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The impact of groundwater and agricultural expansion on the archaeological sites at Luxor, Egypt

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ABSTRACT

Pharaonic monuments represent the most valuable source of ancient Egypt, covering the period of approximately 3000–300 B.C. Karnak and Luxor temples represent the monuments of the east bank of Thebes, the old capital of Egypt. These monuments are currently threatened due to rising groundwater levels as a result of agricultural expansion after construction of the High Dam in the 1970s.

Deterioration of archaeological sites at Luxor includes disintegration and exfoliation of stones, dissolution of building materials, loss of moral paintings, crystallization of salts in walls and columns, stone bleeding, destruction of wall paintings and texts, decreasing the durability of monumental stones, and discoloring.

The hydrogeologic and climatic conditions combined with irrigation practices facilitated the weathering processes to take part in deterioration of archaeological sites at Luxor area. Many varieties of salt species are found in groundwater at the study area which react with country rocks including the archaeological foundations. These salts are not in equilibrium but in a dissolution and/or dissolution–precipitation phases which are responsible for the different types of deterioration features of Luxor and karnak temples including dissolution of the salts or minerals of the building stones and/or precipitation and crystallization of new salts.

1. Introduction

The Nile Valley of Egypt, is one of the oldest agricultural areas in the world, having been under continuous cultivation for at least 5000 years. Before construction of the Aswan High Dam, the agriculture cycle depends on the summer floods, and the year was divided into three seasons: the season of inundation, the season of drought when the Nile is at its lowest level and the in-between season. In July, the main flood discharge would begin with a crest of reddish-brown muddy water from the highlands of Ethiopia. By the middle of August, the inundation would reach its peak. By the end of October, the inundation waned, and water began to subside, with the Nile sinking to its lowest level by May. Then from May to September, the rise of flood water could reach as much as 7 m (Hassan, 2005).

After construction of the Aswan High Dam in the 1970s, the agricultural lands were changed completely to perennial irrigation whereby water is available at any time throughout the year, thus producing two or more crops annually (Abu-Zeid, 1997; Abu-Zeid and El-Shibini, 1997; Hegazi and El Bagouri, 2002). As a consequence, several environmental effects were observed in the Nile Valley including soil salinization and rising of groundwater levels.

The pharaonic monuments at Luxor are becoming progressively worse and urgent measures are needed to avoid the loss of this heritage. The objective of this study is to investigate the impact of groundwater and agriculture in deterioration of Pharaonic Monuments at Luxor, Egypt. Understanding the integrated processes responsible for deterioration of archaeological sites will help in planning for suitable mitigation measures and directing the future research plans.

1.1. Study area

Luxor is in Upper Egypt and the capital of Luxor Governorate with an area of approximately 416 square kilometers (Fig. 1). Luxor was only a City belongs to Qena Governorate whereas it was separated administratively and became a new governorate called "Luxor Governorate" on December 2009. Luxor area constitutes a primary center of Ancient Egyptian Culture where the culture of Ancient Egypt has been imprinted along the Nile Valley by means

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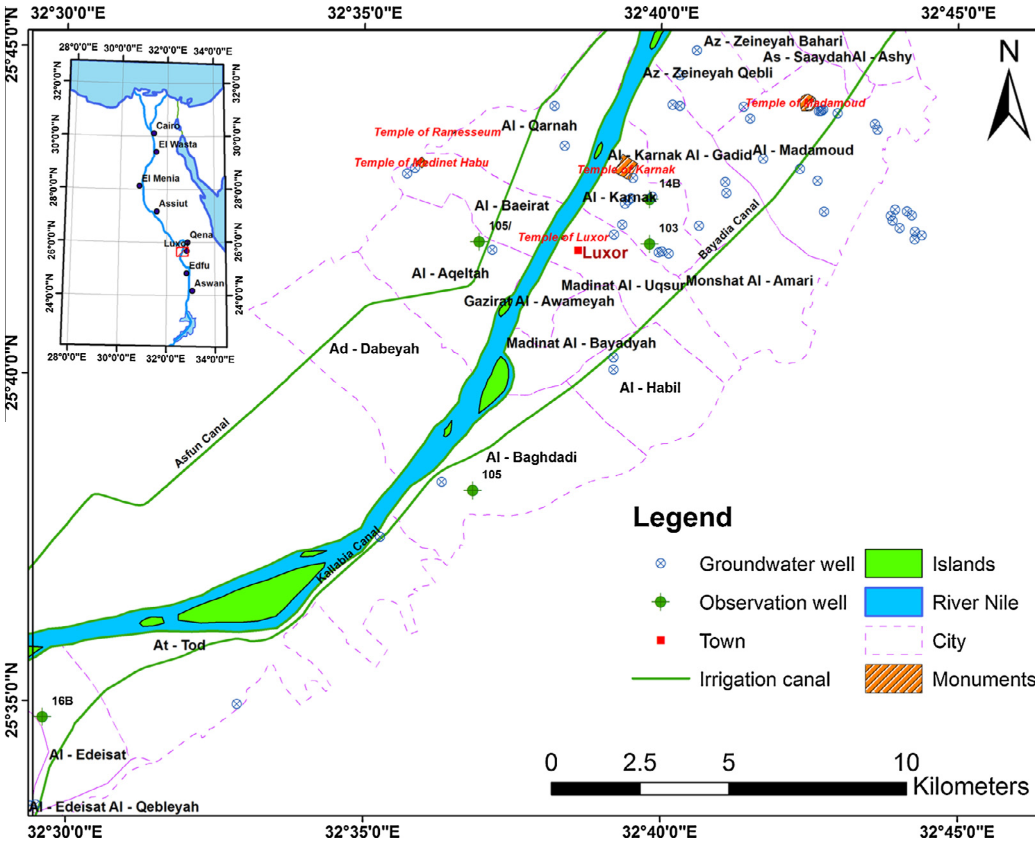

Fig. 1. Location map of study area.

