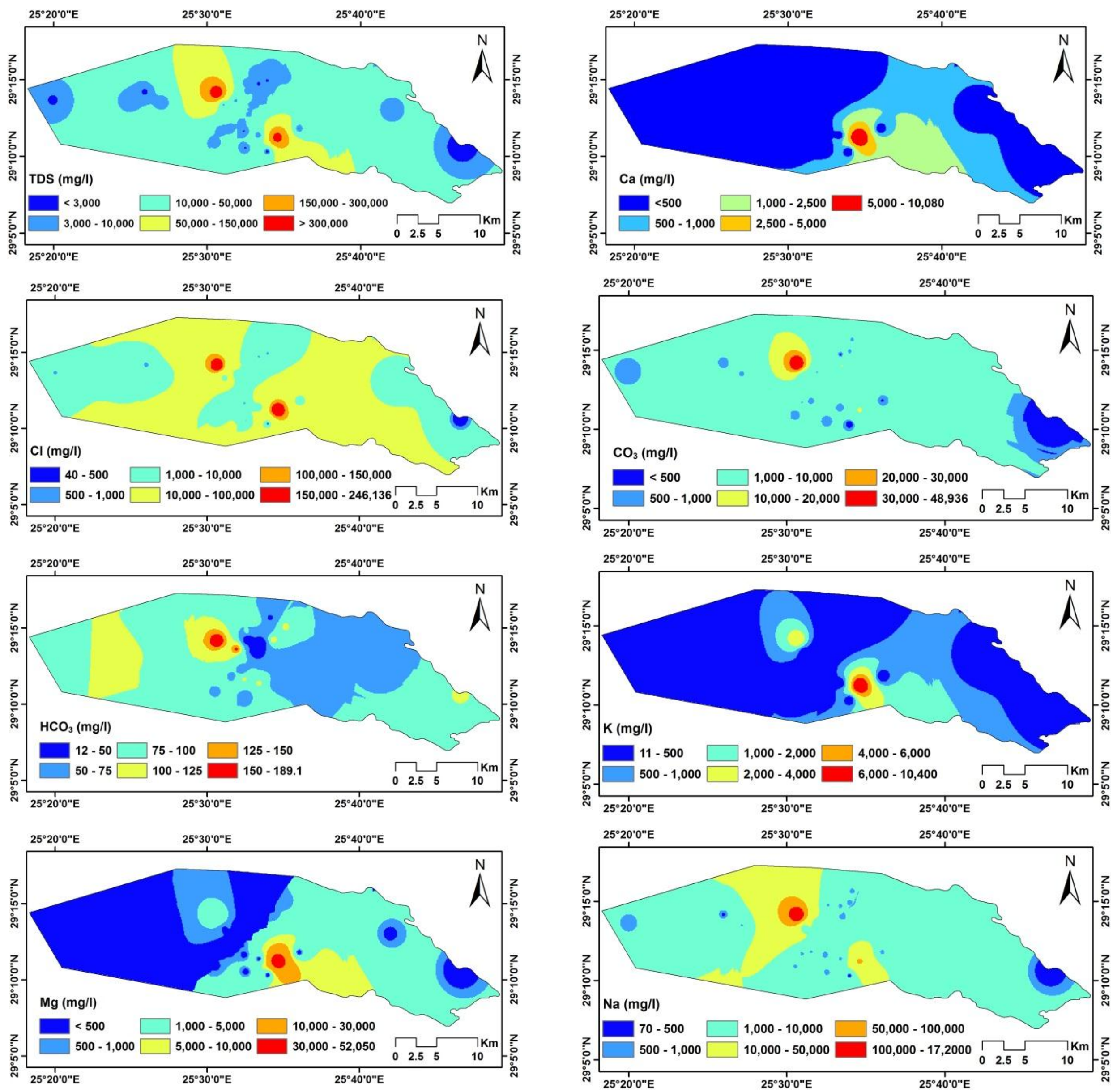


Figure 3: The spatial distribution of TDS and dissolved major constituents in the study area

Table 3: Well depths, pH, and chemical ingredient concentrations and Hydrogeochemical characteristics for all samples in the study area

