SALT MINERALS AT WADI EL NATRUN SALINE LAKES, EGYPT. NEW IMPLICATIONS FROM REMOTE SENSING DATA

Salem Mohamed Salem[a]* and El Sayed Ahmed El Gammal[a]

Key words: Remote sensing, salt lakes, Wadi El Natrun.

The salts of Wadi El Natrun saline lakes are made up of sodium chloride (NaCl, halite), sodium sulfate (Na_2SO_4, thenardite) and sodium carbonate ($Na_2CO_3.10H_2O$, natron) deposited on the bottom of the Lakes and surrounding sabkhas. The lakes of El Raizonia, Umm Risha, El Fasda, El Beida and El Gaar are the most potential lakes for economic halite salts. Furthermore, El Beida Lake contains Na_2SO_4 salts, mixed with halite, and Umm Risha and El Fasda lakes are characterized by natron salt showings. The chemical analysis of the saline water revealed dominant Cl^-, Na^+, Ca^{2+}, CO_3^{2-}, and HCO_3^- as major ions; while Mg^{2+}, SO_4^{2-} and NO_3^- are defined as minor ions. Chemical analysis of the salt deposits of these lakes shows similarity in the mineral composition with that of the saline water indicating that the water of such lakes is the main source of the realized salt minerals.

* Corresponding Author
E-mail: salem_moher@hotmail.com
[a] National Authority for Remote sensing and Space Sciences (NARSS), 23, Josef proztito St. Elnozha Elgedida - P.O. Box 1564Alf maskanCairo, Egypt.

INTRODUCTION

Wadi El Natrun is one of the prominent geomorphological features in the North-Western Desert of Egypt. It is bounded by latitudes 30° 17`to 30°19`N and longitudes 30° 10`to 30° 25`E and is generally situated at 23 m below sea level. It rises gradually to the SW up to Gebel Hadid (185 m) and to the Gebel Qantara limestones (198 m), above sea level (Figures 1 and 2). Several salt lakes and salt flats occupy the floor of the depression along with a total length of 50 km and with an average width of 10 km, follow the NW-SE trend of the depression. The Wadi El Natrun saline lakes in Egypt and the Florida saline lakes in the USA are the only two cases of Soda lakes in the world for natural salt production. The present study focuses on the utility of the hyperspectral data of remote sensing technique for mapping and exploring the saline lakes and related salt minerals at Wadi El Natrun area. The geology of such area suggests an ideal environment for salt-mineral exploration since the occurrence of many saline lakes along the depression. These considerations are the basis for the present study.

Several studies on the geology, hydrogeology, and mineralogy of the saline deposits of Wadi El Natrun were achieved.[1-4] A comparative mineralogical study of saline deposits in the study area was carried out by.[5] Mass developments of sulfide- oxidizing phototrophic bacteria in the upper sediments and in the waters of Wadi El Natrun lakes have been observed.[6] The heavy metal concentrations (e.g. Pb, Zn, Mn, Cu, Cd, Ni, Fe and A1) were measured[3] in surface sediments that largely indicate the influence of weathering on terrigenous land sources. The increased Cl^- ion content in Wadi El Natrun brines can increase metal mobility due to the formation of soluble chloro-complexes of trace elements[4] assumed that Wadi El Natrun deposits contain traces of sodium carbonate in the form of Trona ($Na_2CO_3.NaHCO_3.2H_2O$) or Natron ($Na_2CO_3.10H_2O$), but mainly made up of Burkeite ($Na_2CO_3.2Na_2SO_4$) and Halite (NaCl). The application of the hyperspectral data in the mineralogy have been documented by several researchers.[7-9] The hyperspectral measurements have been used by[10] to determine and differentiate between the iron ore types and ferruginous lithologic units in the Bahariya depression.The hyperspectral imaging was applied by Ref.[11] to map the clay minerals in Northwestern Algeria, using the Spectral Angle Mapper and the spectral signatures of illite and kaolinite.

This study aims at the mapping of the different chemical and environmental zones of the saline lakes of Wadi El Natrun and analyzes the salt minerals within each lake.

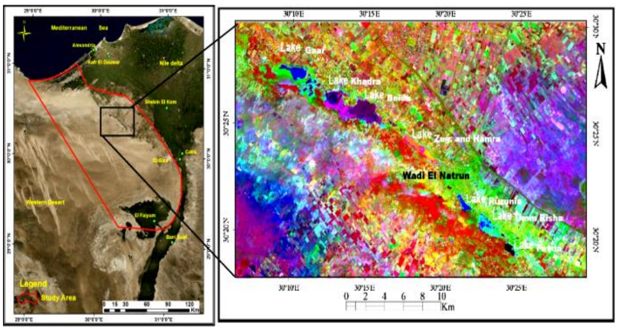

Figure 1. Location map of the Wadi ELNatrun lakes.

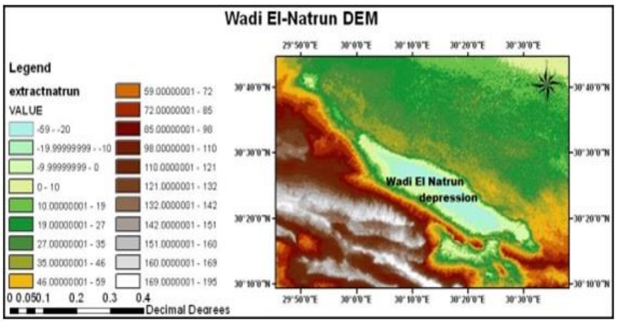

Figure 2. Digital Elevation Model (DEM) of Wadi El Natrun depression.

Geologic and morphotectonic evolution of Wadi El Natrun depression

Seven old branches of the Nile River have been illustrated by[12] using Radar Interferometry. Five of these branches have been deteriorated in the course of time, whereas two branches (Damietta and Rosetta) remain active at present. Along the westernmost part of the Delta, the ancient Canopic branch of the Nile River had silted up as a result of the re-excavation of the Bolbitic canal, which today forms the upper reaches of the Rosetta branch.[12] In this respect, the present passage of Wadi ELNatrun depression seems to be the path of the old Canopic branch. Therefore, the groundwater table is more or less closed to the recent Wadi El Natrun lakes. This is due to mixing of the old Nile bifurcation with the salt water preserved during the Miocene. Wadi El Natrun area comprises many rock units(Figure3) mapped by Ref[13].

