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PROBLEMS THREATENING SUSTAINABILITY IN SIWA OASIS AND RECOMMENDATIONS FOR UNDERSTANDING THE SOURCES OF WATER QUALITY DETERIORATION

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Abstract: Siwa Oasis has been chosen as the location for the current investigations. Siwa Oasis is an isolated closed depression located in Egypt's Western desert. It is surrounded by the Mediterranean Sea to the north (about 330 km), to the west by the Libya-Egypt border (70 km) and Cairo to the east (560 km). There are three major activities in Siwa Oasis: that are represented by agriculture (palm tree, olive, fruits and vegetables), industry, (e.g. mineral water bottling and olive oil extraction), and tourism (medical treatment, safaris). The climate of the Western Desert, particularly in Siwa, is generally torrid and arid. The Siwa depression is occupied by Quaternary deposits (aeolian deposits and lakes), Middle Miocene, Upper Cretaceous (sandstone), and Precambrian (basement complex). The groundwater system in Siwa Oasis hastwo main productive aquifers: a Miocene aquifer (fractured limestone) and a Lower Cretaceous aquifer (Nubian Sandstone). Besides, the Quaternary (clay and sand) uppermost layer is water-bearing because of waterlogging. Siwa Oasis is suffering from waterlogging, increasing soil salinity, and deterioration of water quality in the aquifers. This review includes the problems in Siwa Oasis and recommendations for understanding hydrogeological situations and sources of water quality deterioration to avoid waterlogging and soil salinization through integration of flow modeling, geochemistry and isotopic tracers.

Keywords: *Siwa Oasis, groundwater aquifer system, soil salinity, waterlogging, water quality*

1. INTRODUCTION

In recent decades, much emphasis has been placed on the development of new settlements in Egyptian desert areas with significant groundwater potential in order to preserve the land in the Nile Delta and the Nile Valley. Efforts have been made in several integrated fields of study to achieve these goals. As Egypt is essentially a desert land (about 96 percent), much thought is given to the reclamation and use. Thus, many governmental institutions and private sectors have conducted studies in the fields of geology, geophysics, hydrogeology, and for the selected desert in Egypt over the last two decades. These studies were carried out to ensure proper evaluation of new settlements. These areas include Siwa Oases, which is located in the Western Desert. The current study looks at how geological and hydrogeological techniques can be used to assess the potential of groundwater in the Siwa depression [1].

2. SITE DESCRIPTION

Siwa Oasis is an isolated closed depression located in the northwestern desert of Egypt. It is surrounded by the Mediterranean Sea to the north (about 330 km), to the west by the Libya-Egypt border (70 km) and by Cairo (560 km) from the east *(Figure 1)*. The depression is situated between latitude 29.12 N and longitude 25.43 E. There are three major activities in Siwa Oasis: agriculture (palm tree, olive, fruits and vegetables), industry, (including among others mineral water bottling and olive oil extraction), and tourism (medical treatment and safaris) [3].