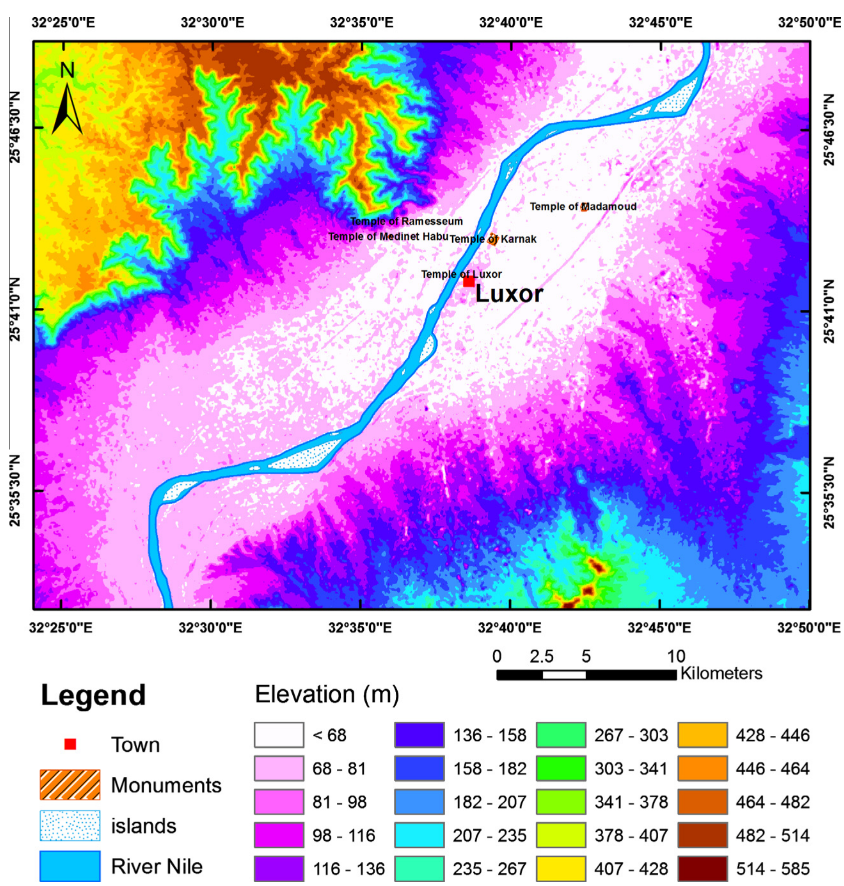

Fig. 2. Topography of Luxor area as depicted from Aster Global Digital Elevation Model (ASTGTM).

of the famous pharaonic monuments standing in a good form of preservation.

Pharaonic monuments represent the most valuable source of ancient Egypt, covering the period of approximately 3000–300 B.C. Karnak and Luxor temples represent the monuments of the east bank of Thebes, the old capital of Egypt. These monuments are the most important Pharaonic temples in Ancient Egypt. They are a real record of history and civilization of Egypt from the Middle Kingdom to the reign of Ptolemies (Baines and Malek, 2000).

1.2. Topography and climate

Luxor is located on the alluvial plains which are represented by the cultivated younger plain occupying the central part of the Nile Valley and the older reclaimed plain at the valley fringes. Topography of the study area as depicted from the Aster Global Digital Elevation Model "ASTGTM" (ASTER, 2009) is characterized by different elevation zones reaching ~585 m at the eastern and western boundaries and ~68 m inside the valley (Fig. 2).

The study area is characterized by arid and desert conditions and its climate is varied during the year (Ibrahim, 1996; Ahmed, 2003; EEAA, 2005; Tyson, 2010). The maximum air temperature varies between 22.9 °C in Jan and 40.9 °C in Jul whereas the average minimum temperature varies between 5.7 °C in Jan and 23.9 °C in Jul. The monthly average of relative humidity in the study area is ranging between 25.0% in May and 55.0% in December. The monthly average of wind speed varies in time and location with monthly average ranging between 5.9 km/h in October and 9.3 km/h in April. Rains are rare and occur randomly throughout the year. The monthly average of precipitation ranges between 0.0 and 0.3 mm (Fig. 3).

1.3. Geologic setting

The area has been studied by a variety of authors (e.g. Said, 1981, 1990; Issawi et al., 1978; Issawi and McCauley, 1992; Omer and Issawi, 1998; Wendorf and Schild, 2002; Kamel, 2004). The sedimentary sequence in the Luxor area (from top to base) as shown in the geologic map (Fig. 2) could be summarized as follows:

Quaternary Rock Units which are divided into the following formations

- Holocene sediments (Arkin Formation, the Modern River Nile sediment).
- Pleistocene sediments (Armant Formation, Qena Sand, and Abassia Formation, Wadi deposits).

