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Hydrogeological and Environmental Studies on Siwa Oasis, Egypt Using GIS Technique

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THIS PAPER studies the environmental conditions of the hydrological setting of Siwa Oasis using *in situ* measurements of water samples integrated with geographical information systems (GIS). Siwa Oasis is relying on groundwater in all their domestic use which, in return put extra pressure on water budget. The groundwater found in five reservoirs in which the Nubian sandstone aquifer is the most appropriate for drinking and domestic use. However, it is a very deep aquifer and few artesian wells are occurred. Carbonate aquifer found to be suitable for some irrigation and agricultural usage and it is more recommended to sustain the Nubian aquifer for drinking purposes. Landuse changes particularly irrigated agriculture is the key controlling factor of the groundwater deterioration.

Keywords: Hydrogeology, Environment, Groundwater, GIS, Siwa Oasis.

Water shortage is the forthcoming crisis for all nations and unless there is a managing system for water quantity and quality we will be at high risk (Cosgrove & Rijsberman, 2000). Oasis areas are under extreme arid climate with lesser rainfall and higher evaporation rate (Thornes, 1995). The consequence of such climatic conditions is the limited surface water that supports the living standard of the local community. The prime source of water in such oasis or/and similar environment is the groundwater. The water demand is particularly to sustain life of the local community in the form of drinking, domestic use and securing food. This would be reflected on the land use land cover changes.

Land use describes the nature of land categories, for example agricultural, residential or industrial, while the land cover describes the vegetation types, building, *etc.* (Sabins, 1997). Agriculture is the highest consumer of water resources for securing food. It is significantly affect the water quality deterioration via high discharge of cations and anions (*i.e.*, pesticides). Remotely sensed data offers frequent real-time information which is very efficient in land use discrimination (Kauth & Thomas, 1976 and Su, 2000) and irrigated land (Wiegand *et al.*, 1986; Palacios-Orueta & Ustin, 1998 and Belward, 1991). Improved techniques and modelling have greatly improved the performance of remote sensing classification; however there is still considerable scope for improvement (Congalton, 1991; Nirala & Venkatachalam, 2000 and El-Magd & Tanton, 2005). Satellite data found to be very efficient in studying soil properties, soil salinity and water logging (Palacios-Orueta & Ustin, 1998;

Amano & Salvucci, 1999 and Engman, 1997). However, GIS is a powerful tool in managing, analysing and modelling large amount of information (Robert & Thompson, 1992).

The topography of the area shows variable terrain with the highest elevation at 154m above sea level and the lowest elevation is 19m below sea level. However, the area has variable geomorphological land forms in response to its geological settings (Said, 1962). These are: limestone plateau in the north, steep escarpment which is running East-West direction, mobile sand dunes which are concentrated in the south, and flat depressions which contains cultivated land, playas and saline lakes.

The area accommodates the local community who are relying on the agriculture development together with grazing. The irrigation development mainly relies on man-made subsurface wells and in some parts from natural springs abstracting good quality of groundwater. The availability of such groundwater either in the form of natural springs or/and pumped wells have boosted the creation and development of such oasis. The initial creation of Siwa oasis was around four surface water lakes, which are Maraqi, Zaitun, Massir and Siwa. Lake Siwa is considered the largest and highly urbanized one.

The water resources at Siwa oasis are under sever strains either naturally or via man made. This includes changing of land use, mismanagement of the water resources, lack of drainage systems, overuse of traditional irrigation systems, the high evaporation rate with less precipitation which resulted in more saline water bodies. The above mentioned factors have escalated the deterioration of the water resources at Siwa Oasis in the last century.

This paper is studying the applicability of integrating *in situ* measurements of the chemical parameters of water samples and GIS analysis to understand the groundwater conditions at Siwa Oasis and studying the factors accelerating the deterioration of such water resources. It also aims at proposing some solutions to minimize the deterioration factors.

Study area

The study area is Siwa Oasis, which covers an area about 7333 km^2 and located in the Northwest corner of the Egyptian Western Desert between 29° N and 30° N and 25° E and 26° E (Fig. 1). The climatic condition of the area is the typical arid and semi-arid climate with very low rainfall with an average of 9.6 mm $year^{-1}$. The area has a very high evaporation with maximum of 13 mm day^{-1} in July (summer) and minimum of 4.2 mm day^{-1} in December (winter). The maximum temperature recorded was in the summer of about 38°C (July) and the minimum temperature record was 15°C in the winter.