The Mamura Formation is the basal rock unit in the sequence and it consists of interbedded fossiliferous shale, gypseous claystone, sandstone and limestone of lower Miocene age. It is followed upward by the Mikheimen Formation, which is formed of grey to yellowish grey conglomerates and conglomeratic sandstones of Miocene-Pliocene age. This section is overlain by the Gar El Muluk Formation of lower Pliocene age, a grayish to dark grey claystone with grey to greenish grey sandstones and few beds of yellowish white fossiliferous limestone.

The Gar El Muluk Formation is overlain by the Solymanya Formation that is of lower Pliocene age and consisting of greenish grey sandstones intercalated with fossiliferous limestone at the top. Upward in the sequence, the Kalakh Formation, which is a pink cross-bedded calcarenite with the karstified columnar structure at the top, is documented and depicts the Pliocene- Pleistocene age. The succession is capped by the Hamzi Formation, which represents the Wadi El Natrun facies with white porcelaneous and pink limestones that are underlain by conglomerates.

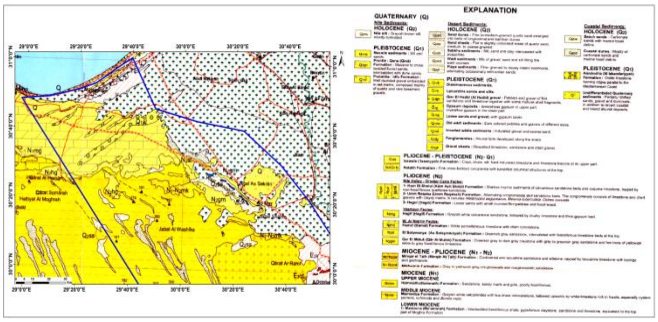

Figure 3. Geologic map of the study area,[13] the blue border shows the area of study.

The morphotectonic surface structure indicates repeated down-faulting towards the SW on the WNW- oriented normal faults. These are further transected by; (1) ENE- to NE-oriented folds of Late Cretaceous to Eocene age (The Syrian Arc Folds), (2) Oligocene to Early Miocene NW-SE trending faults, which were associated with a major uplifting movement to the south, (3) Late Miocene to Pliocene subsidence in the Nile Delta, which are localized along axis of the Nile Valley and controlled by N, NNW and NE oriented faults.[14]

METHODOLOGY

In the present study, the adopted methods to locate the saline lakes and analysis of their mineral potentiality are the remote sensing data (satellite and hyperspectral) and the chemical analyses of the salt minerals and deposits.

Remote sensing data

Satellite data

In the present study, the Landsat 8 (OLI) and Thermal Infrared Sensor (TIRS) images are processed and interpreted. The scene LC81770392016263LGN00, Path177, Row39, Acquisition date 19/9/2015 was used during this study. The data consists of nine spectral bands, with a spatial resolution of 30 m for bands 1 to 7 and 9. The approximate coverage area of such scene is 170 km N-S by 183 km E-W (106 miles by 114 miles). It contains seven spectral data in the visible, near infrared (VNIR) and shortwave infrared (SWIR) bands of the electromagnetic spectrum.

Hyperspectral data

Several field trips were conducted to visit the study area in different seasons. Intensive field work for ground truth using remotely-sensed data and aided by the geological map of the north Western Desert of Egypt[13] (UNESCO, 2006) was achieved. During these trips, representative samples from the various lithologies, lake's bottom sediments, salt deposits, as well as water samples from the Wadi El Natrun lakes have been collected for applying the analytical techniques. The ASD Field Spectroradiometer has been used for detecting different spectral measurements in the study area. The ASD device (Field Spec3) of Full-range detection capacity (350 nm– 2500 nm) has been used for this purpose. It provides uniform Vis/NIR/SWIR data collection across the entire solar irradiance spectrum.

Pre-processing of the remotely-sensed data

The Satellite data of Landsat 8 has been pre-processed for correcting the data from the atmosphere noises influence for valid and enhanced image processing. The pre-processing steps as radiometric calibration and atmospheric correction have been processed using the FLAASH method, Resolution merge and constructing mosaic pictures for the study area.

Moreover, the hyperspectral measurements were pre-processed by Quick Atmospheric Correction (QUAC) to define the atmospheric correction parameters directly from the observed pixel spectra in a scene without ancillary information. The QUAC is the best confident method producing reflectance spectra within a range of approximately 10 % of the ground truth.[15] These measurements were re-sampled to match the Landsat 8 bands after removing the bad and noise bands. The spectral measurements have been interpreted by using the Spectral Angle Mapper (SAM) and Maximum Likelihood Techniques (MLT). The SAM classification is an automated method that compares the spectral similarity between the used image spectra and the ASD measured spectra. It permits a rapid supervised classification as well as an accurate mapping.[16]

Chemical analyses

Selected 10 water samples and 10 salt samples from Wadi El Natrun lakes have been chemically analyzed for the major and trace elements, which are dissolved in saline water and constitute relatively the total salts in these lakes and their nearby Sabkhas. The analyses were conducted using XRF analysis in the Central Laboratory of the Egyptian Mineral Resource Authority (EMRA). The samples were diluted and prepared for measuring of the major elements and ions (e.g. Na, Ca, Mg, K, Cl, SO_4, NO_3, CO_3, HCO_3), and the trace elements such as Mn, Fe, Ni, Cu, Zn, Cd and Pb, total alkalinity of the saline water Lakes was also detected(Tables 1, 2, 3, 4).

RESULTS

Interpretation of the field work and lakes description

The saline lakes along Wadi El Natrun are distributed in a fluvial environment consisting of Hill slopes, Mud plains, and Perennial or Ephemeral Lakes. The Hill slopes form locations of active erosion and transportation of finer sediments to the close Mud plains.[17,18] The width of the Mud plains reaches up to 15 m and consists of fine siliciclastic sands and clays, commonly covered by vegetations. Ephemeral thin crusts of Natron and Halite salts occur interstitially within the Mud at the surface, between May and August.

During the field work, three distinct types of sedimentary deposits within the lakes are recognized; (1) clay-rich siliciclastic sediments deposited in a freshwater marsh environment, intercalated with organic materials, (2) compact Halite and Burkeite crusts, and (3) salt marshes composed of Aeolian quartz sands cemented by salts. The evaporates of the Miocene rocks exposed in the western end of the Wadi ELNatrun (Figure 4) and disappearing to the east in the depression. Several Quaternary structural elements such as fault scarps of NW-SE trend, normal faults of both NW-SE and NE-SW trends and NE–SW trending left-lateral strike-slip faults are also observed (Figure 5).