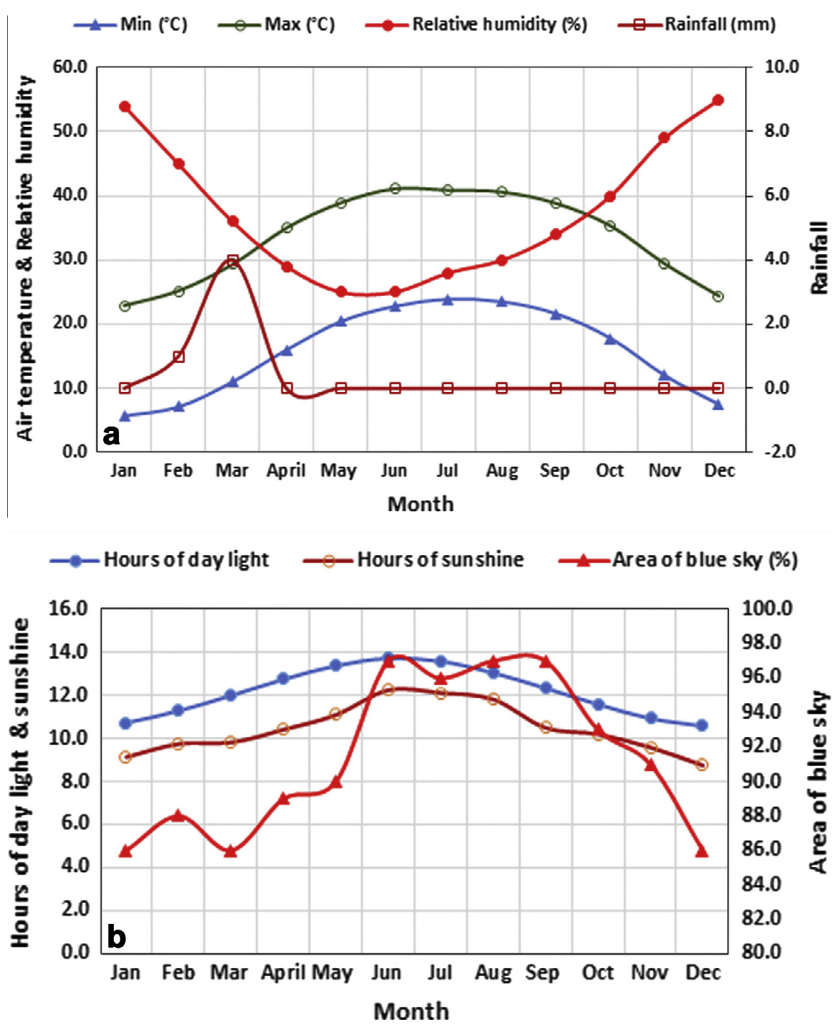

Fig. 3. Climate over Luxor area: (a) Minimum and maximum temperature (°C), relative humidity (%) and rainfall (mm) and (b) hours of day light, hours of sunshine and area of blue sky (%).

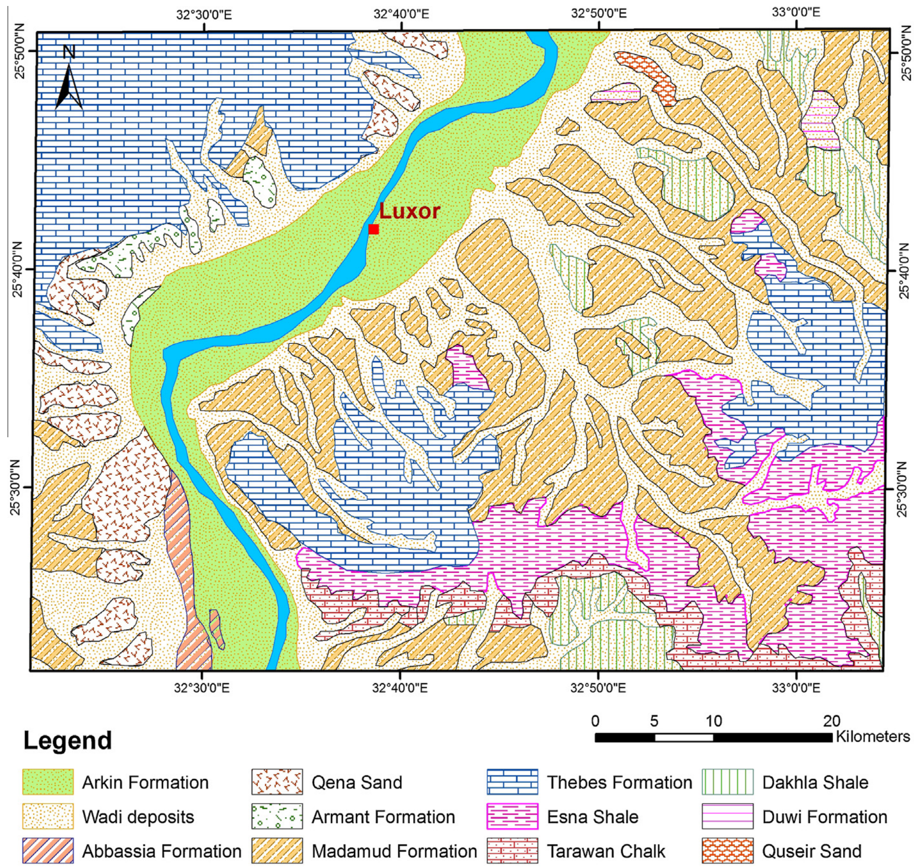

Fig. 4. Geologic map of Luxor area (compiled from Kamel, 2004).

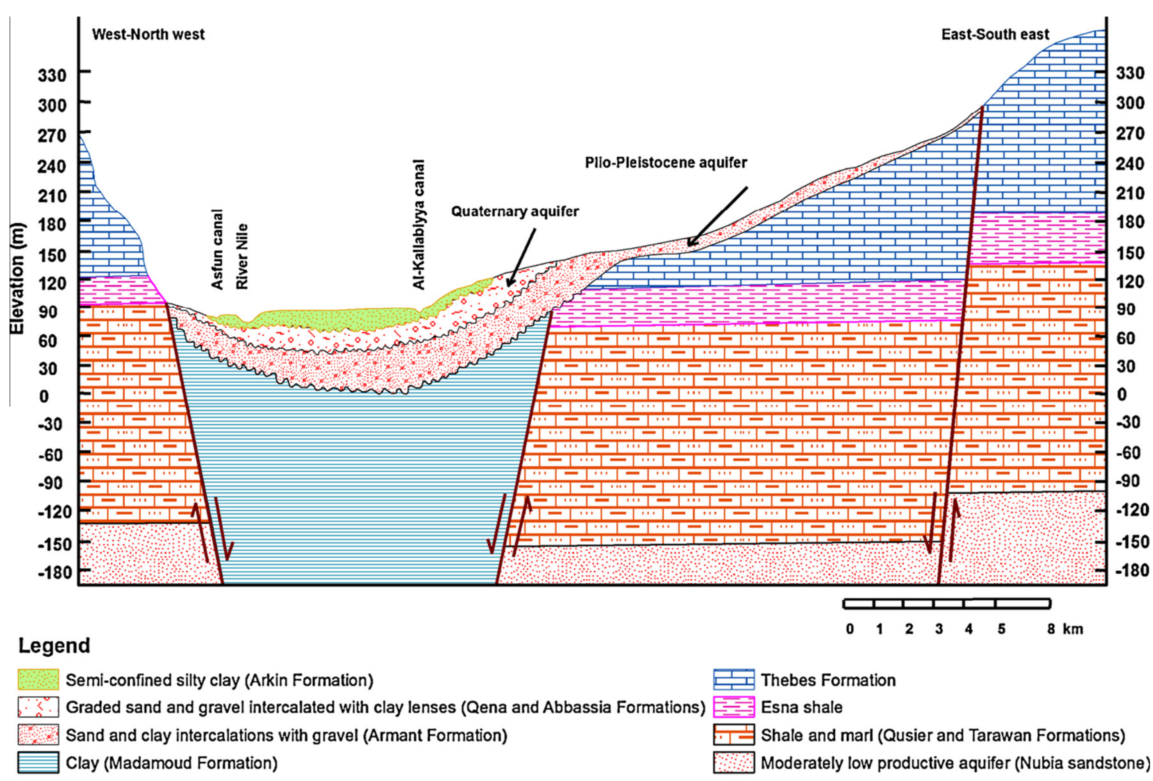

Fig. 5. Simplified hydrostratigraphic section representing Luxor area (compiled from RIGW, 1997a; Kamel, 2004).