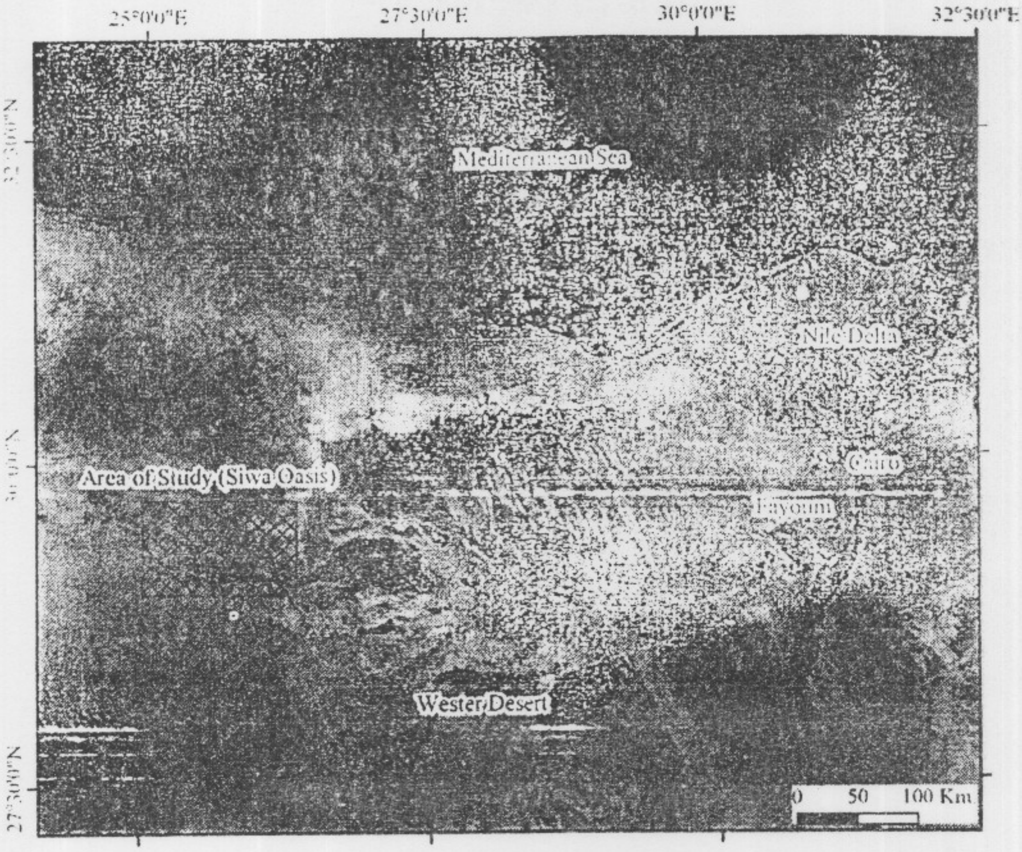

Fig. 1. The study area.

Methodology

Field Survey

Field survey was carried out in 2007 to survey the oasis and to locate the water wells on the base map. Water samples were collected from the different kind of wells and analysed to measure the physico-chemical parameters (Fig. 4). The water samples were collected to represent the variable groundwater aquifers in the area. The result of the chemical analysis was interfaced in a GIS to simulate the distribution pattern of the chemical characteristics of the groundwater aquifer.

Remote sensing

The satellite image was geometrically corrected to the UTM grid system (Zone: 36N, datum: WGS84). Then, the image was radiometrically corrected to remove any noise and additives from the atmosphere (Campbell, 1993). Once geometric and radiometric corrections have done the image is ready for any fur ther analysis.

Enhancement technique in the form of histogram stretching was applied onto the satellite image to present the water bodies and clearly discriminate the shoreline boundary of the water bodies. Fig. 2 is the typical example of the histogram stretching applied to discriminate the lake's water body and the shoreline.

Geographic information system (GIS)

The hydrogeological map was digitised and transformed on to GIS format. The typical process was started with scanning the hydrogeological map at high resolution of 300 DPI (Dot Per Inch) which is thereafter displayed on the screen as background for tracing the hydrogeological features. The digitised features include the location of the groundwater wells, natural springs, the location of the cities (urbanised areas), the drainage network, the road network, land uses and geomorphic features.

Once the digitisation of the water wells finished a link of the water wells locations and the chemical analysis of the water samples is established. Such link was based on the name of the water well.

Finally, GIS system is developed to enable the analysis of the characteristics of each groundwater aquifers. It also used in simulation the water parameters along the whole aquifer to see the spatial pattern of the chemical parameters.

Results

Surface water

Siwa Oasis has four water lakes which were the nuclei for attracting the Bedouin people to live in this area and made the history of this oasis. However, two key environmental factors are controlling the deterioration of the water quality of these lakes. First, the high rate of evaporation, which contributes to the increase of the salinity of the water bodies of these lakes. Second, the high amount of discharge of phosphates and nitrates (*i.e.*, pesticides) from irrigated land also increases the salinity of the lakes. Landuse changes to agriculture particularly furrow irrigation has increased the discharge to the shallow groundwater aquifer as well as the lake water bodies. Such discharge is highly concentrated with cations and anions from pesticides. The limited surface fresh water recharge to these lakes to maintain its freshness has increased significantly the salinity of the water body of these lakes.

In return these lakes also contribute to the high salinity of the shallow groundwater aquifer. Unfortunately, this has limited the use of these lakes in domestic use and/or irrigation purposes. In due course, the demand on the groundwater is significantly increased with more than 95% of the water use in this oasis is relying on the groundwater.

Figure 2 shows these lakes from the satellite imageries, which appear as a mask to most of the background features. The shoreline of these lakes is fluctuated based on the season of the year and the amount of water recharging to the lakes.