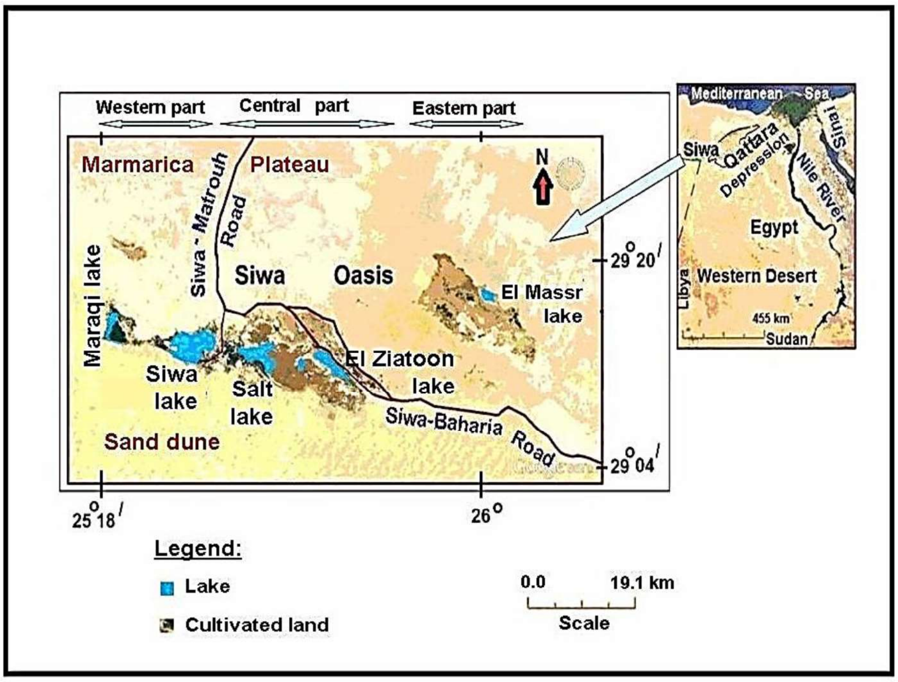

Figure 1
Siwa Oasis location map, Western Desert, Egypt [3]

The length of Siwa depression has elongated shape, which is about 82 km in E-W direction and its width ranges from 2 to 20 km. The total area of Siwa Oasis is approximately 1,050 km^2 (250,000 feddans). In 2010 the population in Siwa Oasis had reached about 23,546 residents [4].

3. GEOMORPHOLOGY OF SIWA OASIS

The topography of Siwa Oasis includes a terrain with an elevation range from 19 m below sea level to 154 m above sea level. The different geomorphological units in the area are mobile sand dunes, which are located along the southern part, a steep escarpment of limestone plateau situated in the northern part, and a flat depression that includes the agricultural land, salt lakes and playas in the center of Siwa Oasis [5, 6]. The major lakes in the flat depression are Maasir, Zeitoun, Aghourmy, Siwa, and Maraqi lakes, from west to east *(Figure 2)*. Water bodies of these salt lakes come from different sources such as drainage water from agricultural land, dug wells and springs [7].

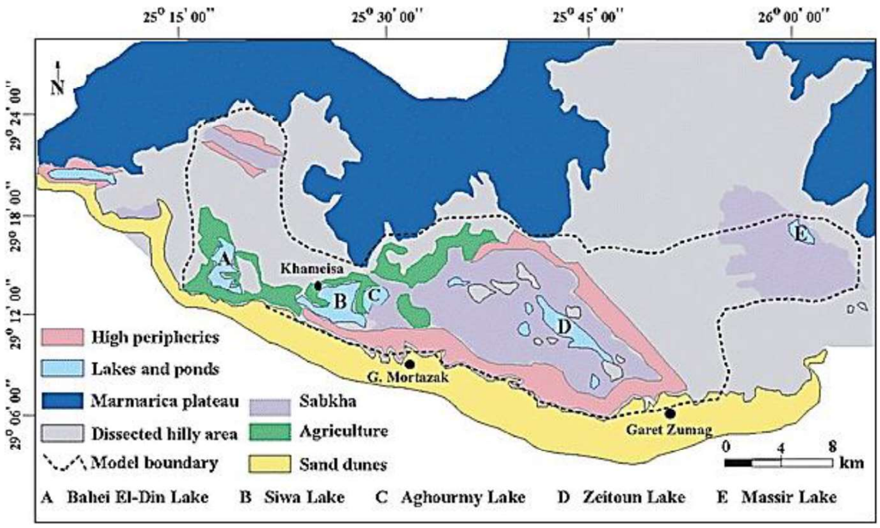

Figure 2
Geomorphological map of Siwa Oasis [7]

4. CLIMATE OF SIWA OASIS

Siwa Oasis is characterized by an extremely arid climate which is cold in winter and hot and dry in summer [8]. The different elements of climate in Siwa area are represented as follows:

4.1. Air temperature

Average air temperature ranges annually from low (14.12 ºC) to high (29.32 ºC) temperatures [8].

4.2. Soil temperature

The temperature of the soil at a depth of about 5 cm reaches a maximum value of 32.8 ºC [9].

4.3. Wind direction

Wind in Siwa Oasis has three different directions: SE, NW and NE with different ratios (12.4%, 24.4% and 18.2%, respectively). The effect of wind from erosion and deflation becomes more obvious in April, when it carries salt particles and loose sand, transporting and depositing them in low land area through sequence in Siwa depression. The impermeable bed of soil is eroded, causing a decrease in the soil profile, hence the water table is raised [9].