Water Body	Sample No.	Location Name	Depth (m)	PH	EC (µS/cm)	TDS (mg/l)	Ca^{+2} (mg/l)	Mg^{+2} (mg/l)	Na^{+} (mg/l)	K^{+} (mg/l)	CO_3^{-2} (mg/l)	HCO_3^{-} (mg/l)	SO_4^{-2} (mg/l)	Cl^{-} (mg/l)
NSSAS	4	Siwa well	950	8.9	0.44	286	10.53	9.633	76	13	12	94.6	66.1	51.4
	15	Qurishate well	900	8.6	0.37	242.4	5.156	8.8	70	11	18	100.7	40	39.1
Tertiary Carbonate Aquifer System (TCAS)	1	Al Hamam well	170	7.4	4.68	3045.2	220	150.3	620	41	12	103.7	500	1450
	5	Al Melook well	90	8.6	3.98	2584.7	154.3	120	560	20	18	91.5	700	966.7
	6	Ismail farm well	55	8.2	3.33	2165.6	150	120	400	17	Nil	76.3	700	740.4
	7	Salam well 65	150	7.8	8.54	5552.9	256	260	1300	24	18	122	1500	2134
	8	Dheiba well 108	150	8.2	6.41	4164.7	210	210	940	24	21	79.3	900	1820
	10	Al tabo well 289	150	7.8	12.14	7890.4	335.7	423.9	1750	50	15	112.9	2200	3059
	12	Zaqawa well	160	8	15.58	10124.9	244.3	457.9	2700	68	15	79.3	1800	4800
	13	Mughazi well	175	9.1	10.51	6832.5	242.3	370.5	2750	57	15	12.2	4285	2777
	14	Abu Shifa well	62	7.9	10.27	6677.6	255.5	331.6	1600	63	6	67.1	1200	3188
	17	Atti well	83	7.9	15.17	9863.3	255.5	601.6	2300	150	15	112.9	1600	4885
	18	Beni Bear well 1	85	8.5	5.6	3640.1	200	224.5	700	51	12	45.8	900	1530
	19	Mousa well	120	7.9	6.92	4499.3	196.5	226.1	1020	53	18	100.7	1200	1735
	20	Beni Bear well 2	105	7.9	5.15	3350.5	174.6	172.9	690	40	15	79.3	1100	1118
	21	Al Salam well	130	7.9	11.26	7321.4	250.7	304.9	1850	78	15	18.3	1600	3214
	22	Al Rabia well 1	130	7.2	11.61	7545.9	270.4	385.9	2000	82	Nil	155.6	873.4	3856
	23	Al Rabia well 2	130	8.4	4.11	2670.4	126	120.4	660	36	12	64.1	696.7	987.2
	24	Boush area well	120	8	3.98	2586.5	143	119.1	530	33	Nil	103.7	1000	709.6
	25	Raml well	130	8.4	2.93	1903.2	96.6	0.279	600	35	15	51.9	333.4	797
	26	Talhemam well	130	8	3.81	2477.1	148.3	121.6	520	35	15	70.2	800	800.1
	27	Abdoallah well	35	8	5.02	3260.6	166.5	157	800	53	18	67.1	580	1453
	28	Tatrbent well	66	8	5.05	3283.4	180.2	165.5	660	65	Nil	15.3	10225	1183
Springs	29	Al Gahilia spring	_	8	5.22	3391.2	169.7	244.9	700	76	15	70.2	517.9	1633
	30	Gobta spring	_	8	4.96	3221.8	180	156	660	50	Nil	91.5	980	1150
	2	Cleopatra spring	_	8.2	4.31	2799.5	168	120	640	32	9	64.1	448.8	1350
	11	Romani spring	_	8.1	11.84	7696.5	300	350	1800	70	18	61	2300	2828
	16	Kapritia spring	_	8.3	12.71	8262.3	334.3	590.5	1700	67	15	106.8	1800	3702
Lakes	9	Siwa lake	_	6.9	706.79	459413	229.6	2970	172000	3800	Nil	189.1	48936	231383
	3	Salt lake	_	6.7	592.37	385042	10080	52050.6	55000	10400	Nil	61	10672	246808

D.L: detection limit of the used analytical procedures

Table 4: Minimum, maximum, average, and standard deviation values of different elements

Elements	Min.	Max.	Mean	Standard Deviation	WHO Desirable limit	WHO Allowable limit	Egypt limit
Electrical conductivity (EC) (µS/cm)	0.37	706.79	353.58	163.77	1500	1500	-
pH	6.7	9.1	8	0.51	6.5-8.5	8.5	7-8.5
Total Dissolved Solids (TDS) (mg/L)	242.4	459,413	32,393	106,450	500	1000	500
Calcium (Ca^{+2}) (mg/L)	5.156	10,080	525	1806.28	75	75	75
Magnesium (Mg^{+2}) (mg/L)	0.279	52,050.60	2052	9457.76	30	30	50
Sodium (Na^{+}) (mg/L)	70	172,000	8587	32,401.40	200	200	200
Potassium (K^{+}) (mg/L)	11	10,400	520	1987.77	10	10	-
Bicarbonate (HCO_3^{-}) (mg/L)	12	189.1	83	37.55	100	100	-
Chloride (Cl^{-}) (mg/L)	39	246,809	17,738	60,219.20	200	200	200
Sulfate (SO_4^{-2}) (mg/L)	40	48,936	3349	8965.18	200	200	400

Table 5: Some hydrochemical coefficients (epm) calculated for water resources, Siwa oasis, Egypt