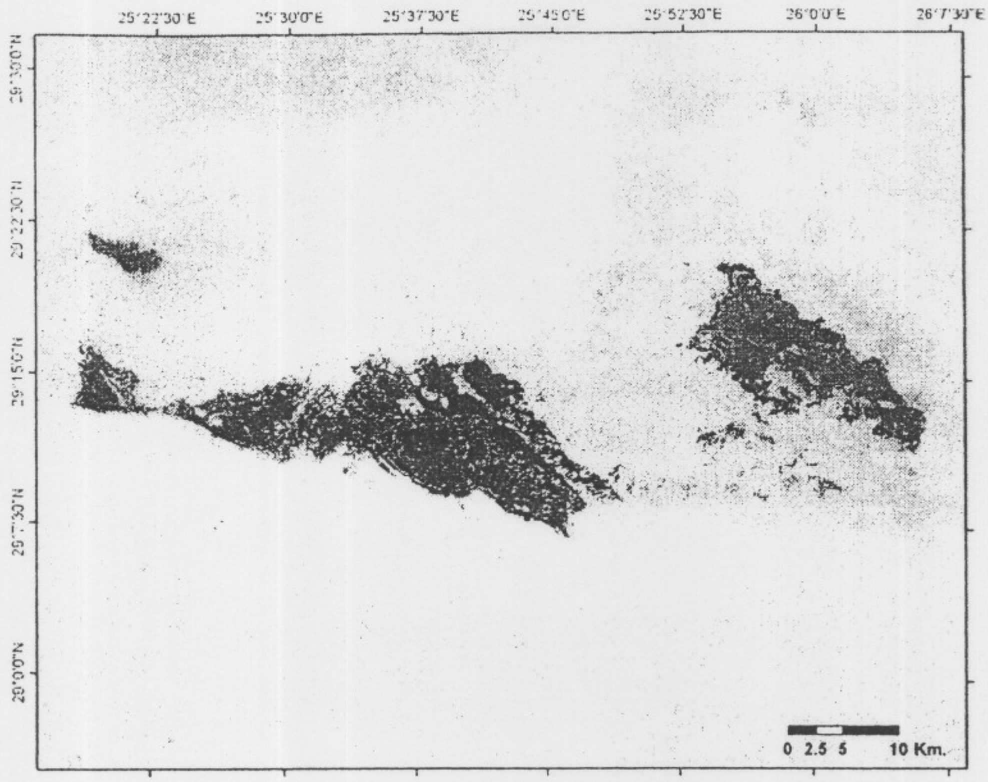

Fig. 2. Enhanced colour composite of landsat image shows the water lakes at Siwa Oasis.

Groundwater

It is clearly obvious that the local community utilize their water need from the groundwater and in particular the Nubian Sandstone aquifer. The hydrogeological setting of Siwa oasis shows three types of rock units that accommodate five aquifers. These are quaternary deposits which host a shallow aquifer (quaternary), carbonate aquifers aged Miocene, Eocene and Upper Cretaceous and sandstone aquifer aged lower cretaceous. All of these aquifers are in use at variable abstraction rates with the higher use of the Nubian sandstone aquifer, since its water quality is most convenient for domestic and drinking use according to the World Health Organisation Guidelines published in 1984 (WHO, 1984).

Analytical studies proved that the Nubian sandstone aquifer is the most suitable for both domestic and irrigation use. The three rock units and the five aquifers are:

1. Shallow aquifer (Quaternary)

This aquifer is shallow and the water is retained in the recent quaternary deposits. The groundwater table could be met at depth of 0.25 m to 1.75 m. The salinity of this aquifer is high reaching 42000 ppm and this high range of salinity is attributed to the recharge from the irrigation systems and the water bodies. The economic use of this aquifer is almost negligible.

2. Carbonate aquifers

Three aquifers are hosted in the fractured limestone which belongs to three different geologic dates. These aquifers are:

a. Miocene

This fractured limestone is of Miocene age which is the top of the geologic column in this area directly under the quaternary cover. The water table of this aquifer is variable in depths, where it could be reached at 40m depth, however in some areas it could be as deep as 130 m.

The salinity ranges from minimum of 2000 ppm to the maximum of 4000 ppm. Most of the wells are taken water from this aquifer which is convenient for irrigation purposes. This aquifer hold sufficient amount of groundwater to pump about 100 million m^3 $year^{-1}$ (RIGW, 2000).

b. Eocene aquifer

This fractured limestone and Dolomite is of Eocene age below the Miocene in the geologic column in this area. The water table of this aquifer is variable in depths, which rely on the level of the fractures occurred in the rock unit. The minimum and maximum depths of the water table are 220 m and 450 m respectively.

The salinity ranges from minimum of 3000 ppm to the maximum of 16000 ppm. Most of the natural springs in the area flow from this aquifer (RIGW, 2000 and Aggour & Faid, 2006).

c. Upper Cretaceous

This limestone unit is of Upper Cretaceous age below the Eocene in the geologic column in this area. The water table of this aquifer is variable in depths, which rely on the level of the fractures occurred in the rock unit. The minimum and maximum depths of the water table are 395 m and 575 m respectively.

The salinity ranges from minimum of 2000 ppm to the maximum of 8000 ppm. Most of the natural springs in the area flow from this aquifer (RIGW, 2000 and Aggour & Faid, 2006), which are in use for medical purposes and tourism.