Tertiary Rock Units which include the following formations

- Pliocene sediments (Madmoud Formation).
- Lower Eocene–Palaeocene sediments (Thebes Formation, Esna Shale, Tarawan Chalk).

Upper Cretaceous Rock Units (Dakhla Shale, Duwi Formation, and Qusir Shale)

The Modern River Nile (the last Neonile) broke into Egypt beginning about 12 ka. It owed its origin to the Holocene Wet Phase, a rainy interval that affected large parts of Africa. This river was grading its bed during the period between 12 ka and 10 ka. This resulted in removal of most of the silts of the previous rivers between Qena and Aswan (including Luxor). However, the silt that presently fills the Nile Valley belongs to the last and existing river. The Holocene Deposits (Arken Formation) are represented by the silty clay layers deposed by the Neonile (the successor of Prenile and the last of the rivers). Middle-Late Pleistocene Sediments of the Prenile are composed of massive cross-bedded fluvial sands, interbedded with clay lenses (Qena Sand). The Qena Sand is overlaid by Abbassia Formation which was composed of conglomerates deposited by ephemeral rivers occupied the channel of the Nile during the middle Pleistocene. The Plio-Pleistocene (Protonile–Prenile) sediments are represented by Armant Formation composed mainly of clays, sands and conglomerates. The Pliocene Sediments of the Paleonile are composed of brown or chocolate clays interbedded with thin fine-grained sand and silt laminae (Madamud Formation). These sediments represent about 20% of the river's sediments in the Nile Valley and crop out along the banks of the valley and in many wadis which drain into the valley. The Paleocene–Eocene sediments comprise Tarawan Chalk (carbonate unit) overlying the Dakhla Shale (dark grey papery shale and marl with interbedded siltstone, sandstone and limestone) and underlying Esna Shale (laminated green and grey shale), and Thebes Formation (limestone with flint bands). The Upper Cretaceous sediments include Quseir Shale (thin bedded and highly variegated color shale, siltstone and sandstone), Duwi Formation (alternating beds of claystone, sandstone, siltstone and oyster limestone, intercalated with phosphate and phosphatic beds), and Dakhla Shale.

1.4. Hydrogeology

The surface water hydrology of the area is mainly represented by the River Nile and irrigation canals. There are evidences of the impact of geologic structures on the hydrogeologic setting of the study area where it is affected by a series of normal faults and forming a graben-like feature at the middle of the valley (Fig. 5). The faulting in the study area contributed in the distribution of groundwater aquifers and variation of their hydraulic properties. There are two principal groundwater aquifers in the study area; the Quaternary and the Plio-Pleistocene aquifers. The Quaternary

Fig. 6. Deterioration of archeological sites at Luxor: (a) Effects of salt attack on columns of temple of Luxor, (b) weakness and collapse of building stones at temple of Karnak, (c) salinization and salt efflorescence on the ground and walls of temple of Karnak, (d) fracturing, crushing and collapse of building stones of Karnak, (e) stone bleeding at temple of Luxor, (f) salt efflorescence and collapse of moral paintings at temple of Karnak.

aquifer on both sides of the Nile Valley comes into contact with the Plio-Pleistocene aquifer at the valley fringes due to faulting. The following is a brief description of these aquifers:

1.4.1. The Quaternary aquifer

The aquifer occupies the central strip on the Nile Valley forming the old cultivated lands on both sides of the Nile and forms the most important water-bearing formation in Luxor area. This aquifer can be categorized into two hydrogeological units: the upper Holocene aquitard and the lower Pleistocene aquifer.

The Holocene aquitard including the phreatic groundwater is equivalent to the Neonile sediments (Arkin Formation) (Said, 1981). This unit is made up of two sequential layers, a silty clay layer (18.5 m thick) which changes laterally into clay and fine sand, and a clayey silt layer (13.5 m thick) at the base. This later layer has greater thickness near the river channel and vanishing near the valley fringes. This unit has low horizontal and vertical permeability and receives the surface water seepage forming subsoil water and acting as an aquitard to the underlying aquifer (Barber and Carr, 1981; Ahmed, 2003, 2009; Kamel, 2004).

According to Said (1981) classification of Post-Eocene sediments in the Nile Valley, the river has undergone great changes since its down cutting in Late Miocene times and five rivers succeeded one another in the valley which are from oldest to youngest; the Eonile (Late Miocene), Paleonile (Late Pliocene), Proto – Pre and Neoniles (Pleistocene). The Pleistocene aquifer is equivalent to the Protonile sediments of Early Pleistocene (Armant Formation) and the Prenile sediments of the Middle Pleistocene (Qena and Abbassia formations). It is mainly formed of unconsolidated pebbly and bouldary gravel changes laterally into medium to coarse sands and gravel. The Pleistocene sediments attain about 64.5 m thick in Luxor area (Kamel, 2004) and underlain by more than 100 m of brown clays of the Pliocene unit (Madamud Formation).

The Pleistocene aquifer has high horizontal and vertical conductivity (Farrag, 1982; Awad et al., 1997). The aquifer is highly productive and of good water quality. It is recharged mainly from irrigation water and seepage from irrigation canals through the Holocene aquitard (Abu-Zeid, 1995; Shamrukh et al., 2001; Shamrukh and Abdel-Wahab, 2008; Brikowski and Faid, 2006; Ahmed, 2003; Kamel, 2004). Discharge of this aquifer is through groundwater pumping for irrigation and drinking purposes and natural discharge towards the River Nile (RIGW/IWACO, 1997; Shahin, 1991; Awad et al., 1997; Ahmed, 2003, 2009).