water body	sample number	Local name	r(Na+K)/rCl	rCa/rMg	rSO4/rCl	Water type
TCAS	1	Al Hamam well	0.68	0.89	0.25	NaCl
	5	Al Melook well	0.91	0.78	0.53	NaHCO3
	6	Ismail farm well	0.85	0.76	0.70	NaCl
	7	Salam well 65	0.95	0.60	0.52	NaCl
	8	Dheiba well 108	0.81	0.61	0.36	NaCl
	10	Al tabo well 289	0.90	0.48	0.53	NaCl
	12	Zaqawa well	0.88	0.32	0.28	NaCl
	13	Mughazi well	1.55	0.40	1.14	NaCl
	14	Abu Shifa well	0.79	0.47	0.28	NaCl
	17	Atti well	0.75	0.26	0.24	NaCl
	18	Beni Bear well 1	0.74	0.54	0.43	NaCl
	19	Mousa well	0.93	0.53	0.51	NaCl
	20	Beni Bear well 2	0.98	0.61	0.73	NaCl
	21	Al Salam well	0.91	0.50	0.37	NaCl
	22	Al Rabia well 1	0.82	0.42	0.17	NaCl
	23	Al Rabia well 2	1.06	0.63	0.52	NaCl
	24	Boush area well	1.19	0.73	1.04	NaSO4
	25	Raml well	1.20	209.92	0.31	NaCl
	26	Talhemam well	1.04	0.74	0.74	NaCl
	27	Abdoallah well	0.88	0.64	0.29	NaCl
	28	Tatrbent well	0.91	0.66	6.38	NaSO4
NSSAS	4	Siwa well	2.51	0.66	0.95	NaHCO3
	15	Qurishate well	3.02	0.36	0.76	NaHCO3
Springs	29	Al Gahilia spring	0.70	0.42	0.23	NaCl
	30	Gobta spring	0.92	0.70	0.63	NaCl
	2	Cleopatra spring	0.75	0.85	0.25	NaCl
	11	Romani spring	1.00	0.52	0.60	NaCl
	16	Kapritia spring	0.72	0.34	0.36	NaCl
Lakes	9	Siwa lake	1.16	0.05	0.16	NaCl
	3	Salt lake	0.38	0.12	0.03	MgCl

4.1.3. Spring Water

The aqueous solution present in springs is characterized by an alkaline nature, denoting a pH greater than 7, and is also observed to be brackish in nature; with TDS ranging from 2799.5 to 8262.3 mg/l. Sodium and chloride predominate in the ionic compositions. The dissolved main components in all water samples exhibit the following ionic dominance: Na^+, Mg^{+2}, Ca^{+2}, K^+, Cl^-, SO_4^{-2}, and HCO_3^-. The significant resemblance in the hydrochemical composition of spring water and TCAS groundwater suggests the possibility of the existence of a similar geochemical setting in which the water is discharged.

4.1.4. Lake Water

The water located in the Siwa Lake and Salt Lake regions has been identified as the most mineralized within the study area. This has been attributed to the significant concentrations of main ions and Total Dissolved Solids (TDS), which have experienced a notable increase due to the impact of evaporation. The water is characterized by its salinity and acidic nature, with a pH lower than 7. Additionally, the total dissolved solids content exceeds 380,000 mg/l. The water samples exhibit varying quantities of major ions, with particular emphasis on the prevalence of magnesium, sodium, and chloride species. The hydrochemical composition of Salt Lake's water exhibits the chloride calcium type of marine features, whereas Siwa Lake's water reflects the sulphate sodium type, indicating the terrestrial circumstances in which the water exists. Certain categories of water may have arisen as a result of various influences, with the most crucial of these being the amount and chemical constitution of water conveyed to the lakes, as well as the chemical composition of the soil through which the water travels from drainages, springs, and boreholes to the lakes.

The EC is a crucial measure for determining irrigation appropriateness and salinity concerns. The electrical conductivity (EC) exhibits variability ranging from 0.37 to 15.58 µS/cm, while The majority of the samples, about 61%, are moderately saline, with TDS values ranging from 3,000 to 10,000 mg/L, indicating that most of the water samples collected from wells meet the groundwater quality standards for drinking purposes. Only small proportions, approximately 4% of the samples, are characterized as very saline and are therefore unsuitable for drinking. For springs' samples 20% slightly saline whereas 80% moderately saline and that indicate its suitability for drinking purposes. While it was noted that 100% of the lakes are brine where the TDS values exceed greatly 380,000 mg/l. The elevation in salinity levels could potentially arise from the dissolution of minerals, namely evaporates that are prevalent in the sediments, or the release of salts from the soil as return flow mingles with groundwater. The accumulation of salts within the soil profile is attributable to the elevated rates of evaporation that are typical of dry and hot climates. In general, wells and springs can be relied upon for drinking purposes, while lakes are not as shown in **Table 6.**

Table 6: Classification of water types according to TDS referring to Hem [54]

TDS (mg/l)	Classification	Wells		Springs		Lakes	
		No. of locations	%	No. of locations	%	No. of locations	%
<1,000	Freshwater	2	9	0	0	0	0
1,000 - 3,000	Slightly saline	6	26	1	20	0	0
3,000 - 10,000	Moderately saline	14	61	4	80	0	0
10,000-35,000	Very saline	1	4	0	0	0	0
>35,000	Brine	0	0	0	0	2	100

The concentration of Ca+2 and Mg+2 are the primary factors that determine the overall hardness of water, as these ions are commonly found in groundwater. Hard water can result in the formation of Peels within pipes, boilers, and other household appliances, whereas soft water can be more corrosive and contain greater amounts of metal contaminants due to water pipe leaching [55]. According to the TH classification [56], approximately 91 % of the groundwater samples from wells are hard to very hard, indicating dissolution of limestone and dolomitic limestone prevalent in the western half of the research area, and only 9 % soft suitable for drinking. Whereas the springs and lakes are all very hard and unsuitable **Table 7**.