3. Nubian sandstone

a. Cretaceous

The Nubian Sandstone is of Lower Cretaceous age below the upper cretaceous in the geologic column of the area. It represents the main source of fresh water in this area. It has a very low salinity which ranges from 500 – 600 ppm. The depth of the water table could be reached at depth of 950m to 1200m (RIGW, 2000). This aquifer is the main source of nearly 90% of the drinking and domestic use of the oasis and most of the irrigation purposes.

Chemical Properties

54 sample wells were sued to obtain water samples and conduct physico-chemical analysis along the groundwater aquifers at Siwa Oasis. Fig. 3 shows the location of these sampled wells on earth. Some of these wells are natural springs that flow under confined pressure and others are pumped wells.

Eleven physico-chemical properties were measured directly from the water samples and other three newly parameters were calculated from these eleven parameters. The measured parameters are Electric Conductivity (EC), potential of Hydrogen-ion (pH), Total Dissolved Salts (TDS), Calcium (Ca^{++}), Manganese (Mg^{++}), Sodium (Na^{+}), Potassium (K^{+}), Carbonate (CO^{3--}), Bicarbonate (HCO^{-3}), Sulphate (SO^{4--}) and Chlorine (Cl^{-}) (Fig. 4). However, the newly calculated variables are sum cations, sum anions and SA Ratio (Fig. 5).

These parameters were attached into the tabular information to the GIS layer of the well locations. Then, Geographic Information System is used to interpolate these variables between the different wells to understand the real condition of the groundwater. This interpolation would help to see the spatial distribution of these variables in space. This interpolation would help in standing on the edge of the environmental factors controlling the increase or decrease of any of these variables in the groundwater.

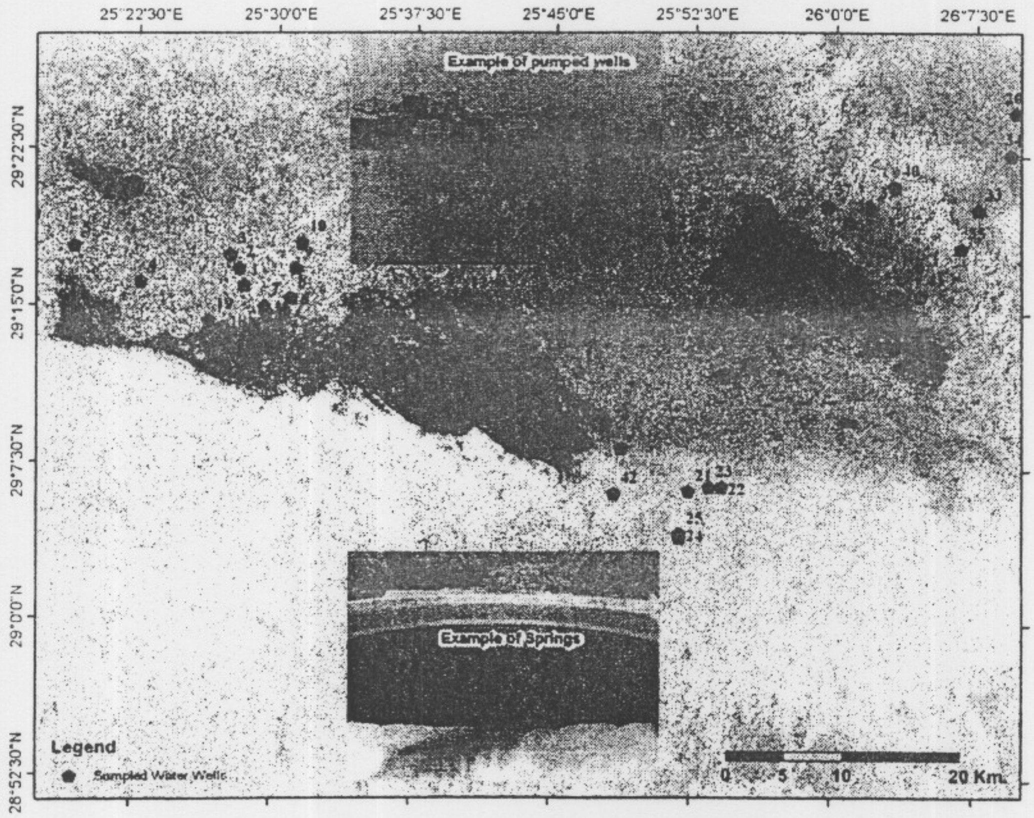

Fig. 3. Location of the sampled water wells.

Cations

Cations are represented by Calcium, Magnesium, Sodium and Potassium (Ca^{++}, Mg^{++}, Na^{+} and K^{+}). Fig. 4 shows the distribution curve of these cations along the different aquifers. It clearly appears that quaternary aquifer is the highest among the groundwater aquifers containing high concentration of cations followed by Eocene aquifer. The least aquifer shows least concentration is the Nubian sandstone aquifer. It also appears that sodium (Na^{+}) is the highest cation followed by Magnesium (Mg^{++}) and calcium (Ca^{++}), however potassium (K^{+}) is the least concentration.