1.4.2. The Plio-Pleistocene aquifer

This aquifer represents the secondary aquifer in the study area and exposed at the outer fringes of the Nile aquifer system adjacent to the floodplain. It is represented by Armant Formation

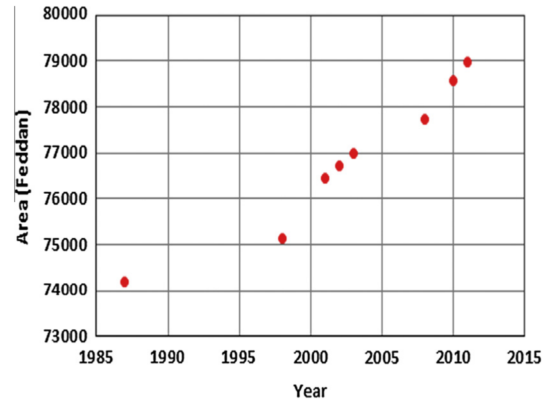

Fig. 7. Agricultural expansion at Luxor area based on analysis of landsat imagery.

which is composed of clay, sand and gravel (Awad et al., 1997; Kamel, 2004; Ismail et al., 2005). The aquifer has more thickness near the Quaternary aquifer and decreases towards the Eocene limestone boundary on both sides of the Nile valley. At the valley fringes, the groundwater in this aquifer is under phreatic conditions. This aquifer is of low productivity and its recharge is mainly from excess irrigation from the reclaimed and desert lands and from deeper aquifer systems (RIGW, 1997a). Discharge of this aquifer is through the groundwater pumping or to the adjacent groundwater aquifers (Awad et al., 1997).

2. Methodology

2.1. Deterioration of archaeological sites

Field observations are carried out on October 2011 for Temples of Karnak and Luxor to characterize the deterioration features of the temples and gather informations and evidences of the impact of groundwater rise on deterioration of these temples.

2.2. Agricultural expansion

Landsat MSS (Multi Spectral Scanner), Landsat Thematic Mapper (TM), and Enhanced Thematic Mapper (ETM+) images (Path 145/Row 42) acquired for the period 1986–2011 were used for analysis of agricultural expansion at Luxor area. The Landsat images were georeferenced to UTM coordinate system, zone 36 North based on topographic maps of study area and subjected to different processes such as layer stacking, subsetting, destribing, supervised classifications and change detection. Erdas Imagine

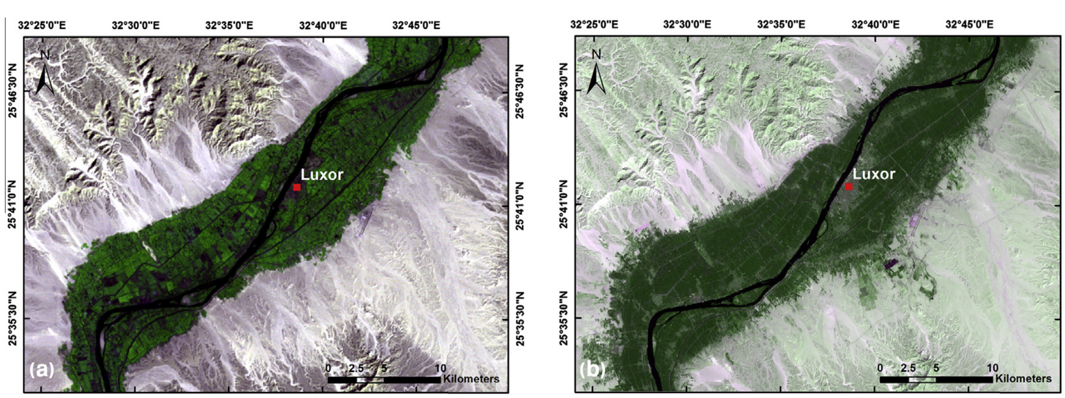

Fig. 8. Composites of landsat images of years 1986 and 2011 showing the agricultural areas in green color. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2010 (ERDAS, 2010) and ArcGIS 9.3 (ESRI, 2006) were used for image analysis and visualization of results.

2.3. Groundwater rise

The available historic groundwater levels for Luxor area were collected from RIGW (1997b) and analyzed for assessment of groundwater rise as a result of agricultural expansion after construction of the Aswan High Dam.

2.4. Hydrochemical properties of groundwater

Fifty four groundwater samples representing the groundwater of the Quaternary aquifer were collected from the study area for investigation of the hydrochemical properties of groundwater and its impact on the archaeological sites. A GPS system is used for locating the sampling sites. The samples were analyzed for pH, EC, TDS and major ions according to the standard methods of analysis of APHA et al (1995). ArcGIS 9.3 (ESRI, 2006) was used