Table 7: Categorization of groundwater quality depending on the Total Hardnes

TH (mg/l)	Class.	Wells		Springs		Lakes	
		No. of locations	%	No. of locations	%	No. of locations	%
<75	Soft	2	9	0	0	0	0
75-150	Moderate hard	0	0	0	0	0	0
150-300	Hard	1	4	0	0	0	0
>300	Very hard	20	87	5	100	2	100

4.2. Groundwater quality evaluation for the purpose of drinking and domestic usage

Groundwater quality is impacted by both natural occurrences and human activities. In assessing the quality of groundwater intended for consumption and household use, it is necessary to consult the established benchmarks prescribed by various organizations, such as the WHO drinking water standards [57] and the Egyptian standards for drinking water [40] as shown in **Table 4**. Upon conducting an analysis of the data, it has been observed that a notable correlation exists between the domestic and drinking standards, which highlights that a mere 35% of the groundwater and springs samples collected are deemed appropriate for consumption due to their low salinity levels (TDS < 1,000 ppm). Conversely, it has been deduced that the overwhelming majority of samples, accounting for 65%, are deemed unsuitable for consumption as a result of their high salinity levels (TDS > 1,000 ppm).

An overwhelming majority of the groundwater samples gathered, amounting to 91%, exhibit a level of hardness that ranges from hard to very hard, thereby rendering them unfit for domestic applications owing to their Total Hardness, as indicated in **Table 7**.

4.3. Groundwater quality evaluation for the purpose of irrigation

The Siwa Oasis relies heavily on agriculture as its primary economic activity, which is sustained by groundwater sourced from around 1199 wells and springs. These sources contribute a total annual discharge of approximately 255 million cubic meters to the oasis [58]. Salinity has the potential to negatively affect the growth of plants, either through physical limitations resulting from modifications in osmotic processes that restrict water uptake or chemically through metabolic reactions triggered by toxic constituents [41]. The quality of water used for irrigation is a crucial factor in influencing the soil properties and yield potential of agricultural land [58]. The hydrochemical attributes that hold great importance in ascertaining the viability of groundwater for the purpose of irrigation have been extracted and tabulated in **Table 8**.

Table 8: The parameters that define the quality of irrigation water for the groundwater samples in the study zone

Water body	Water type	Irrigation Parameters							
		TDS (mg/l)	TH (mg/l)	KR	Na%	SAR	MH%	PI %	PS
WELLS	NaHCO3	286	66	2.51	73.40	5.76	60.14	91.82	2.14
	NaHCO3	242.4	49	3.10	77.21	6.15	73.79	100.51	1.52
	NaCl	3045.2	1168	1.16	54.54	11.16	52.98	55.04	46.11
	NaHCO3	2584.7	879	1.39	58.59	11.62	56.19	60.27	34.56
	NaCl	2165.6	868	1.00	50.67	8.35	56.89	52.61	28.17
	NaCl	5552.9	1709	1.65	62.58	19.35	62.62	63.46	75.81
	NaCl	4164.7	1389	1.47	59.92	15.52	62.26	60.68	60.71
	NaCl	7890.4	2583	1.47	59.98	21.19	67.56	60.04	109.20
	NaCl	10124.9	2494	2.35	70.50	33.26	75.56	70.14	154.14
	NaCl	6832.5	2130	2.81	73.98	36.66	71.61	73.36	122.93
	NaCl	6677.6	2003	1.74	64.01	22.00	68.16	63.50	102.42
	NaCl	9863.3	3114	1.61	62.52	25.36	79.52	61.03	154.45
	NaCl	3640.1	1423	1.07	52.74	11.42	64.93	52.01	52.52
	NaCl	4499.3	1421	1.56	61.67	16.65	65.49	61.58	61.45
	NaCl	3350.5	1147	1.31	57.50	12.53	62.03	57.71	43.00
	NaCl	7321.4	1881	2.14	68.68	26.24	66.73	67.48	107.31
	NaCl	7545.9	2263	1.92	66.32	25.86	70.18	65.94	117.88
	NaCl	2670.4	810	1.77	64.66	14.27	61.18	64.88	35.10
	NaSO4	2586.5	847	1.36	58.52	11.20	57.87	59.65	30.43
	NaCl	1903.2	242	5.39	84.79	23.72	0.47	84.87	25.95
	NaCl	2477.1	871	1.30	57.46	10.84	57.49	57.89	30.90
	NaCl	3260.6	1062	1.64	63.00	15.10	60.87	62.47	47.01
	NaSO4	3283.4	1131	1.27	57.32	12.07	60.24	55.13	139.80
SPRINGS	NaCl	3391.2	1432	1.06	53.09	11.38	70.42	51.66	51.44
	NaCl	3221.8	1091	1.32	57.88	12.29	58.84	57.78	42.64
	NaCl	2799.5	913	1.52	61.08	13.03	54.09	61.52	42.75
	NaCl	7696.5	2189	1.79	64.66	23.67	65.80	64.02	103.72
	NaCl	8262.3	3265	1.13	53.68	18.30	74.45	53.40	123.17
LAKES	NaCl	459413.1	12795	29.24	96.73	935.4	95.52	95.52	7036.5

	MgCl	385041.6	239358	0.50	35.70	69.15	89.49	32.15	7073.3

4.3.1. *Sodium percentage (Na %)*

Percent sodium is critical in determining irrigation appropriateness. Sodium forms bonds with soil to restrict its permeability, Sunitha in [60] determined sodium percentage (Na%) by using the following formula:

$$Na\% = \frac{(Na^{2+}+K^{+})}{(Ca^{2+}+Mg^{2+}+Na^{2+}+K^{+})} \times 100 \quad (1)$$

Alkaline soils are a result of the chemical process involving sodium and carbonate, while saline soils stem from the reaction between sodium and chloride. The existence of these soil types poses a negative impact on the growth and development of plants. Elevated concentrations of sodium in irrigation water prompt the migration of ions towards clay particles through the omission of Ca^{2+} and Mg^{2+} ions via a process of Base Exchange. In soil, this Base Exchange process curtails the water movement capacity, consequently restricting water supply during wet conditions and leading to the formation of hard and dry soils.