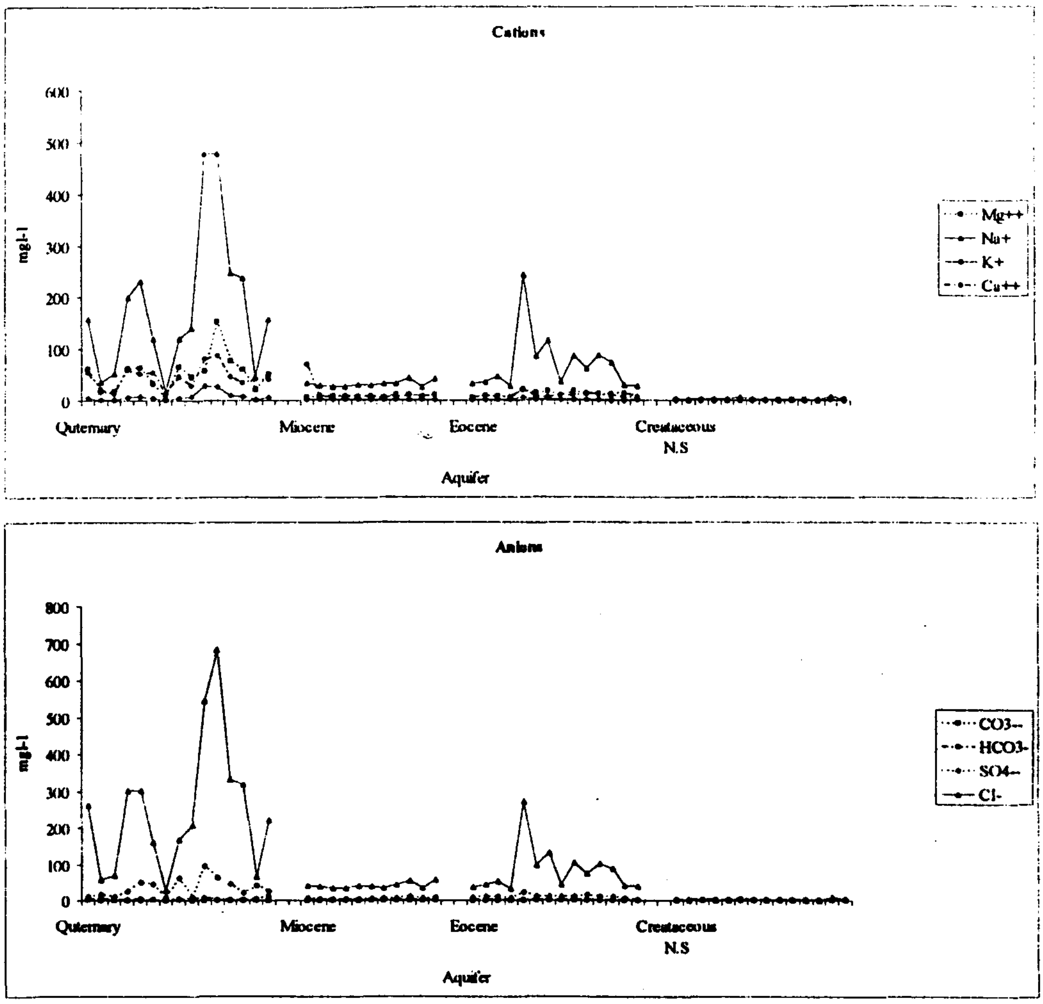

Fig. 4. Distribution curve of cations and anions concentration along the groundwater aquifers.

Sum cation is the total sum of cations of Calcium, Magnesium, Sodium and Potassium (Ca^{++}, Mg^{++}, Na^{+} and K^{+}). Fig. 5 shows the distribution curve of the sum of these cations in the different aquifers. From this figure it clearly appears that the quaternary aquifer is the highly water reservoir containing high amount of cations which reached 750 mgl^{-1} in some wells like NW – Aghou and school. This higher cations values could be attributed to the recharge from the agricultural land with higher pesticides concentrations. Some of the wells that show high concentrations of sum cations are near to the lake water bodies, which is probably a contribution from seepage from the lake's water bodies to the aquifer. The least aquifer showing concentration of cations is the cretaceous aquifer (Nubian Sandstone), which is below the WHO guidelines and more suitable for drinking and domestic usage. The Miocene aquifer shows less concentration of cations which ranged between 40 to 70 mgl^{-1}. This range is suitable for irrigation and most of the livestock.

Figure 6 shows an example of the spatial interpolation between the different wells and springs in the carbonate aquifers (Eocene and Miocene) to see the distribution of these cations in space. It clearly appears that most of the wells are less than 100 mgl^{-1} (green colour), however, there are few wells show higher concentrations of cations (red colour). Some of these wells are close to the lake water bodies and probably there is recharge along the fractures to these reservoirs from the lake water bodies or/and the soluble dissolved minerals from the bearing carbonate rock.

Anions

Anions are represented by carbonate, bicarbonate, sulphate and chlorine (CO^{3--}, HCO^{-3}, SO^{4--} and Cl^{-}). Figure 4 shows the distribution curve of these anions along the different aquifers. It clearly appears that quaternary aquifer is the highest among the groundwater aquifers containing high concentration of anions followed by Eocene aquifer. The least aquifer shows least concentration is the Nubian sandstone aquifer. It also appears that Chlorine (Cl^{-}) is highest anion followed by sulphate (SO^{4--}). However, carbonate and bicarbonate the least concentration is potassium (CO^{3--}, HCO^{-3}).