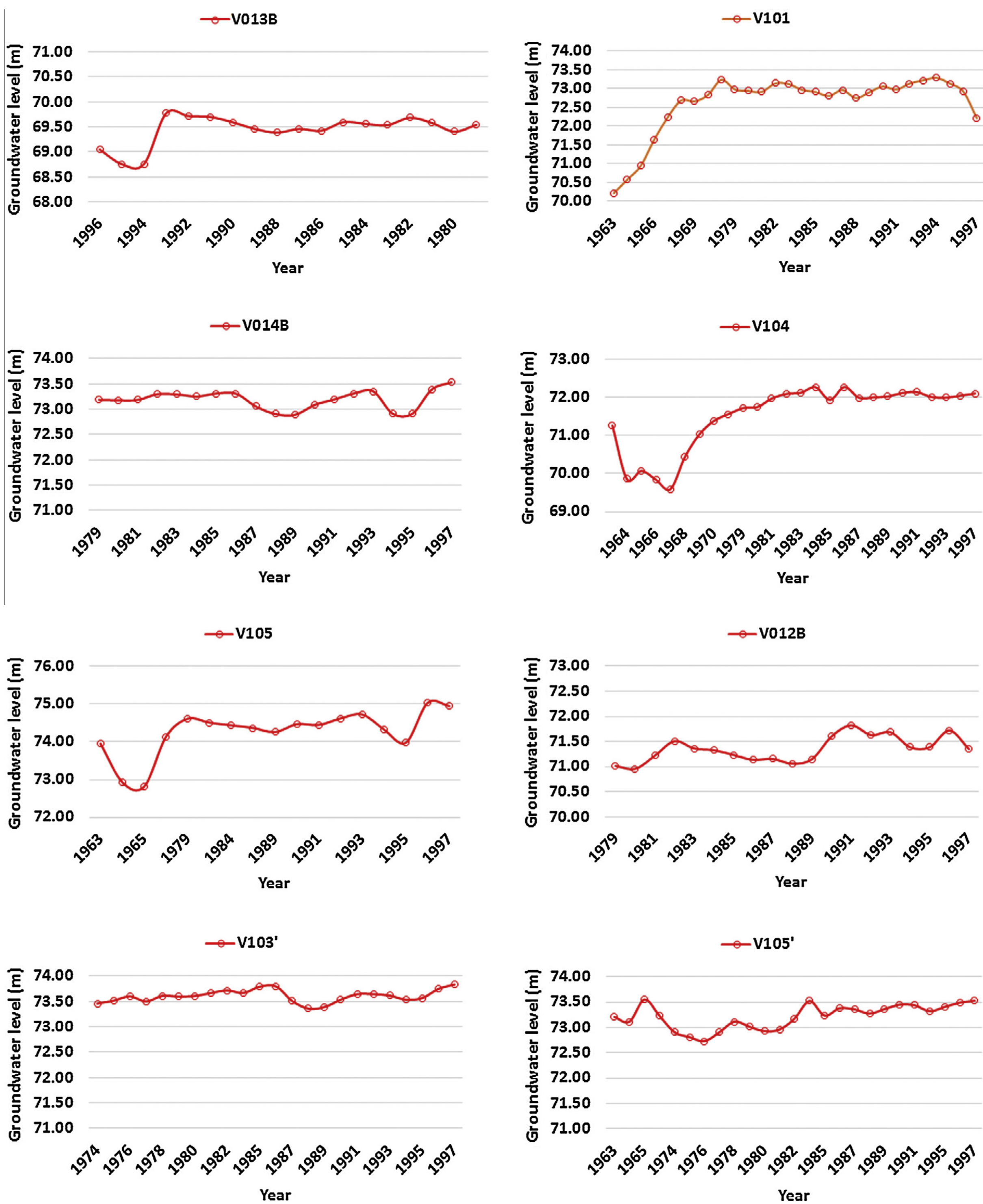

Fig. 9. Historical change of groundwater levels at Luxor area.

Table 1
Crop pattern and cropped area for year 2011 at Luxor (Ministry of Agriculture 2012).

Season	Crop	Cropped area (feddan)[a]
Permanent	Sugar cane	65296.68
	Fruit trees, orchards, date palms	8757.25
	Alfalfa	4412.21
Winter	Clover	4547.21
	Wheat	44203.75
	Tomato	8958.57
	Dry beans	400.21
	Garlic	216.42
	Vegetables, water melon	3373.51
	Barley	270.17
	Onion	648.42
	Fenugreek	3
Summer and Nili	Maize[b]	18446.2
	Sesame	2418.5
	Vegetables[b]	2650.33
	Peanuts	144.33
	Roselle	470.29
	Sorghum[b]	578.29
	Soybean	100
	Tomato	839.96

[a] Feddan = 2400 m^2.
[b] May be grown as Nili crop.

for analysis of the hydrochemical data and visualization of results using the techniques of the Inverse Distance Weight (IDW) interpolation method and the 3D spatial analysis.

2.5. Rock–water interaction

In order to study the rock–water interaction and processes governing the different mineral phases in the study area, the WATEQ4F speciation model (Appelo and Postma, 1994) was used for the calculation of the saturation indices (SI) of the different minerals in groundwater. Generally, the saturation indices are used to express the water tendency towards precipitation or dissolution of specific mineral contents. The degree of water saturation with respect to a mineral is given by:

$$SI = \log(K_{IAP}/K_{SP})$$

where K_{IAP} is the ion activity product, K_{sp} is the solubility product, and SI is the saturation index of the concerned mineral. When SI is equal to zero, then the water is at equilibrium with the mineral phase, whereas SI values less than zero (negative values) indicate undersaturation and that the mineral phase tends to dissolve, while SI values over zero (positive values) indicate supersaturation and then the mineral phase tends to precipitate. ArcGIS 9.3 (ESRI, 2006) was used for analysis of the spatial distribution of the SI indices for the different mineral species using the techniques of the Inverse Distance Weight (IDW) interpolation method and the 3D spatial analysis.

3. Results

3.1. Deterioration of archaeological sites

Field observations revealed the deterioration of archaeological sites at Luxor with different degrees including disintegration and exfoliation of building sandstones, dissolution of building materials and crystallization of salts, loss of the surface layers of sandstone which carry moral paintings, soil salinization, crystallization of salts in walls and columns, stone bleeding, destruction of wall paintings and texts, decreasing the durability of monumental sandstones, seepage of capillary groundwater and discoloring (Fig. 6).

3.2. Agricultural expansion

The analyzed Landsat imagery acquired for the time period 1987–2011 revealed a continuous expansion in agriculture of about 4790 feddan for the investigated period 1987–2011 (Fig. 7). The total cultivated area observed at Luxor is about 79,000 feddan. Land reclamation is taking place and extending agriculture into the desert margins and adjacent wadis, making the transition from arable to desert habitats very sharp (Fig. 8).

According to the national strategy for land reclamation, about 45,000 feddan of the low land desert areas at Luxor were planned to be reclaimed and invested for agriculture (EEAA, 2005). According to the present landsat imagery analysis, there is about 40,000 feddan are still planned for reclamation. Since construction of the High Dam and availability of irrigation water all of the year, crops are cultivated in three distinct planting seasons which are winter (November to May), summer (April/May to October) and Nili seasons (July/August to October). The Nili season corresponds to late July to early November and takes its name from agricultural practices dating back before the control structures on the Nile when the River still used to flood every year (FAO, 1995; El-Nahrawy, 2011; Ahmed et al., 2013). Furthermore, crops for one season may sown before those of the previous season have been harvested. Thus providing yields for 2–3 crops annually (Table 1).