The presence of Na% in the sampled wells signifies that roughly 43% of the collected groundwater is suitable for irrigation purposes, whereas approximately 56% of the water samples are deemed questionable or unsuitable as in **Table 9**. Springs were found to be suitable for irrigation purposes in 60% of cases, while 40% of springs were deemed doubtful. In contrast, lakes were deemed appropriate for irrigation in only 50% of cases, with the remaining 50% deemed unsuitable for such use.

Table 9: Quality of irrigation water based on Sodium Percentage (Na %)

Na %	Class.	Wells		Springs		Lakes	
		No. of locations	%	No. of locations	%	No. of locations	%
<20	Excellent	0	0	0	0	0	0
20-40	Good	0	0	0	0	1	50
40-60	Permissible	10	43	3	60	0	0
60-80	Doubtful	12	52	2	40	0	0
>80	Unsuitable	1	4	0	0	1	50

4.3.2. *Sodium Adsorption Ratio (SAR)*

The sodium adsorption ratio (SAR) constitutes one of the crucial chemical parameters that help evaluate the suitability of water for agricultural purposes [61]. The evaluation of the potential hazards associated with the alkalinity or sodium levels present in agricultural commodities is a critical metric of considerable significance. A high SAR value impairs soil texture by lowering hydraulic conductivity, which reduces irrigation efficacy. The SAR is given by the below equation (Richards, 1954), where the expression of ion concentrations is demonstrated in milligrams per liter (mg/L)

$$SAR = \frac{Na^{2+}}{\sqrt{(Ca^{2+}+Mg^{2+})/2}} \quad (2)$$

Calcium and magnesium present in soils play a crucial role in enhancing their permeability, thereby aiding the growth of crops. Conversely, a surge in sodium content in soils leads to the replacement of calcium and magnesium elements, which further leads to the hardening and compression of the soil, adversely impacting its infiltration and internal drainage capacity. According to the information presented in **Table 10**, it has been discovered that roughly 13% of the groundwater situated within the study area can be classified as falling within the low-sodium category, with an excellent rating (S1: <10).

Additionally, it has been revealed that 48% of the groundwater falls within the good rating (S2: 10–18) for irrigation purposes. As a result, it can be concluded that a grand total of 61% of the wells' water is deemed suitable for irrigation. It turns out that for springs, 60% is good for irrigation and 40% is doubtful. The lakes are completely unsuitable for irrigation. Nonetheless, the FAO guideline specifies that water is regarded as inappropriate once the SAR surpasses 10.

Table 10: Quality of irrigation water based on SAR

SAR	Alkalinity hazard	Class.	No. of Locat-ions	%	No. of Locat-ions	%	No. of Locat-ions	%
<10	S1	Excellent	3	13	0	0	0	0
18-10	S2	Good	11	48	3	60	0	0
18-26	S3	Doubtful	6	26	2	40	0	0
>26	S4	Unsuitable	3	13	0	0	2	100

4.3.3. *Kelley's Ratio (KR)*

The Kelly ratio reflects the water's high salt concentration. KR is also a critical factor in in situations where high KR values are present, it is recommended to employ gypsum to decrease the deleterious effects of sodium ions. The calculation of KR is achieved through the utilization of the subsequent formula [62]:

$$KR = \frac{Na^{2+}}{(Ca^{2+}+Mg^{2+})} \quad (3)$$

The KR values observed in the groundwater sample exhibit a broad spectrum of values, spanning from 0.5 to 29.24. However, the mean value of KR is determined to be 2.65 across the entirety of the water body. Observing **Table 11**, water within KR >1 is unsuitable. It is readily apparent that a significant majority of the collected water samples do not possess the requisite qualities to be deemed suitable for employment in the context of irrigation. Despite the existence of a singular example that satisfies the aforementioned condition (KR < 1) within the context of highly saline lakes, we have successfully demonstrated to the remaining irrigation standards the significant prevalence of sodium concentrations within these bodies of water, rendering the surface lakes unsuitable for irrigation purposes.

Table 11: Quality of irrigation water based on KR

KR	Class.	Wells		Springs		Lakes	
		No. of locations	%	No. of locations	%	No. of locations	%
<1	Suitable	0	0	0	0	1	50
>1	Unsuitable	23	100	5	100	1	50

4.3.4. Magnesium hazard (MH)

The prevalence of an elevated level of Mg^{+2} is frequently associated with the presence of exchangeable Na^{+} in soil that undergoes irrigation, and it is widely acknowledged that calcium and magnesium maintain a state of balance in such circumstances. The presence of an excessive amount of Mg^{+2} can alter the quality of the soil, resulting in an alkaline state that adversely affects crop production and agricultural yields. The degree of Mg hazard can be ascertained by utilizing the provided equation below [63]:

$$MH = \frac{Mg^{2+}}{(Ca^{2+} + Mg^{2+})} \times 100 \quad (4)$$

The majority of water sources, including wells, springs, and lakes, are deemed unfit for irrigation due to hazardous levels of magnesium exceeding 50%. Only a mere 4% of well samples are considered suitable for irrigation with magnesium levels below 50%, as evidenced by data presented in **Table 12**.