Sum anions is the total sum of anions of Carbonate, bicarbonate, sulphate and Chlorine (CO^{3--}, HCO^{-3},SO^{4--} and Cl^{-}). These are the anions which chemically compound with the cations formulating the different soluble elements in groundwater. Figure 5 shows the distribution of the sum of these anions in the different aquifers. From this figure it clearly appears that the anions is matching with the cations, due to they pond together to formulating the elements. Therefore, the quaternary aquifer shows the highest amount of anions which reached 750 mgl^{-1} in some wells like NW – Aghou and school. This higher anions value could be attributed to the recharge from the agricultural land with higher pesticides concentrations. It is also near to the lake water body which contribute to the increase of the anions in this aquifer.

The least aquifer showing concentration of anions is the cretaceous aquifer (Nubian Sandstone), which is below the WHO guidelines and more suitable for domestic and drinking usage. The Miocene aquifer shows less concentration of anions which ranged between 40 to 70 mgl^{-1}. This range is suitable for irrigation and most of the livestock.

Figure 6 shows an example of the spatial interpolation between the different wells and springs in the carbonate aquifers (Miocene and Eocene) to see the distribution of these cations in space. It clearly appears that most of the wells are less than 100 mgl^{-1}, whoever, there are few wells shows higher concentrations of anions (red colour). These wells are close to the lake water bodies and probably the recharge along the fractures to these reservoirs from the lake water bodies or/and the soluble dissolved minerals from the bearing carbonate rock.

It clearly appears from Fig. 5 that sodium chloride, manganese sulphate, potassium sulphate and potassium chloride are the significant soluble minerals in the aquifers making the high concentration of cations and anions. This confirms that most of these minerals are coming from discharge from irrigated agriculture.

Sodium Absorption Ration (SAR)

This is the ratio between sodium, calcium and magnesium, which shown in equation (1). SAR is a measure of the suitability of irrigation water for sustained soil and crop health. Water with a higher ratio is less suitable for irrigation.

$$SAR = \frac{Na^{+}}{\left[\sqrt{\frac{Ca^{2++} + Mg^{2+}}{2}}\right]} \qquad \text{.................................. Equation (1)}$$

Figure 5 shows the distribution curve of the SA Ratio in the different wells. This ratio is function of the concentrations of both cations and anions, therefore the aquifer that contains higher concentrations of cations and anions, it is expected to have higher SAR ratio. Fig. 5 shows that the quaternary aquifer is the highest aquifer containing SAR ratio which exceeded 60 mgl^{-1} in some wells such as school. The Eocene aquifer shows also higher values of SAR similar to the quaternary in some wells such as Gaz,ob,md. The least SAR values are shown in the Nubian Sandstone aquifer (Cretaceous) which is the most suitable aquifer for domestic and drinking use.

Figure 6 shows an example of the spatial distribution of the SA Ratio in the carbonate aquifer (Miocene and Eocene). The peaks in the figure tie with the cations and anions concentration where most of the aquifer has SAR less than 20 mgl^{-1}. However, three wells (NW-Aghou, school and Gaz,ob,md) show higher SAR value in the middle which reached up to 60 mg l^{-1}. This aquifer is suitable for irrigation and most of the livestock purposes.