4.4. Relative humidity and evaporation

The relative humidity in Siwa Oasis is about 45.3%. The rate of evaporation increases in Siwa due to high solar radiation and dryness of depression. Evaporation rate reaches 16.8 mm/d in summer, while in winter it attains about 5.4 mm/d [8]. High evaporation and evapotranspiration play an important role in salt weathering, leading to capillary rise of ground water to the surface sediments. For this reason, salt crystals are concentrated in surface soil and accelerate salt weathering [9].

4.5. Rainfall

Rainfall in the Siwa area is negligible, with annual precipitation about 10 mm [8].

5. Geology of the Siwa depression

5.1. Surface geology

The stratigraphy of rocks that are exposed to the surface of Siwa Oasis is outlined as follows:

a) Quaternary deposits: these deposits include sand dunes in the southern part of Siwa depression and sabkhas (evaporite deposits of clay and silts) (see *Figure 9*),
b) Middle Eocene: these rocks consist of chalky limestone and neritic limestone intercalated with shale, which covers the southern area of the depression.

In the northern part of Siwa there are several drainage lines that are affected by a fracture system having two major directions (NE-SW and NW-SE).

5.2. Subsurface geology

The sequence of subsurface stratigraphy includes Palaeozoic, Mesozoic and Cainozoic strata. This sequence consists of two major cycles of deposition (clastic and carbonate deposition) *(Table 1, Figure 4)*.

The formation of Paleozoic and Mesozoic represent a clastic facies cycle (oldest sedimentary rocks). The cycle of carbonate facies consist of two formations (tertiary Eocene and Miocene). A Paleozoic, Mesozoic and Cainozoic stratigraphic sequence is located above basement rocks and affected by normal faults in different directions (N-S, E-W, NW-SE and NE-SW, *Figure 3*) [5, 10].

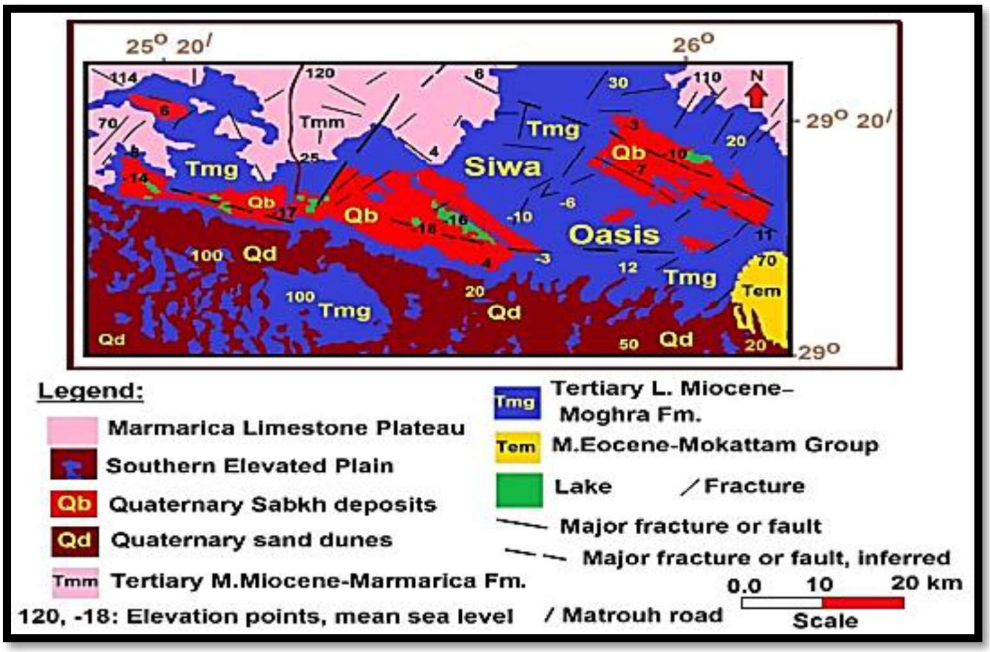

Figure 3
Surface geologic map of Siwa Oasis [11]