Figure 4. The evaporites of the Miocene rocks in the western end of Wadi ELNatrun.

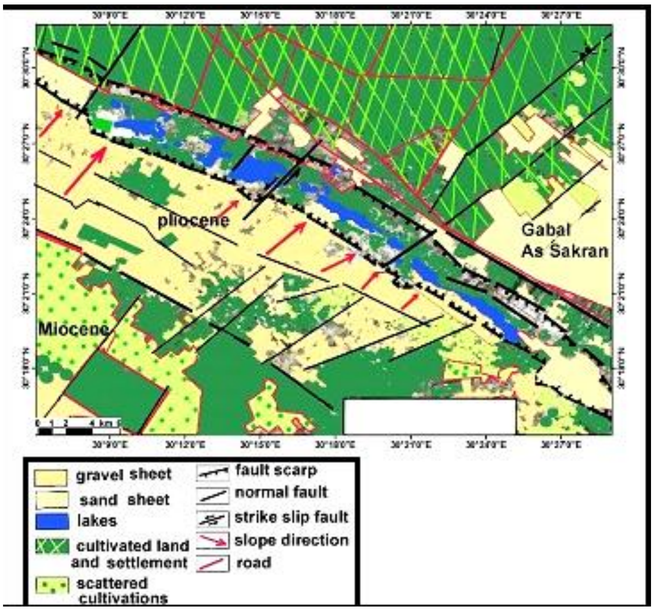

Figure 5. Morpho-structural map of the Wadi El Natrun area prepared from Landsat 8 image 2016.

Moreover, during the field work, a composite sketch diagram (Figure 6) for the Wadi El Natrun lakes has drawn. Field photographs for each lake, its lithology, and related geological features have been described as follows:

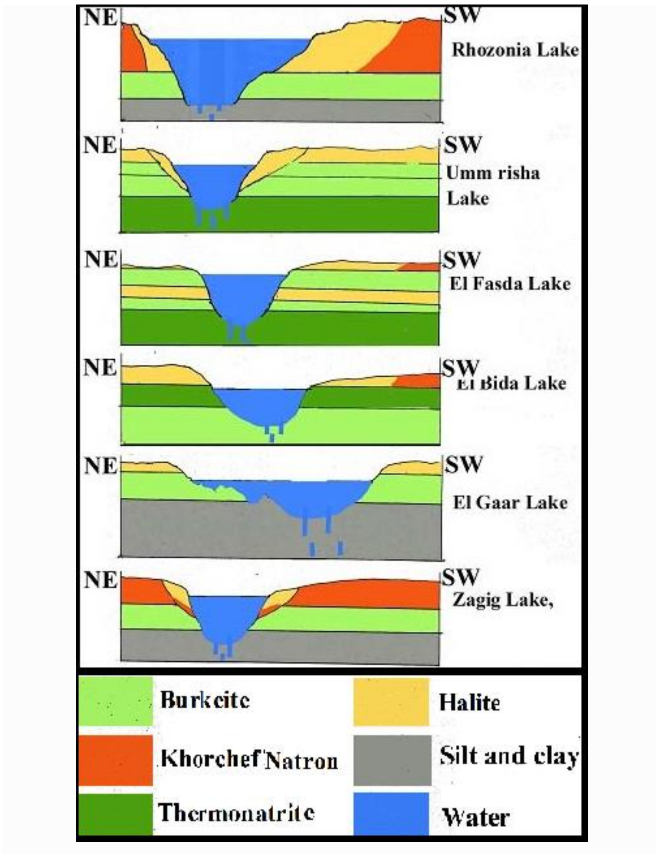

Figure 6. A composite sketch diagram illustrating the different lakes of the Wadi El Natrun and their related geological features, from N to S.

El Gaar Lake

It forms one of the biggest lakes in Wadi El Natrun area. It is never dry and contains permanently a water typical composition surrounded by Sabkhas, all over the year. Halite is an abundant salt component in the water of the lake along with Sabkha‘s precipitates. Other accessory salts of mixed carbonates and sulfates (Trona and Burkeite) are also recorded.

El Beida Lake

El Beida Lake area characterizes by white color, where it is almost dry with only limited water showings at the left of its center and edges due to variation in depths. The Sabkhas and salt precipitates consist of varicolored salt types occupying vast areas from the lake, which is exploited for Halite and Thenardite production.

Zug-Hamra Lakes

Zug and Hamra lakes are connected together by a small canal in the northwestern end of Zug Lake. They form together a longitudinal single lake. The water of the lake stands above a bottom surface of the evaporate deposits of Halite and Torona to a depth of a few centimeters. The Sabkha deposits and the salt precipitates extend across the entire width of the lake to a depth of 10 cm, consisting of thick deposits of Halite and sodium sulfates (Thenardite) surrounded by Kerchief deposits (Natron).

Lake Ruzounia (Razunia)

Ruzounia Lake has been worked for Halite salt production as the sulfate and carbonate salt minerals are found in the lower bedding altitudes, while the Halite salt is relatively dominant in the upper layers.

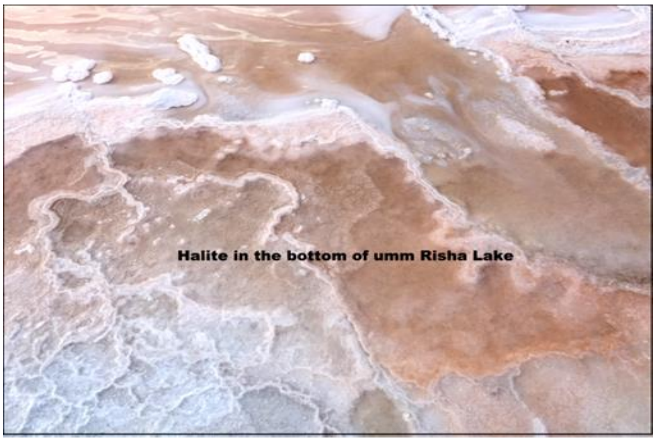

Figure 7. A hard Halite crust of Umm Risha Lake

Umm Risha Lake

Umm Risha is a shallow lake has pinkish brown water and has been explored for halite salt production. A hard crust of Halite is formed over a fluid mass of crystalline phases and brine within the lake. The Sabkhas of the lake show white, off-white, brown and pink colors of salts and Sabkhas (Fig.7). Pools are frequent where the water existed beneath the surface crust.