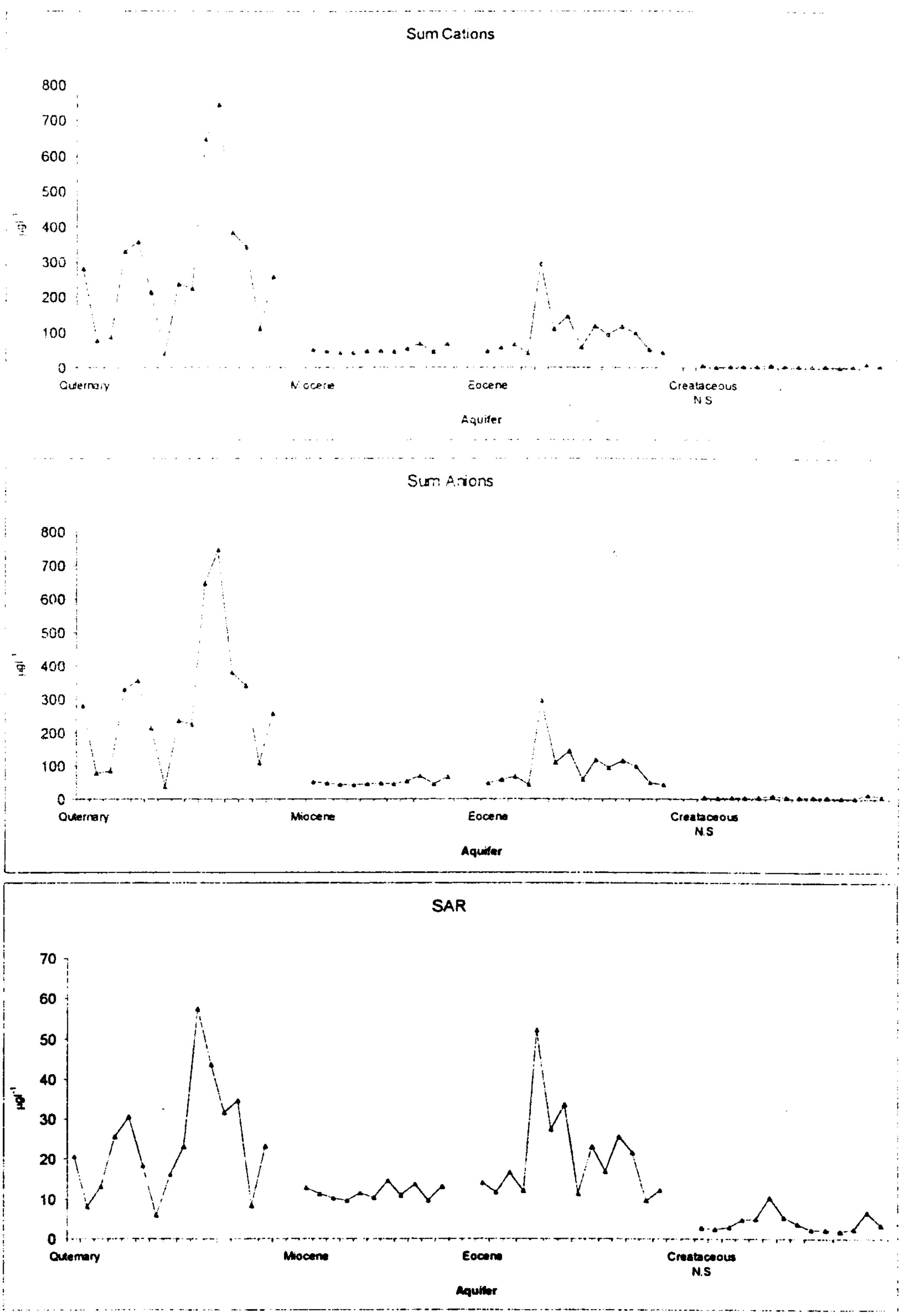

Fig. 5. Distribution curves of sum cations, sum anions and sum SAR along the groundwater aquifers.