Table 12: Quality of irrigation water based on MH

MH %	Class.	Wells		Springs		Lakes	
		No. of locations	%	No. of locations	%	No. of locations	%
<50	Suitable	1	4	0	0	0	0
>50	Unsuitable	22	96	5	100	2	100

4.3.5. Permeability index (PI)

The Permeability Index represents a crucial parameter in the classification of soil permeability for irrigation purposes. PI values are determined by the Doneen method shown in the equation below [64], which is commonly employed, utilizing an equation that accounts for the primary factors impacting soil infiltration and permeability rates and the influence of Na^{+}, Ca^{+2}, Mg^{+2}, and HCO_3^{-} ions present in soils. Where all the ions are expressed in meq/L.

$$PI = \frac{Na^{+} \pm \sqrt{HCO_3^{-}} \times 100}{Ca^{+2} + Mg^{+2} + Na^{+} + K^{+}} \quad (5)$$

For all water body, this region's PI values range from 32.15 to 100.5. The categorization of PI is based on three distinct classes, namely Class I, comprising a 75% suitability, Class II, encompassing a good range of 25-75%, and Class III, indicating an unsuitability of 25%.13% of the ground water belongs to the first category and 87% of the ground water belongs to the second category. The water under the first category and the second category is recommended for irrigation. As for the springs, most of the samples fall into the second category recommended for irrigation. In terms of lakes, they are suitable for irrigation, as they fall into the first and second classifications as well, which is good to moderate for irrigation as illustrated in Table 13.

Table 13: Quality of irrigation water based on PI

PI %	Water quality	Class.	Wells		Springs		Lakes	
			No. of locations	%	No. of locations	%	No. of locations	%
>75	Class I	Good	3	13	0	0	1	50
75–25	Class II	Moderate	20	87	5	100	1	50
<25	Class III	Poor	0	0	0	0	0	0

4.3.6. Potential salinity (PS)

According to Doneen (1964), the appropriateness of water for the purpose of irrigation cannot be determined based on soluble salts alone. This is due to the fact that low-solubility salts tend to precipitate in the soil and collect with each subsequent irrigation, thereby leading to an increase in the concentration of highly soluble salts and ultimately resulting in soil salinity. Potential salinity is a term that denotes the sum of the chloride concentration and half of the sulfate concentration, as demonstrated in the following formula [60]:

$$PS = Cl^{-} + 0.5 * SO_4^{-2} \quad (6)$$

The water samples from all types of bodies analyzed exhibited a potential salinity range between 40 and 48936 meq/l, with an average value of 3349 meq/l. With the exception of only 9% of groundwater samples, as shown in **Table 14**, it has been postulated that the salinity potential in the groundwater of the studied area is generally high, rendering it unsuitable for irrigation purposes. The high concentration of sulfates, which are among the primary minerals extracted from the study site, may potentially be responsible for the elevated salinity levels observed in the area.

Table 14: Quality of irrigation water based on PS

PS	Class.	Wells		Springs		Lakes	
		No. of locations	%	No. of locations	%	No. of locations	%
<3	Suitable	2	9	0	0	0	0
>3	Unsuitable	21	91	5	100	2	100

4.4. Statistics analysis

4.4.1. Correlation analysis

The use of the correlation coefficient is commonplace in evaluating the association between two given variables. It is essentially a metric employed to demonstrate the extent to which one variable can accurately forecast the other. Correlation matrices for TDS, TH, and major ions are shown in Table 15. TDS has a high positive correlation with major cations (Na^{+}, K^{+}, Ca^{+2}, Mg^{+2}) and major anions (Cl^{-}, SO_4^{-2}). A strong positive correlation is evident between TH and Ca^{+2} (r = 0.99), Mg^{+2} (r = 1.00), and K^{+} (r = 0.95), thereby implying that the hardness of groundwater is intrinsically linked to these elements. Conversely, the pH exhibits a feeble negative correlation with other parameters, indicating that it is an autonomous metric that is unassociated with the remaining factors.

Correlation analysis can provide valuable insights into the origins of major ions. In the present study, it was observed that the occurrence of Na^{+} and Cl^{-} was positively correlated with each other (r = 0.86). This correlation indicates that the dissolution of chloride minerals, which are found in the study area in the form of pockets in limestone and filling the cracks of Pliocene clay, is responsible for the presence of these ions.

Table 15: Correlations coefficient of Na^{+}, K^{+}, Ca^{+2}, Mg^{+2}, HCO_3^{-}, SO_4^{-2}, Cl^{-}, EC, pH, TDS for the samples of the study area

variables	Ca^{+2}	Mg^{+2}	Na^{+}	K^{+}	HCO_3^{-}	Cl^{-}	SO_4^{-2}	CO_3^{-2}	TH	PH	TDS
Ca^{+2}	**1**										
Mg^{+2}	**0.998**	**1**									
Na^{+}	0.274	0.321	**1**								
K^{+}	**0.939**	**0.956**	**0.586**	**1**							
HCO_3^{-}	-0.101	-0.076	0.485	0.083	**1**						
Cl^{-}	**0.721**	**0.754**	**0.864**	**0.914**	0.297	**1**					
SO_4^{-2}	0.160	0.206	**0.973**	0.478	0.420	**0.783**	**1**				
CO_3^{-2}	0.017	0.011	0.023	-0.091	0.203	-0.045	0.117	**1**			
TH	**0.999**	**1.000**	0.316	**0.954**	-0.079	**0.751**	0.201	0.013	**1**		
pH	-0.508	-0.517	-0.554	**-0.615**	-0.467	**-0.661**	-0.494	0.028	-0.516	**1**	
TDS	**0.629**	**0.666**	**0.920**	**0.856**	0.352	**0.992**	**0.851**	0.023	0.662	-0.653	**1**

Bold values indicate high correlation between variables.