El-Fazda Lake

It is a fairly dry lake formed of a thin dark brown silty layer, followed upward by Halite and Burkeite precipitates, which is in turn covered by a massive pinkish white layer mostly composed of sodium carbonates (Natron) with traces of Halite and Trona.

Interpretation of the spectral measurements

The Spectral Angle Mapper (SAM) tool has been used for detecting and locating the sabkha and salt minerals in all of the investigated Lakes. These sabkhas and related salt minerals appear on the Landsat 8 image in pale blue color. The waters are represented by different shades of blue color ranging from navy and azure to indigo blue. Except for Ruzounia and Umm Risha Lakes, the waters therein are shallower and appear in teal blue color (Figures8a, 9a, 10a, 11a, 12a, 13a). Applying the Maximum Likelihood Technique, each lake has been classified into three environmental zones; saline water, salts and Marshlands (Figures8b, 9b, 10b, 11b, 12b, 13b).

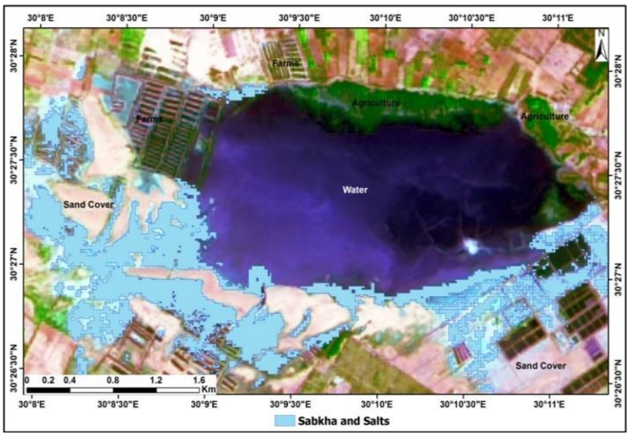

Figure 8a. SAM image of El Gaar Lake showing sabkhas and salts in pale blue color.

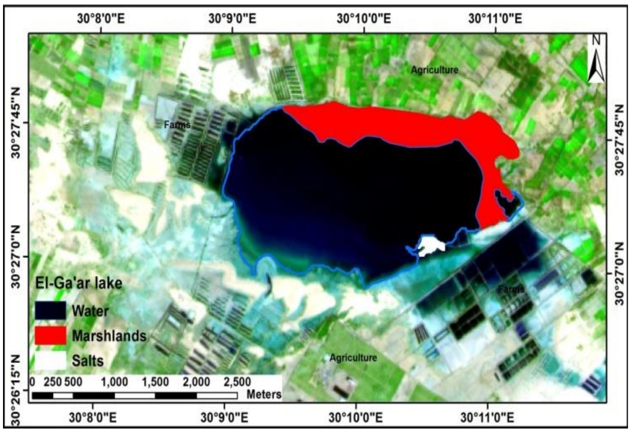

Figure 8b. Maximum Likelihood classification map of El Gaar Lake showing the different environmental zones.

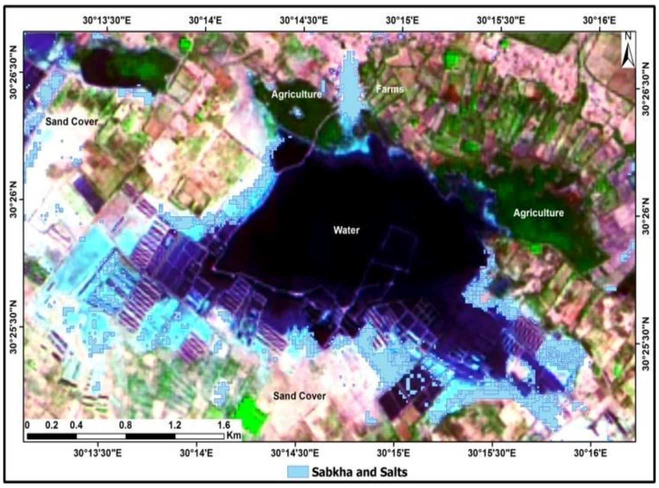

Figure 9a. SAM image of El Beida Lake showing sabkhas and salts in pale blue color.

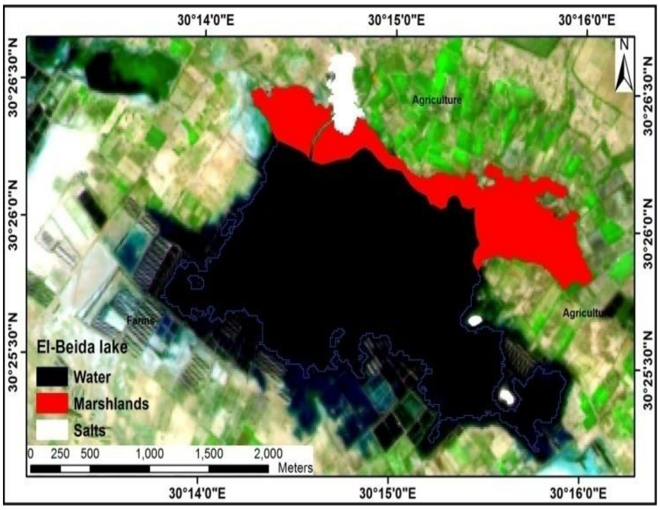

Figure 9b. Maximum Likelihood classification map of El Beida Lake.

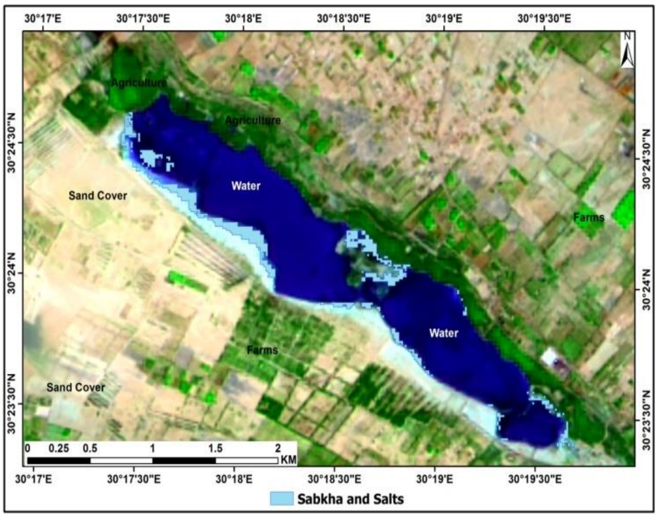

Figure 10a. SAM image of Zug-El-Hamra Lake showing sabkhas and salts in pale blue color.