Table 1
Geologic formations of Siwa Oasis, Egypt [10–12, 13]

Era	Age		Log	Average Thickness	Lithic description	Depositional environment
Cenozoic	Tertiary	Miocene		250 m	Limestone with marl (Marmarica Fm.) Sandstone, siltstone, shale (Moghra Fm.)	Shallow marine Fluvio-Marine
		Eocene		350 m	Limestone intercalated with shale, marl, evaporites beds (Mokattam Gr.)	Shallow marine
Mesozoic	Cretaceous			600 m	Sandstone with shale and carbonate intercalations (L. Cretaceous), overlain by impermeable layer of carbonaceous shale and argiliceous limestone (U. Cretaceos)	Shallow marine, near shore
Paleozoic	Carboniferous			912 m	Sandstone with shale and limestone	Near shore, Continental
	Devonian			347 m	Mudstone, siltstone, carbonaceous sandstone, limestone & dolomite	Fluviatile, Continental, Shallow marine
	Silurian			626 m	Mudstone and siltstone (Kohla Fm.)	Fluviatile, Marine
	Ordovician / Cambrian			315 m	Sandstone intercalated with shale and siltstone beds	Continental
Pre-Cambrian				?	Basement complex, Granite, Gneisses	

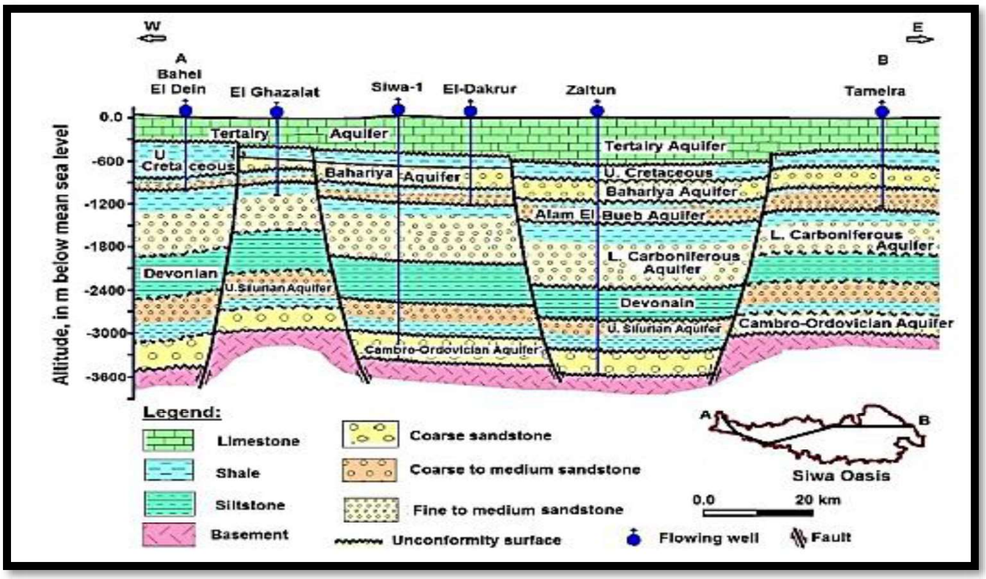

Figure 4
Cross section of hydrogeology in Siwa Oasis [14]