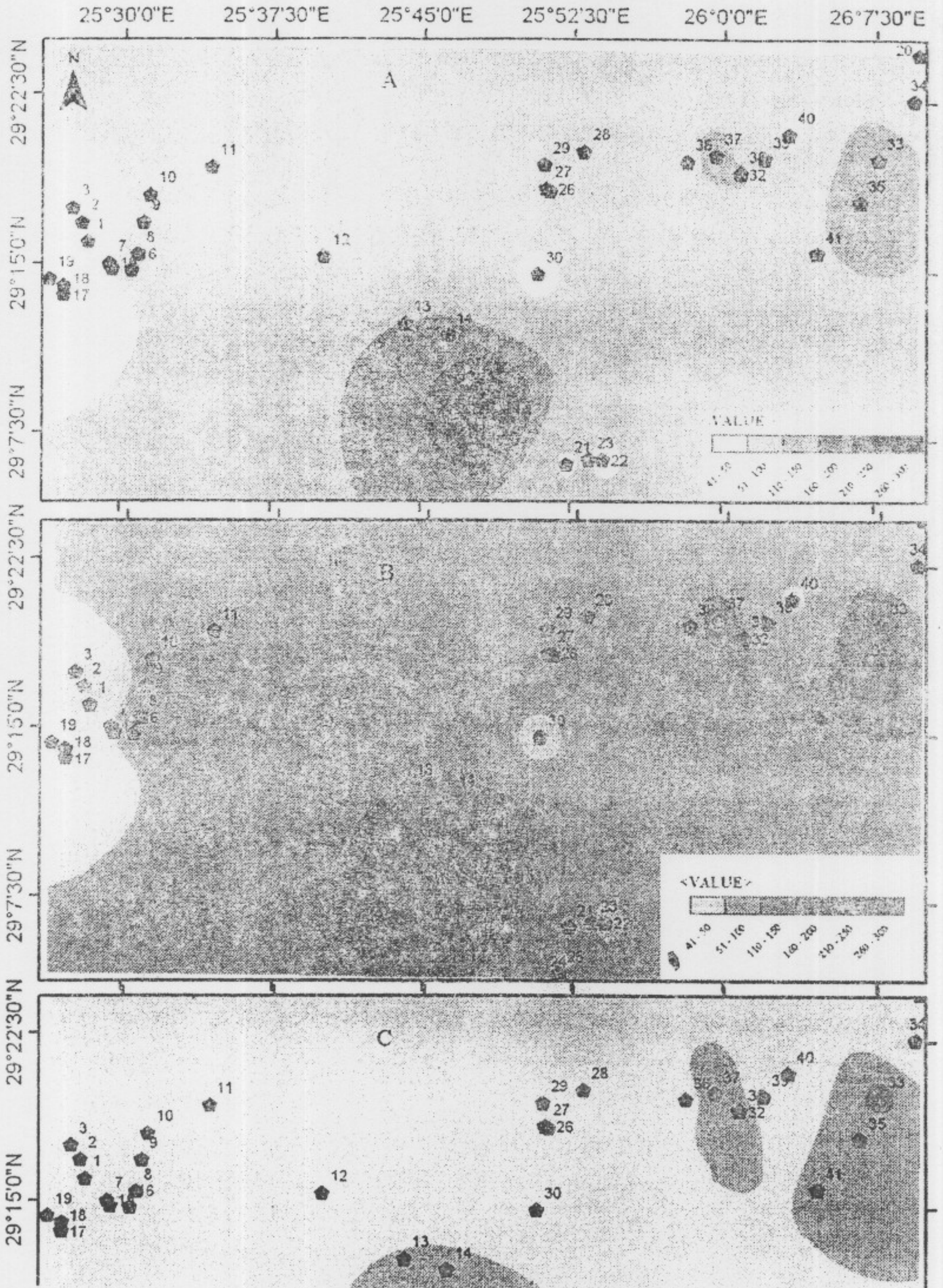

Fig. 6. Simulations of the sum cations (A), sum anions (B) and adjusted SAR (C) in the Eocene/Miocene Carbonate Aquifer.

Conclusion

Siwa Oasis is relying on the groundwater for 95% of their domestic and agricultural use. Five aquifers were recognised through 54 sampled wells. The top shallow aquifer is the quaternary which has high concentrations of cations and anions and therefore the SAR ratio is significantly high. The contribution of these high concentrations (*i.e.*, cations and anions) is coming from the discharge from the irrigation and/or the highly saline lake water bodies. This aquifer is not completely suitable for domestic use or even irrigation purposes.

Carbonate aquifer (*i.e.*, Miocene) have water with variable chemical properties, which is less in salinity than the quaternary aquifer. This reservoir is not suitable for drinking; however it is more likely suitable for irrigation purposes. It is recommended to use the Miocene and in some parts Eocene aquifer in most of the livestock in the area, which is supposed to increase the life time of the Nubian sandstone aquifer (the main aquifer). Therefore, the idea of limiting the use of the Nubian sandstone aquifer for drinking only and divert the irrigation to the Miocene/Eocene aquifers; it is supposed to increase the lifetime of the Nubian sandstone aquifer.

Nubian sandstone aquifer found to be the freshest water and suitable for all purposes particularly drinking. The chemical properties of this aquifer are below the limit for human use in drinking according to the World Health Organisation Guidelines (1984). However, this aquifer has no recharge since it is inherited from old geologic eras. So, its lifetime is based on the abstraction rate.

The rest of aquifers are based on their location and the pathway of the groundwater. Some of the fractured limestone of the Eocene era is under confined pressure which allow for natural springs. Most of these springs are not completely suitable for domestic use; however their chemical properties made them best fit for medical and tourism activities.

GIS found to be a powerful tool to analyse the spatial data of the groundwater and interpolate the chemical properties of the water wells. This gave an idea about the picture of the properties of the groundwater as reality as possible. The interpolation presented the spatial distribution of cations, anions and SAR ratio (Fig. 6).

This paper came up with few recommendations to minimise the deterioration of the water resources in this area:

- It is recommended to install a subsurface drainage system in the agricultural land, which would reduce the recharge of the irrigation water with high concentration of pesticides to either the shallow quaternary aquifer or the surface water bodies.
- It is recommended to use the Miocene fractured limestone aquifer for irrigation purposes particularly for the newly adapted crops.

- It is also recommended to stop the aggressive abstraction of water from the Nubian sandstone aquifer for irrigation purposes to increase the reserve or/and lifetime usage of this aquifer for drinking and domestic use.
- It is also recommended to introduce the plantation of new GM crops (Genetic Modified) that would be able to adapt with this extreme environment and the chemical properties of the water.

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دراسات هيدروجيولوجية وبيئية على واحة سيوة بإستخدام وسائل نظم المعلومات الجغرافية

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الهيئة القومية للإستشعار من البعد وعلوم الفضاء - القاهرة - مصر.

يهدف هذا البحث إلى دراسة الظروف البيئية المحيطة بالمياه الجوفية فى واحة سيوة بإستخدام التكامل بين القياسات الحقلية لعينات المياة ونظم المعلومات الجغرافية و تعتمد واحة سيوة بدرجة كبيرة على المياة الجوفية فى معظم أغراض الإستخدام الأدمى مما ترتب عليه زيادة الضغط على إحتياطى المياة فى المنطقة. ولقد وجدت المياة الجوفية فى خمس خزانات منها خزان الحجر الرملى النوبى والذى يعد أكثر الخزانات الجوفية ملائمة للشرب والإستخدام الأدمى ولكن المياة فى هذا النوع من الخزانات يتواجد على أعماق بعيدة. كما أن القليل من هذه الأبار يتواجد تحت الضغط الإرتوازى والتى تفيض فى شكل عيون مائية. وأثبتت الدراسة أن خزانات الحجر الجيرى (الميوسين) مناسبة أكثر لعمليات الرى والإستخدام الزراعى. ويوصى الفريق البحثى بإستخدام مياة خزانات الحجر الجيرى فى هذا النوع من الإستخدام (الرى) وذلك لتوفير مياة خزانات الحجر الرملى النوبى لغرض الشرب فقط. ومن المتوقع بتطبيق هذه التوصية أن يزيد العمر الإفتراضى لهذه الخزانات. وقد وجد أن التغييرفى إستخدام الأراضى وخصوصا الأراضى الزراعية (الرى الفيضى) من العوامل الرئيسية المؤثرة فى تدهور المياة الأرضية.