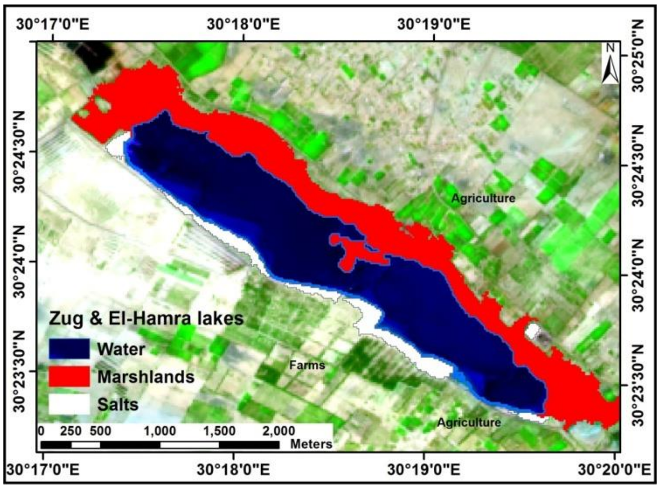

Figure 10b. Maximum Likelihood classification map of Zug-ElHamra Lakes illustrating the various environmental zones.

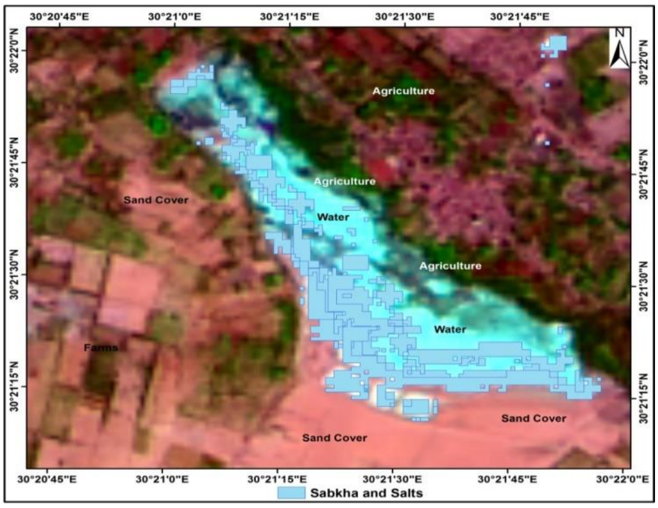

Figure 11a. SAM image of Ruzounia Lake showing sabkhas and salts in pale blue

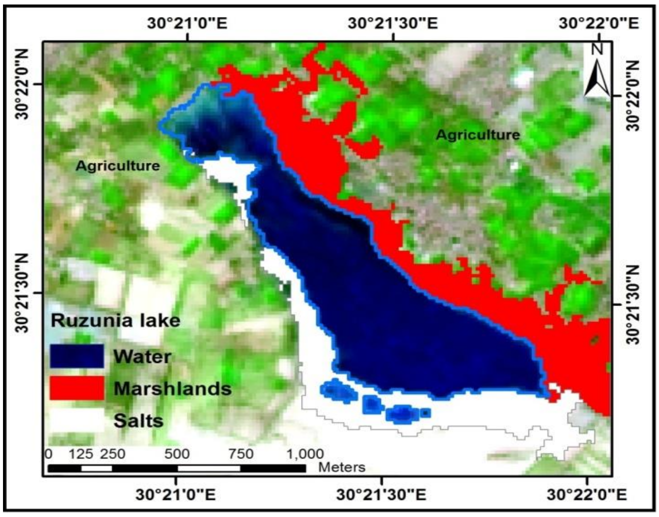

Figure 11b. Maximum Likelihood classification map of Ruzounia Lake.

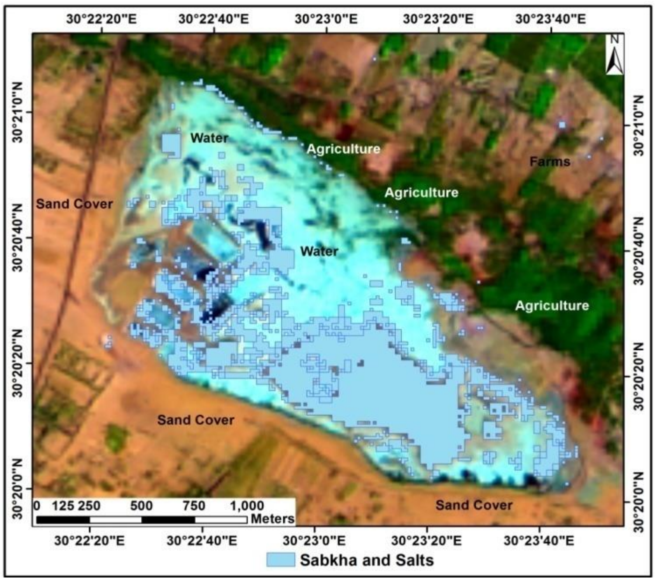

Figure 12a. SAM image of Lake Umm Risha showing sabkhas and salts in pale blue color.

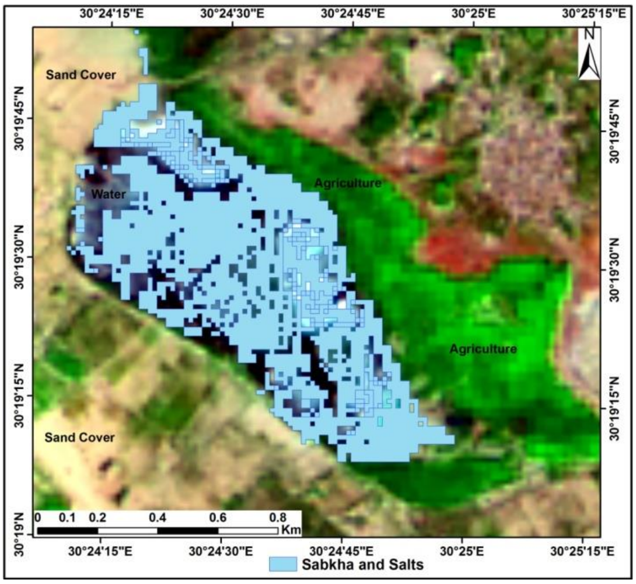

Figure 13a. SAM image of Lake El Fazda showing sabkhas and salts in pale blue color.