3.3. Groundwater rise

The historical records on groundwater levels at Luxor area showed a general increase in groundwater levels (Fig. 10). The investigated observation wells (indicated in Fig. 1) indicated fluctuations of groundwater levels during the investigated period and ranged between 0.9 m (well V103’) and 2.7 m (well V104). The change in groundwater levels is corresponding to the change

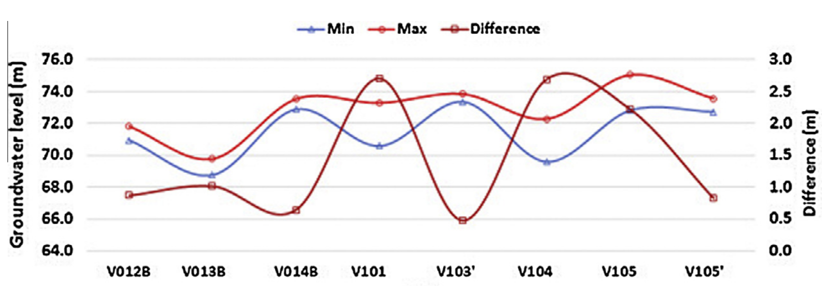

Fig. 10. Variation of groundwater levels at Luxor area.

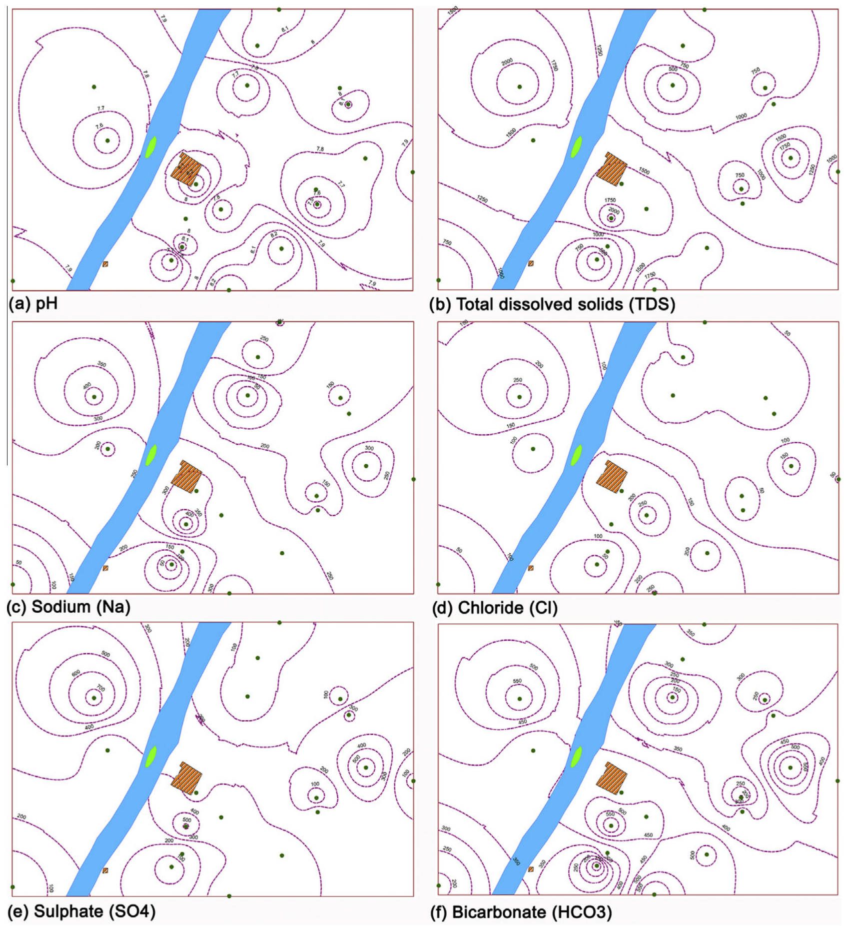

Fig. 11. Variation of major ions at Luxor area.

Table 2
The mineral species and the calculated SI indices of groundwater at Luxor area.

No.	Mineral	Chemical formula	SI index		
			Min	Max	Average
1	Anhydrite	CaSO4	−3.45	−0.63	−2.17
2	Antlerite	Cu3(SO4)(OH)4	−8.78	0.94	−4.65
3	Aragonite	CaCO3	−0.61	1.12	0.22
4	Artinite	Mg2(CO3)(OH)2·3H2O	−7.75	−3.18	−4.97
5	Atacamite	Cu2Cl(OH)3	−6.02	1.46	−2.84
6	Azurite	Cu3(CO3)2(OH)2	−5.46	3.46	−1.60
7	Brochantite	Cu4(SO4)(OH)6	−9.41	2.84	−4.19
8	Brucite	Mg(OH)2	−5.77	−3.12	−4.25
9	Calcite	CaCO3	−0.46	1.26	0.37
10	Chalcanthite	CuSO4·5H2O	−10.70	−6.04	−8.73
11	Dolomite (d)	CaMg(CO3)2	−1.37	2.18	0.47
12	Dolomite (c)	CaMg(CO3)2	−0.82	2.73	1.02
13	Epsomite	MgSO4·7H2O	−5.83	−2.75	−4.24
14	Fluorite	CaF2	−3.82	0.14	−2.39
15	Gypsum	CaSO4·2H2O	−3.23	−0.41	−1.95
16	Halite	NaCl	−8.47	−4.45	−6.35
17	Huntite	CaMg3(CO3)4	−6.37	1.36	−2.03
18	Hydromagnesite	Mg5(CO3)4(OH)2·4H2O	−17.05	−6.65	−10.50
19	Langite	Cu4(SO4)(OH)6·2(H2O)	−10.86	1.39	−5.64
20	Magnesite	MgCO3	−1.19	0.91	0.07
21	Malachite	Cu2(CO3)(OH)2	−2.79	2.93	−0.32
22	Melanothallite	Cu2OCl2	−20.36	−12.99	−17.24
23	Mirabilite	Na2SO4·10H2O	−9.32	−4.14	−6.20
24	Monteponite	CdO	−7.08	−4.52	−5.83
25	Nahcolite	NaHCO3	−5.23	−3.05	−3.85
26	Natron	Na2CO3·10H2O	−10.27	−6.28	−7.58
27	Nesquehonite	MgCO3.3H2O	−3.60	−1.50	−2.34

(continued on next page)

Table 2 (*continued*)