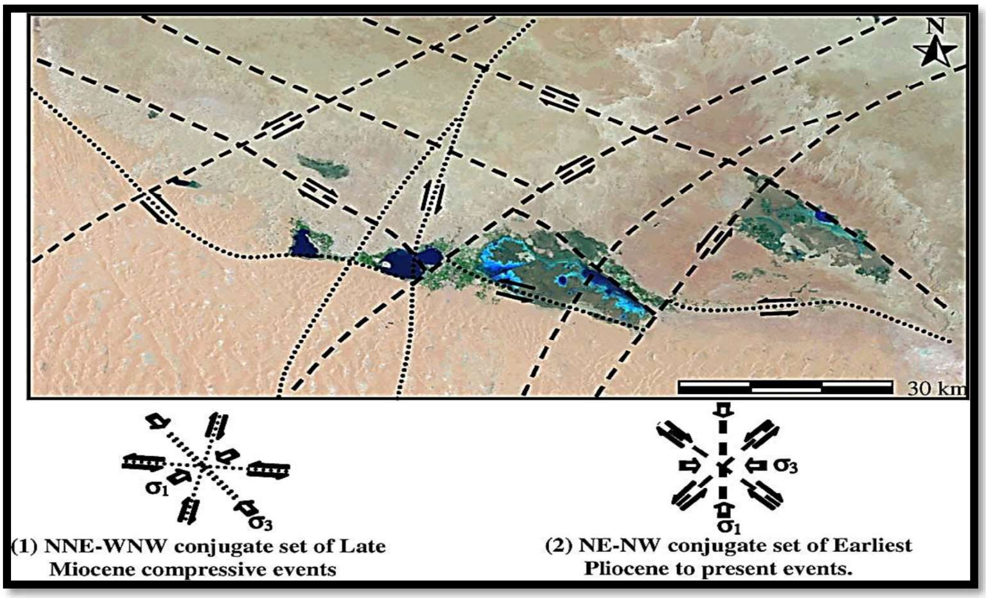

Figure 5
Major morphotectonic conjugate set of faults overlaying the Landsat742 RGB of 2003 image and proposed model of deformation in Siwa region [15]

6. TECTONIC ARCHITECTURE AND RELATIONSHIP TO THE HYDROGEOLOGICAL SETTING

Siwa depression is characterized by different tectonic architectures such as faults and fractures, but these features are poorly exposed because they are covered by sand dunes. However, these fracture zones on the earth's surface are important with respect to subsurface fluid flow. Siwa Oasis was formed by successive tectonic events and took its shape through topographic processes. The presence of surface linear features such as springs, lakes, and surface ponds gives an indication of vertical and near vertical fracture zones. The main controlling factor of connection between groundwater aquifers and lakes is fractures and faults. There are four main directions of vertical and near vertical fracture zones (NW-SE, NE-SW, WNW-ESE and NNE-SSW) in addition to, two sets of faults nearly perpendicular. The high conductivity between Siwa Lakes and groundwater is the result of the two sets of faults intersecting these lakes [15].

7. WATER RESOURCES

7.1. Surface water

The main reason for attracting Bedouin people to live in Siwa area was the presence of four water lakes before deterioration of the water quality of lakes by high salinity. The two major factors responsible for the increasing salinity of water lakes are the high evaporation rate and discharge from drainage of agricultural land.

Recently Siwa Oasis has begun to have serious problems with waterlogging. This problem derived from over-irrigation by flooding, where the excess water seeps downward to a shallow aquifer which is separated from the Miocene aquifer below; hence, the water table rises to or near to the ground surface. Drainage water from agricultural land contains a high concentration of anions and cations that causes increasing salinity of the shallow aquifer. Because of high salinity of water lakes, it is no longer suitable for domestic use, meaning that the demand for extraction of groundwater from the aquifer increased. More than 95% of water users in the Siwa area depend on groundwater [16].

7.2. Groundwater

Based on the hydrogeological setting of Siwa depression, there are five aquifers arranged from top to base:

1. Quaternary deposits (shallow aquifer),
2. Miocene,
3. Eocene,
4. Upper Cretaceous (carbonate aquifer),
5. Nubian sandstone aquifer (lower Cretaceous) [14, 17].

The most important aquifer is the Nubian aquifer, which is used for drinking, domestic use, and irrigation. It is characterized by high water quality of water according to WHO (1984).

7.2.1. Aquifer systems

There are five major aquifers in Siwa Oasis [6].

a) Shallow aquifer (Quaternary deposits)

People in Siwa do not use the Quaternary aquifer for irrigation or domestic use due to deterioration of water quality of the aquifer. This aquifer contains water with salinity (42,000 ppm) higher than the Miocene, Eocene and Nubian aquifers. The higher salinity comes from the downward seepage of water from agricultural land. The water table is found in shallow depths ranging from 0.25 m to 1.75 m below ground surface.