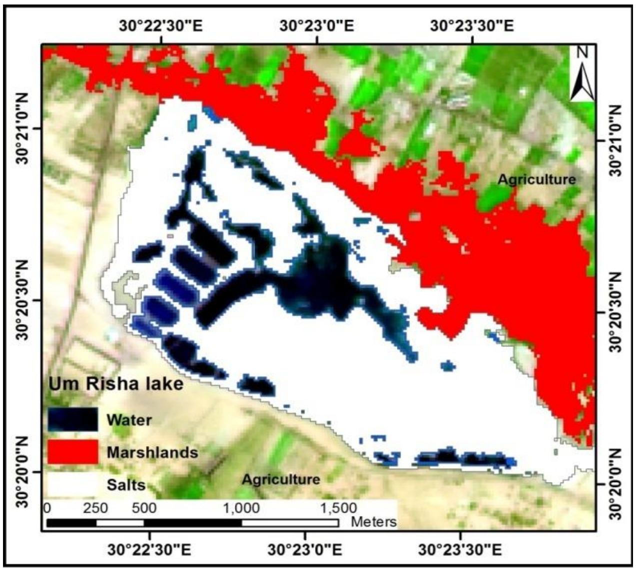

Figure 12b. Maximum likelihood classification map of Umm Risha Lake.

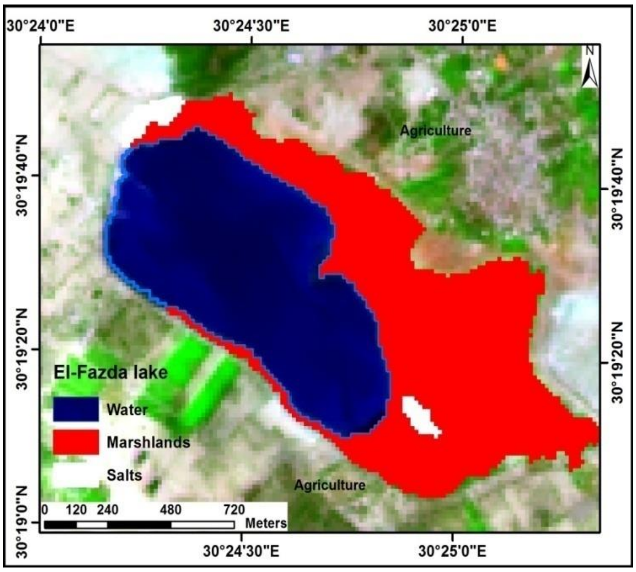

Figure 13b. Maximum Likelihood classification map of El Fazda Lake.

Chemical Analyses and Mineral Potentiality

The results of XRF analysis of the water and salt samples for major and minor elements were given in Tables 1, 2, 3, 4. The water analyses show an increase in Cl^- with the increasing of Na^+ and SO_4^{2-} coinciding with a decrease in Ca^{2+}, Mg^{2+}, and HCO_3^- in all lakes (Table 1), reflecting a predominance of Halite. In Wadi El Natrun brines, the minor elements (Table 2) shows that the concentration of Zn is much lower than that of Pb, indicating a significant loss of Zn from the surface water. The high concentration of Pb is due to the solution of Pb from the clastic material derived from surrounding weathered sediments. The metal concentrations decrease in the order Pb > Cu > Cd > Ni >Zn > Fe > Mn. This order is similar to the relative strength of the stability constants of the chloro-complexes of these metals except that of Cu which is higher than that of Zn (Table 3).

The salt analyses revealed abundance in Cl, Na, and K in all lakes, except Zug-El Hamra Lake, which shows low values of these elements. Rhozonia, Umm Risha, and El Beida lakes show a relative increase in sulfate-ion when compared to other lakes, which show normal values for these salts, suggesting a valid environment for the occurrence of sodium sulfate in the three lakes.

The content of carbonate-ion content is high in all lakes except in the Zug Lake, where it is low. The Ca-ion and Mg-ion are present in low amounts approximately in all lakes. This drop may be due to the precipitation of these elements as alkaline earth carbonates with an excess of hydrogen carbonate free of calcium and magnesium (Table 3). The increasing of Pb, Zn, Ni and Cd and in turn the decreasing of Fe and Mn in the salt samples is typical the behavior of these traces in salt samples have been originated from the saline water (Table 4).

Table 1. Chemical analyses of major elements (in ppm) in waters of Wadi El Natrun lakes.

Lake name	**Na^+**	**Cl^-**	**Ca^{2+}**	**Mg^{2+}**	**SO_4^{2-}**	**NO_3^-**	**CO_3^{2-}**	**HCO_3^-**	**Total alkalinity**
Rhozonia	279.6	86.4	n.d.	--	43.4	46.4	33.2	5.3	38.5
Rhozonia	279.6	86.4	n.d.	-	44.9	46.4	43.4	279.6	n.d
Umm Risha	291.5	92.3	n.d.		40.1	66.8	36.6	2.0	38.6
Umm Risha	281.4	81.0	0.02		37.8	13.9	36.7	1.9	38.7
Fazda	274.0	85.8	0.02	n.d.	48.1	88.6	37.9	0.7	38.7
Fazda	270.3	91.2	n.d.	n.d.	41.7	87.2	36.4	2.0	38.5
El Bida	154.4	74.5	n.d.	n.d.	27.0	41.1	17.9	n.d.	22.9
Gaar	155.3	56.6	n.d.	n.d.	24.8	43.1	20.6	n.d.	22.9
Gaar	155.3	59.2	n.d.	0.02	27.5	72.1	20.4	n.d.	22.7
Zug-El Hamra	30.2	12.7	0.03	0.004	9.0	40.2	0.2	0.0	0.29

Table 2. Chemical analyses of minor metal ions (in ppm) in waters of Wadi El Natrun lakes.