4.4.2. Factor analysis

Factor analysis was used as a statistical tool to determine the major factors influencing groundwater parameters at the research location. It is a statistical approach used in multivariate analysis to minimize the number of variables while recognizing their interdependence. This approach is effective for discovering underlying elements that contribute to perceived variability in a dataset that would be difficult to determine using typical analytical procedures [65]. It was used to distinguish between dependent and independent variables. Table 16 presents the results of factor analysis for all samples examined in the research region. Results indicate three factors that govern the chemistry of the groundwater, and **Figure 4** represents that.

Table 16: Factor analysis of Na^{+}, Ca^{+2}, Mg^{+2}, K^{+}, HCO_3^{-}, SO_4^{-2}, Cl^{-}, and TH for the study area

Variable	F1	F2	F3
Ca^{+2}	**0.852**	0.073	**-0.097**
Mg^{+2}	**0.976**	0.189	**0.053**
Na^{+}	**0.934**	-0.196	**-0.062**
K^{+}	**0.742**	0.046	**0.364**
HCO_3^{-}	-0.033	**0.891**	**-0.213**
Cl^{-}	**0.962**	0.088	**0.177**
SO_4^{-2}	**0.793**	**-0.404**	**-0.455**
CO_3^{-}	0.006	0.131	**-0.336**
TH	**0.984**	0.172	**0.008**
Eigenvalue	**5.630**	**1.094**	**0.547**
Variability (%)	**62.553**	**12.153**	**6.078**
Cumulative %	**62.553**	**74.706**	**80.784**

Bold values demonstrate a high connection between variables.

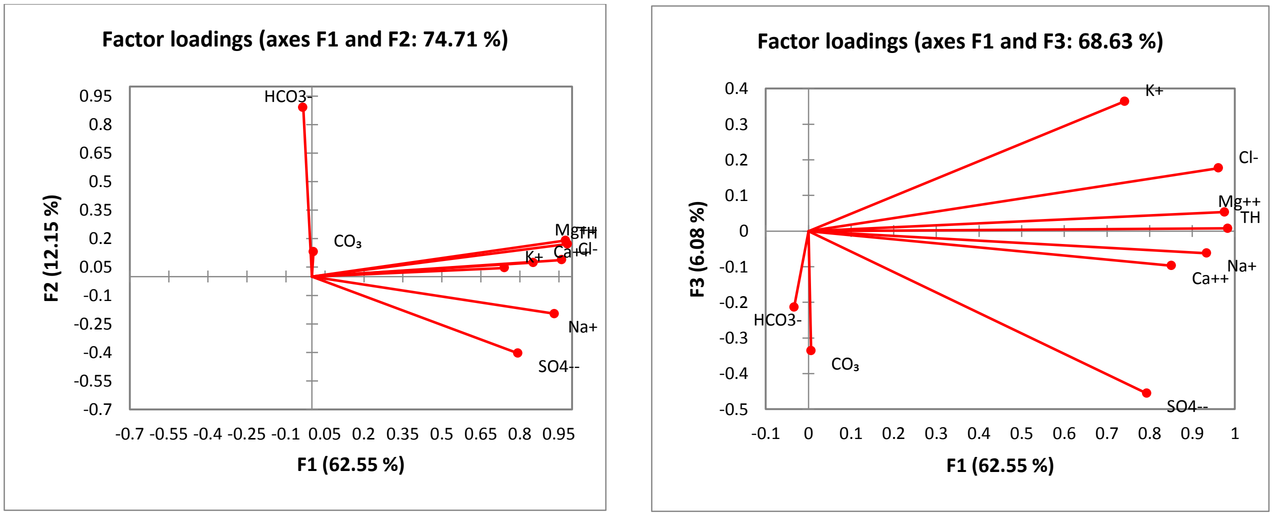


Figure 4: The results of factor analysis for all samples examined in the research region

Factor 1 is responsible for approximately 62.6% of the overall variance, as shown in

Table 15. This factor comprises high quantities of TH, Mg^{+2}, Cl^{-}, Na^{+}, Ca^{+2}, SO_4^{-2} and K^{+} in their respective order, with loading values of 0.984, 0.976, 0.962, 0.934, 0.852, 0.793, and 0.742.

Factor 2 accounts for about 12.2% % of the total variance and includes HCO_3^{-} and SO_4^{-2} which have loading values of 0.891 and -0.404 respectively.

Factor 3 accounts for only 6.078% of the total variance and includes SO_4^{-2} with loading negative value of -0.455 and K^{+} with 0.364. Factor 1 shows a gradual increase in the concentration of most elements in groundwater.