b) Miocene aquifer

This is the main aquifer in Siwa Oasis for irrigation purposes because of its low cost in drilling compared to the Nubian aquifer. This aquifer consists of fractured limestone which is located below the Quaternary aquifer. The water table depth in the Miocene aquifer ranges between 40 and 130 m below ground level. In some areas, the water quality of Miocene aquifer began to deteriorate, where salinity ranges from 2,000 to 4,000 ppm. The amount of water extracted from this aquifer reached about 100 million m^3 per year [19].

c) Eocene aquifer

This aquifer is not used for irrigation or drinking water as a result of the high salinity of its water, which ranges from 3,000 ppm to 16,000 ppm. The depth of the water table in the Eocene aquifer ranges between 220 m and 450 m.
The Eocene aquifer is composed of fractured limestone and dolomite and overly upper Cretaceous aquifer. Most of the springs in Siwa Oasis flow from this aquifer [19, 20].

Upper Cretaceous aquifer

This aquifer is a carbonate aquifer consisting mainly of fractured limestone intercalated with shale and overlain Nubian sandstone aquifer. There is not a large number of wells to extract groundwater from this aquifer owing to its salinit,y which ranges between 2,000 ppm and 8,000 ppm.
The water table is found at different depths between 395 m and 575m BGL. Most of the springs that flow naturally in the Siwa area feed from this aquifer and are used for medical purposes and tourism [19, 20].

d) Nubian sandstone aquifer (NSSA)

The NSSA is considered to be the main aquifer responsible for life in Siwa Oasis. It contains water with high quality which is suitable for both drinking and irrigation. Salinity of groundwater in the Nubian sandstone aquifer is the lowest in Siwa, ranging from 500 ppm to 600 ppm. Farmers in Siwa find it difficult and expensive to drill wells in this aquifer due to its depth, ranging between 950 m and 1200 m [19]. About 95% of domestic, irrigation and drinking water comes from this lower Cretaceous aquifer (NSSA).

8. DESCRIBING THE HISTORICAL DEVELOPMENT OF THE STUDY AREA

In 1963, there were less than 200 springs of any use with depth about 12 m below the ground level [21]. From 1981 to 1996, farmers began to drill thousands of wells in the fractured limestone aquifer with poor design, which produced an excess of water and formed the lakes in the low land of the Siwa depression and led to the continuous deterioration of agricultural land. During this period, all wells were drilled in the shallow aquifers (carbonate aquifer) with no controlling valves and no casing. The total discharge from these wells reached to 400,000 m^3/d, where only 60% wasused for irrigation and excess water was discharged into lakes [22]. From 1996 to 2001, different actions occurred. One of them aimed at the rehabilitation of poorly designed wells (400 wells), while 665 wells were still with low priority. Continuous drilling of new wells made the problem worse with time.

9. GROUNDWATER DISCHARGE

The total amount of water that is discharged into different lakes is about 146 million m^3/year, *Table (2)* [22].

Table 2

Daily and annual flow from springs and wells

Catchment Area	Discharge rate (m^3/day)	Discharge rate (m^3/year)
El Maraqi	60,000	21,900,000
Siwa	140,000	51,100,000
Aghourmi	120,000	43,800,000
Zeitoun	80,000	29,200,000
	400,000	**146,000,000**

As a result of measured taken by the government from 1996 to 2001, the total amount of ground water discharge was reduced to 130 million m^3/year, *Table (3)*. The total amount of groundwater discharged into the lakes caused by poorly designed wells is 51 million m^3/year.

Table 3

Daily and annual flow from springs and wells [22].

Catchment Area	Total discharge rate (m^3/ y)	Cult. Area (Fed.)	Demand (m^3/y)	% Losses to the Lake related to total discharge
El Maraqi	25,820,940	1413	10,597,500	49 %
Siwa	65,208,600	5066	38,000,000	42 %
Aghurmy	26,417,820	2751	20,632,500	22 %
Zeitun	12,249,120	1283	9,622,500	22 %
Total	**129,696,480**	**10,513**	**78,847,500**	**39 %**

10. THE MAIN FACTOR CONTROLLING THE SUSTAINABLE DEVELOPMENT OF SIWA OASIS GROUNDWATER QUALITY

Water quality changes from the deeper aquifer (NSSA) to shallow aquifers (fractured limestone aquifers). Water in the Nubian sandstone aquifer is characterized by high quality, and water salinity ranges from 200 ppm in the upper zone (500 m thick) to 1500 ppm in the lower part of the aquifer. There is water quality deterioration for the fractured limestone aquifers through the leaching of salts during movement of water upward and interaction with the shale, clay and evaporite that are intercalated with the carbonate rocks [14].