Lake name	**Fe**	**Ni**	**Mn**	**Cu**	**Pb**	**Zn**	**Cd**
Rhozonia	62	120	34	126	276	113	118
Rhozonia	70	115	31	130	199	110	118
UmmRisha	44	118	24	132	126	110	117
UmmRisha	12	119	2	127	176	110	119
Fasda	64	120	21	126	156	100	118
Fasda	60	118	2	128	114	100	119
Bida	63	116	35	130	242	116	119
Gaar	2	12	115	128	104	121	141
Gaar	11	117	2	128	161	106	119
Zug	5	—	3	128	277	103	120

Table 3. Chemical analyses of major elements in salts of Wadi El Natrun lakes.

Lake Name	**Na^+**	**Cl^-**	**K^+**	**Mg^{2+}**	**SO_4^{2-}**	**CO_3^{2-}**	**Ca^{2+}**
Rhozonia	279.2	89.40	86.4	6.40	100.0	79.6	1.6
Rhozonia	295.1	41.4	93.0	7.10	40.9	95.2	12
UmmRisha	221.5	96.8	92.3	6.80	210.1	91.5	1.5
UmmRisha	281.4	13.9	81.0	13.9	37.8	81.4	12
ElFasda	244.0	88.6	85.8	8.6	48.1	274.0	13
ElFasda	250.3	87.2	91.2	7.2	41.7	270.3	11
El Bida	154.4	41.1	74.5	1.1	27.0	154.4	11.
El Gaar	135.3	43.1	56.6	3.1	24.8	155.3	0.7
El Gaar	125.3	72.1	59.2	2.1	27.5	155.3	0.02
Zug	30.2	40.2	12.7	70.2	9.0	30.2	0.04

Table 4. Trace metal ion concentrations (ppm) in salts of Wadi El Natrun lakes.

Lake name	Fe	Ni	Mn	Cu	Pb	Zn	Cd
Rhozonia	53	110	46	110	280	120	93
Rhozonia	60	120	40	120	210	120	93
Umm Risha	33	98	22	120	115	140	80
Umm Risha	16	99	7	88	190	100	100
Fasda	70	90	20	110	160	100	90
Fasda	63	100	2	128	120	110	90
Bida	63	116	35	130	242	116	119
Gaar	2	12	115	128	104	121	141
Gaar	11	117	2	128	161	106	119
Zug	5	—	3	128	277	103	120

Discussion

Interpretation of the integrated hyperspectral measurements (applied by TIR and SWIR bands of Landsat 8) together with the field verifications and chemical analyses, were used to map the saline lakes of Wadi El Natrun and to differentiate between salt types and surrounding areas in each Lake as well as to define the different environmental zones (waters, marshland and sabkhas) within these lakes.

Ref[13] have described the geology of Wadi EL-Natrun depression as filled by Neogene clastic sediments in the Miocene-Pliocene age. These sediments were deposited in a river with fewer meanders and a greater slope gradient than the other branches of the Nile; and, thus got a larger part of the water passing through it. The distribution and origin of the saline water and salt minerals in Wadi El Natrun have been discussed by many authors. The origin of the lakes waters is suggested to be from the Nile water infiltrating through the sands and gravels forming the main strata separating Wadi El Natrun from the Nile River.[19] These percolating waters wash the salts from the rocks through which they travel and turn into weak brines. Hence waters that flow primarily through limestones usually produce brines rich in lime and carbonates, dolomite gives waters rich in magnesium and shales and sulfide-rich rocks yield sulfates.[20] The distinct spatial-temporal distribution of the salt minerals at Wadi ELNatrun area suggests emplacement by re-sedimentation rather than an authigenic or artifact origin.[21] Microbial mats grow periodically under a 1 mm thick layer of sand on the lake floors as well as along their margins 3. Due to the microbial propagations, the Perennial saline lakes appear in different colors. A model for salt differentiation have been proposed by Ref[22], as the water evaporates at 85 % of the starting volume; the first mineral Halite begins to precipitate. This continues and is joined by Burkeite and Nahcolite when the water is down to about 45 % and 30 % respectively. Since salinity of the lake's water is fluctuate between concentration and dilution due to the evaporation rates, the salt precipitation from the saline waters is seasonally controlled, depending on the salt types, grade of concentrations and the associated minor and trace elements in the saline waters. The salt minerals that precipitate during the evaporation sink to the bottom of the lakes forming solid crusts of mixed salts, which are often extensively extended outside the lakes.

Conclusion

The result of remote sensing, fieldwork, and analytical techniques enabled to an accurate mapping of the significant areas of the saline lakes, as well as characterizing the environmental zones of these Lakes and associated salt type of each Lake. The chemical analyses showed that the salts of sodium chlorides, sodium sulfates and sodium carbonates and bicarbonates are the most minerals accumulated and deposited in these lakes and surrounding areas with a dominance of Halite in all of the lakes. The chemical characterization and lithology of the saline lakes illustrated that El Rhozonia is the most economic Lake, as it includes the Halite salt in the upper layers and the sulfate and carbonate minerals in the lower bedding altitudes. Umm Risha Lake shows pink to reddish pink colors due to the presence of high sulfate and carbonate minerals in lower bedding altitudes, and high Halite content in the upper layers. El Fazda Lake contains a large thickness of sodium carbonates and Halite in the upper layers. El Bida Lake is also an economic salt lake as it comprises 72 % of Halite, 15 % Na_2SO_4, 6 % K_2CO_3 and 7 % Natron. El Gaar Lake is mainly dominated by Halite (~70 %), Na_2SO_4 is 8 %, K_2CO_3 10 %, and Natron 5 %. Zug-Hamra Lake comprises thick deposits of Na_2SO_4 and is surrounded by Kerchief deposits and overlain by Halite. The high concentrations of sulfate in El-Beida and Gaar Lakes are possibly due to the weathering of Miocene evaporates.

This study demonstrates the dominance of chloride ions in the saline water of Wadi El Natrun lakes suggesting that the source of these waters came from the Mediterranean Sea water that passed as seepage water through the NW-SE trending fractures to the lakes (Sea water intrusion). The saline waters of these lakes are composed of varied solute minerals and ions leached from the lithologies into which these waters pass to such lakes. These dissolved minerals have precipitated under certain conditions and limitations leaving deposits from the corresponding soluble salts in the floors of the lakes and their environs. The continuous evaporation of the waters under the climatic changes from the past (Pliocene) to the Present in temperatures, pH of the water and morphology of the lakes, which became more shallower, led to the deposition of salt types under the present conditions are different from those Natron salts that were deposited and dominated in the past and gave the name Natrun to the Wadi El Natrun itself. Now, there is abundance and dominance of Halite, mixed carbonates and sulfates (Burkeite and Thenardite) with some sodium sulfates at the expense of the Natron salts which are found as relics in low quantities in some lakes.