4. Conclusions and Future Work

Groundwater has become more important in recent decades as the oasis's agricultural, tourism, and economic needs have grown. Hundreds of water wells were built to accommodate the growth of the farmed land, urbanization activities, and food enterprises.

Both the pressure head and quality of the groundwater decreased as a result of the incorrect distribution of these wells and overuse of the water supply. This study aimed to evaluate the groundwater quality of water resources (groundwater, springs, and lakes) in Siwa Oasis for irrigation. It also sought out indicators of water quality and agricultural expansion appropriateness. The research concentrates on the center and eastern regions of the oasis, which contain the majority of the producing wells. It is carried out based on the chemical ingredients (major cations and anions) that have been analyzed. To assess the suitability of groundwater with respect to irrigation practices the following indicators calculated and summarized in **Table 17.**

Based on the summary table of water quality indicators for irrigation purposes, the percentage of sodium (Na%) in the total samples of groundwater wells showed that 43% is suitable for irrigation purposes and the rest is used for other purposes, such as industrial, and that the springs are suitable for irrigation purposes by 60%, while the lakes are not suitable and are used for drainage. Based on the analysis of sodium absorption rates (SAR), the results of the study indicate that water sourced from underground wells and springs exhibits the lowest sodium absorption rates. As such, this water is deemed most appropriate for irrigation purposes, with a commendable excellent rating of 13% to a good 60%, respectively. Conversely, the salinity levels of lakes render them unsuitable for irrigation purposes due to the discharge of all water resources therein. It is clear from Kelly's ratio (KR) that the samples are not suitable for irrigation; although a sample of the lakes was recorded for the condition of suitability, it is considered a deviation because the lakes were proven to be unfit for irrigation from the rest of the standard criteria for irrigation due to their extreme salinity. Therefore, it is recommended to use gypsum in cases of high salt concentrations to reduce the effects of the sodium ion. The analysis of the samples revealed that they are susceptible to the deleterious effects of magnesium (MH), notwithstanding the presence of Ca^{+2} and Mg^{+2} to sustain equilibrium. Nonetheless, the superfluous amount of magnesium in the water samples is increased due to the elevated concentrations of sodium, thereby rendering the samples unsuitable for irrigation.

Table 17: Groundwater classification based on irrigational water quality indicators

Parameter	Classification	Range	Reference
TDS	Fresh water	<1,000	US Geological Survey (2000)
	Slightly saline	1000-3000	
	Moderately saline	3000–10,000	
	High saline	10,000–35,000	
	>35,000	Brine	
TH	Soft	<75	Sawyer et al. (1967)
	Moderate hard	75-150	
	Hard	150-300	
	Very hard	>300	
%Na	Excellent	<20	Eaton (1950)
	Good	20-40	
	Permissible	40-60	
	Doubtful	60-80	
	Unsuitable	>80	
KR	Suitable	<1	Kelly (1940)
	Unsuitable	>1	
PI	Class I- Good	>75	Doneen (1964)
	Class II- Moderate	75–25	
	Class III- Poor	<25	
MH	Suitable	<50	Szaboles and Darab (1964)
	Unsuitable	>50	
PS	Suitable	<3	Doneen (1962)
	Unsuitable	>3	
SAR	S1-Excellent	<10	Richards (1954)
	S2-Good	18-10	
	S3-Doubtful	18-26	
	S4-Unsuitable	>26	

Based on the summary table of water quality indicators for irrigation purposes, the percentage of sodium (Na%) in the total samples of groundwater wells showed that 43% is suitable for irrigation purposes and the rest is used for other purposes, such as industrial, and that the springs are suitable for irrigation purposes by 60%, while the lakes are not suitable and are used for drainage. Based on the analysis of sodium absorption rates (SAR), the results of the study indicate that water sourced from underground wells and springs exhibits the lowest sodium absorption rates. As such, this water is deemed most appropriate for irrigation purposes, with a commendable excellent rating of 13% to a good 60%, respectively. Conversely, the salinity levels of lakes render them unsuitable for irrigation purposes due to the discharge of all water resources therein. It is clear from Kelly's ratio (KR) that the samples are not suitable for irrigation; although a sample of the lakes was recorded for the condition of suitability, it is considered a deviation because the lakes were proven to be unfit for irrigation from the rest of the standard criteria for irrigation due to their extreme salinity. Therefore, it is recommended to use gypsum in cases of high salt concentrations to reduce the effects of the sodium ion. The analysis of the samples revealed that they are susceptible to the deleterious effects of magnesium (MH), notwithstanding the presence of Ca^{+2} and Mg^{+2} to sustain equilibrium. Nonetheless, the superfluous amount of magnesium in the water samples is increased due to the elevated concentrations of sodium, thereby rendering the samples unsuitable for irrigation.

The soil water permeability indicators (PI) in most of the water resource samples in the oasis achieved the two classifications of good to moderate permeability, which makes them suitable for irrigation. The potential salinity (PS) index indicates the possibility of using well water for irrigation under close and continuous monitoring of sodium concentrations. As for the rest of the samples from springs and lakes, it is not recommended to use them for irrigation due to the high salts from evaporation and random drilling, which lead to dispersion and deviation in the concentrations of ions. Utilizing statistical factor analysis represents an optimal approach for determining the degree of correlation existing among variables. The favorable correlation observed between Na^+ and Cl^- (r = 0.86) denotes the dissolution of chloride minerals present in the area of study.

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