11. THE MAIN PROBLEMS THROUGH PREVIOUS WORK IN SIWA OASIS

Waterlogging is the most significant problem in Siwa Oasis, with a continuous rise in the water table. Furthermore, there is deterioration of fertile soil because of soil salinization. The water table rose by 1.33 cm per year in the period from 1962 to 1977 but this rate changed to 4.6 cm per year in the period from 1977 to 1990. The main factors behind this phenomenon are the expansion in agriculture, with poor management and over-irrigation by flooding with poor drainage systems [23].

There is a decrease in vegetation cover in Siwa Oasis and an increase in soil salinity due to over-irrigation, which resulted in the rising water table. This appeared between 1987 and 1999. The salinity index was increased to double over 12 years. The water table was elevated from 1.2 m below the ground surface in 1987 to 0.54 m in 1999 [24].

The Siwa depression contains different tectonic architectures such as faults and fracture systems that are poorly exposed to the ground surface as a result of sand dune cover. The main reason for the formation of springs, lakes and surface ponds is the presence of vertical or near vertical fracture zones. Moreover, the two sets of faults make a connection between groundwater and lakes. The fracture system took three main directions NW-SE, NE-SW, WNW-ESE and NNE-SSW [25].

After 2000, soil salinization increased in Siwa Oasis, which led to the death of plants and agricultural deterioration. The reason for increasing soil salinization is the lack of good drainage system, poor management of available water resources, over-irrigation by flooding, and a very small amount of precipitation [25].

The total area of salt flats surrounding the lakes in Siwa depression increased by 20.55 km^2 from the year 1933 to 2002. The activity of salt weathering changes from one place to another according to changes of acceleration process. In low land areas around saline lakes, the activity of salt weathering reaches its maximum value [9].

Agriculture is progressively deteriorating in Siwa Oasis as a result of desertification. The negative impact of desertification appears in decreasing vegetation cover from date palms and olive trees [27].

The salt lakes in Siwa depression could be converted to a basin through the construction of a wall around marshes and lakes. The high evaporation rate in the summer will reduce the water level of lakes and produce karshef, a material made up of fossilized salt that settles on the shores of Siwa lakes. It is collected, mixed with mud and water, and used to construct low-rise buildings with thick walls and shallow foundations. Walls constructed of karshef can help make the land be suitable for agriculture again [28].

The soil in Siwa depression contains 34 elements (Ca^{2+}, Na^{+}, Al, Mg^{2+}, V, Mn, Ti, Cr, Fe, Zn, Br, Ni, As, Co, Sr, Br, Zr, Rb, Cs, Sb, Ba, I, Eu, Ce, Tb, Nd, Dy, Yb, U, Tm, Ta, Hf, Th). The origin of iodine and chloride are the Siwa lakes, while arsenic originated naturally in soil owing to the absence of industrial activity. The elements Hf, Sc, La, Zr and Th, which have low solubility, originated from sediments and continental rocks [29].

There is variation in the water quality in different locations within Siwa Oasis. Salinity hazards increased at a high rate and resulted in excessive deterioration of water quality and the water became not within the acceptable limits of irrigation. The poor water quality is due to unsafe abstraction from NSSA, where it reduces the vertical movement of fresh water from NSSA to shallow limestone aquifer. Toxic elements such as boron are presented in specific locations exceeding the permissible level of concentration [30].