The results of this study appreciate the role of remote sensing detection of the salt minerals as a cost-effective alternative method in salt minerals exploration in Egypt, and in similar settings worldwide.

Acknowledgments

Great thanks to the National Authority for Remote Sensing and Space Sciences (NARSS) for providing the hyperspectral data and chemical analyses used during this study.

References

[1]Abdallah, A.Y., Petrology of some Pliocene-Recent Rocks in Wadi El Natrun, Beni Suef Area, Egypt. M.Sc. Thesis, Faculty of Science, *Ain Shams University, Cairo, Egypt* **1970.**

[2]Said, R. Geomorphology chapter 2 in: The Geology of Egypt, Edited by R. Said. *Balkema, Rotterdam.*, **1990,** 9-26.

[3]Taher, A., Inland saline lakes of Wadi El Natrun Depression, Egypt. Intern. *J. Salt Lake Res.***1999,** *8*, 149-169. doi: 10.1007/ BF02442128.

[4]Shortland, A.J., Degryse, P., Walton, M., Salou, L., The evaporitic deposits of Lake Fazda (Wadi Natrun, Egypt) and their use In Roman glass production. *J. Archaeometry*, **2011,** *53*, 916-929. doi: 10.1111/j.1475-4754.2010.00573.x

[5]Bolis, S.N., Comparative Mineralogic study of the "Korchef" Saline Deposits of Wadi El-Natrun, Egypt, U.A.R. M.Sc. Thesis, *Faculty of Science, Ain Shams University, Cairo* **1969.**

[6]Imhoff, J.E, Sahl, H.G., Soliman, G.S.H., TriJper, H.G., The Wadi Natrun: Chemical composition and Microbial Mass Developments in Alkaline Brines of Eutrophic Desert Lakes. *Geomicrobiology,* **1979,** *1*(5), 219-234. http://dx.doi.org/10.1080/01490457909377733

[7]Goetz, A.F., Srivastava, V., Mineralogical mapping in the Cuprite mining district, Nevada. *Third Annual JPL Airborne Geoscience Workshop.* Vol1: AVIRIS Workshop; **1985,** p 147–149.

[8]Kruse F. A. Use of airborne imaging spectrometer data to map minerals associated with hydrothermally altered rocks in the northern grapevine mountains, Nevada, and California. *Remote Sens Environ.,* **1988,** *24(1):* 31–51. https://doi.org/10.1016/0034-4257(88)90004-1

[9]*Zhang, X.,* Li, P., Lithological mapping from hyperspectral data by improved use of spectral angle mapper. *Int. J. Appl. Earth Obs. Geoinf.,* **2014**, *31*, 95-109. doi.org/10.1016/j.jag.2014.03.007

[10]Salem, S.M., ASD field hyperspectral measurements for discrimination of the ferruginous rocks and the iron ore types at El Gedida-Ghorabi area, Bahariya Oasis, Western Desert, Egypt. *Arab. J. Geosci,.* 2016,10:166. DOI 10.1007/s12517-017-2944-x.

[11] Zazi, L. Boutaleb, A., Guettouche, M. S., Identification and mapping of clay minerals in the region of Djebel Meni (Northwestern Algeria) using hyperspectral imaging, EO-1 Hyperion sensor. *AJS,* **2017**, *10:* 252. DOI 10.1007/s12517-017-3015-z

[12]Cherif, O., Gabr, S. El Bastawesy, M., and El Saadawi, O., Evaluation of subsidence in the Nile Delta by using Radar Interferometry. *STDF project cooperation between NARSS with Michigen University (US), final report*, **2016.**

[13]UNESCO**,** The geological map of Egypt. *Project Capacity Building for the Egyptian Geological Survey and National Authority for Remote Sensing and Space Sciences, Egypt*, **2006.**

[14]EGPC**.** Nile Delta & North Sinai: Fields, Discoveries and Hydrocarbon Potentialities *(A Comparative Overview). EGPC, Cairo, Egypt***, 1994.**

[15]Bernstein, L.S., Adler-Golden, S.M., Jin, X., Gregor, B., Sundberg, R.L., Quick atmospheric correction (QUAC) code for VNIR-SWIR spectral imagery: Algorithm details. In Hyperspectral Image and Signal Processing *(WHISPERS), 4th Workshop* **2012**, 1-4. https://doi.org/10.1109/WHISPERS.2012.6874311

[16]Hunter, E.L., Power, C.H., An assessment of two classification methods for mapping Thames Estuary intertidal habitats using CASI data. *Int. J. Remote Sens.***, 2002,** *23*, 2989-3008. doi/pdf/10.1080/01431160110075596

[17]Eugster, H.P., Hardy, L.A., Saline lakes, in Lakes; chemistry, geology, physics. *(ed. A. Lerman), Springer-Verlag, New York*, **1978.**

[18]Renaut, R.W., Long, P.R., Sedimentology of the saline lakes of the Cariboo Plateau, Interior British Columbia, Canada. *Sedim. Geol*. **1989,** *64*,239–364. https://doi.org/10.1016/00370738(89)90051-1

[19]Atia, A. K. M., Hilmy, M. E., Bolous, S. N., Mineralogy of the encrustation deposits of Wadi E1 Natrun. *Desert Institute Bulletin*. **1970,** *2*, 301-325.

[20]Warren, J., Evaporites; their evolution and economics, *Blackwell Science, Oxford*, **1999.**

[21]Stanley, D. J., Sheng, H., Trona in Nile Cone Late Quaternary sediments: Probable redepositional origin. *Marine Geology,* **1979**, *31(1-2):* M21-M28. https://doi.org/10.1016/00253227(79)90049-5

[22]Shortland, A.J., Evaporites of the wadi natrun: seasonal and annual variation and its implication for ancient exploitation. *J. Archaeometry*, **2004,** *46*,497–516. DOI: 10.1111/j.14754754.2004.00170.x

Received: 20.11.2017.
Accepted: 08.04.2018.