The water resources in the western and central part of Siwa depression have different characteristics. NSSA contains fresh water with low TDS, pH > 7(alkaline), meteoric water, and less mineralized water. The concentration of heavy metals in NSSA is lower than in springs, lakes and TCAS. In the central part of Siwa Oasis there are increasing concentrations of radiochemical constituents such as TDS, heavy metals and major ions. The activity concentration of ^{40}K, ^{232}Th and ^{226}Ra reached maximum values of 25.6 ±5.9 Bq/l (TCAS), 6.7 ±1.6 Bq/l (TCAS) and 5.6 ±0.7 Bq/l (NSSA) respectively. TCAS contains brackish water with TDS ranges from 1903 mg/l to 10,125 mg/l, $p^H > 7$ and three genetic types of water, Cl-Ca, Cl-Mg and SO_4-Na. The first and second type of water refer to the interaction of water with evaporite and marine deposits while the third type indicates the recharge from NSSA. Most of the springs contain brackish water with pH > 7 and have two genetic types of water (Cl-Ca and Cl-Mg types) indicating marine origin. Water of the lakes contains brine water with pH < 7 (acidic) and two genetic types of water, SO_4-Na and Cl-Ca [3].

There is low diversity in the bacterial composition of the three lakes (Maraqi, Zeiton and Aghormy) in Siwa Oasis, which indicates a hypersaline environment. The three lakes contain Bacteriodetes-like phylotypes while Maraqi and Zeiton are also characterized by the presence of Alphaproteobacteria-like phylotypes [3].

Surface water in Siwa Oasis came from deeper aquifers passing through fracture system and fault plain. The two major fault lines in Siwa depression are ESE-WNW and ENE-WSW. Salts became concentrated in lakes because of evaporation [31].

The most serious problems associated with the groundwater in Siwa Oasis are the following: waterlogging phenomenon [32], rapid falling water level and groundwater depletion [33–34,35], salt water intrusion [36–37,38] and disturbance to the overall groundwater system [39–42,43], and contamination of high groundwater quality of the deep Nubian sandstone aquifer with radionuclides [44]. The situation becomes worse when high natural discharge of poor-quality groundwater through natural springs and/or uncontrolled dug wells is involved, which is observed in Siwa Oasis.

12. RECOMMENDATIONS AND REQUIRED ANALYSIS TO UNDERSTAND THE HYDROGEOLOGICAL SYSTEM OF SIWA OASIS FOR SUSTAINABLE MANAGEMENT

12.1. Goals

This proposal aims at groundwater management to maintain and improve the state of water resources in Siwa Oasis. The principal objectives of water resources management and plans are to grant the increasing water demands for different uses in the most environmentally effective, socially acceptable, and economically efficient manner. Additionally, it is necessary to evaluate factors in the deteriorating groundwater quality in Eocene, Miocene and Nubian sandstone aquifer using geochemical modeling and isotope traces.

12.2. Methodology

12.2.1. Sampling

Water samples should be collected from groundwater aquifer systems including Nubian sandstone, Eocene, Miocene and Quaternary aquifers as well as surface waters (lakes, springs and drains). The sampling plan should cover the entire Siwa Oasis.

12.2.2. Measurements and analyses

The required analyses are as follows:

a. ***Field parameters*** including water temperature, pH, TDS, TSS, dissolved oxygen, electrical conductivity and salinity.

b. ***Laboratory measurements*** including ammonia, nitrate, nitrite, ortho-phosphate, sulfate, chloride, total hardness, total alkalinity, calcium, magne-sium, sodium, potassium, and heavy metals.

c. **Isotope analysis** such as stable isotopes $\delta^{18}O$, $\delta^{2}H$, $^{87}Sr/^{86}Sr$, ^{11}B, uranium ^{235}U, thorium, radon Ra, chlorine isotopes ^{36}Cl and ^{37}Cl.

d. **Data analysis and modelling**

- Analysis of potentiometric data and depth-pressure profiles to understand hydrodynamic conditions.
- Groundwater modeling of Siwa Oasis and its environs to understand driving forces, hydrodynamic processes and to provide predictions and analyze groundwater extraction scenarios.
- Geochemical modeling of groundwater-rock interaction (NETPATH Geocehmical Model) to detemine groundwater origin and boundary conditions for solute transport models.

- Solute transport modeling using the calibrated groundwater model to simulate salinization processes and to provide predictions and a management plan for decision makers.
- Synthesis of results and reporting: In the final stage of the reserach, the results achieved should be analyzed and synthesized to provide a coherent hydrogeological-geochemical description of the Siwa Oasis system and to provide recommendations for sustainable groundwater management.

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