No.	Mineral	Chemical formula	SI index		
			Min	Max	Average
28	Otavite	$CdCO_3$	−1.27	0.31	−0.52
29	Portlandite	$(Ca(OH)_2)$	−11.39	−9.22	−10.36
30	Pyrochroite	$Mn(OH)_2$	−6.89	−4.01	−5.81
31	Rhodochrosite (d)	$MnCO_3$	−1.83	0.84	−0.77
32	Rhodochrosite (c)	$MnCO_3$	−1.09	1.58	−0.03
33	Tenorite	CuO	−1.20	1.33	−0.11
34	Thenardite	Na_2SO_4	−10.25	−5.06	−7.13
35	Thermonatrite	$Na_2CO_3{\cdot}H_2O$	−11.71	−7.72	−9.02
36	Trona	$Na_3(HCO_3)(CO_3){\cdot}2(H_2O)$	−16.56	−10.46	−12.49

(d) Disordered.
(c) Crystalline.

in recharge from excess irrigation associated with the agricultural expansion in the study area.

3.4. Hydrochemical properties of groundwater

Hydrochemical properties of groundwater varied considerably at Luxor area (Fig. 11). The pH values of groundwater ranged between 7.2 and 8.51 with an average of 7.92 which reflect slightly alkaline conditions. Total dissolved solids (TDS) almost ranged between 284.3 and 2801 with an average of 1104.47 mg/l. According to Davis and De Wiest (1967), salinity of groundwater in the study area can be classified as fresh to brackish water.

Major ions showed considerable variation at Luxor area; Potassium ranged between 0.33 and 146.3 with an average of 13.65 mg/l. Sodium concentration ranged between 19.6 and 574.0 with an average of 217.03 mg/l. Magnesium content ranged between 1.5 and 142.0 with an average of 27.43 mg/l. Calcium content ranged between 7.3 and 64.99 with an average of 27.89 mg/l. Chloride content ranged between 6.18 and 273.6 with an average of 81.78 mg/l. Sulphate content ranged between 5.0 and 721.31 with an average of 178.04 mg/l. Bicarbonate content ranged between 91.29 and 671.7 with an average of 358.17 mg/l.

In the study area, the total dissolved solids, chlorides, and sulphates are elevated at the agricultural lands which indicated that

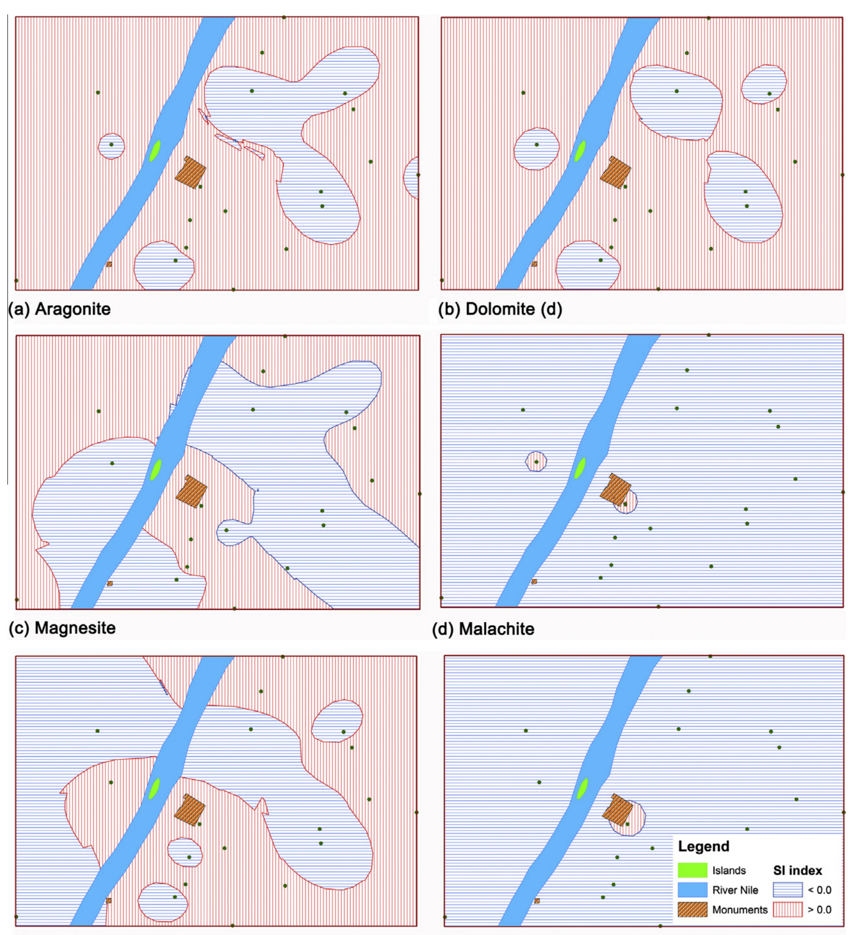

Fig. 12. Dissolution–precipitation phases of mineral species at Luxor area.

agriculture may contributed in increasing the concentration of these parameters in groundwater.

3.5. Rock–water interaction

Results of speciation model showed various phases of rock–water interaction in the study area involving a wide range of mineral species (Table 2). Two mineral phases are present in the study area as follows (Fig. 12).

3.5.1. Phase I: dissolution

The minerals of this phase are undersaturated and tend to dissolve. The minerals of this phase include Anhydrite, Artinite, Brucite, Chalcanthite, Epsomite, Gypsum, Halite, Hydromagnesite, Melanothallite, Mirabilite, Monteponite, Nahcolite, Natron, Nesquehonite, Portlandite, Pyrochroite, Thenardite, Thermonatrite, Trona.

3.5.2. Phase II: dissolution–precipitation

The minerals of this phase include dissolution and precipitation of the same minerals depending on the location in the study area which include Antlerite, Aragonite, Atacamite, Azurite, Brochantite, Calcite, Dolomite (d), Dolomite (c), Fluorite, Huntite, Langite, Magnesite, Malachite, Otavite, Rhodochrosite (d), Rhodochrosite (c), Tenorite.

4. Discussion

Irrigation without adequate drainage or groundwater management continued to raise the water table and salinity of shallow groundwater adjacent to the monuments at Luxor, thereby threatening the structural and artistic integrity of these irreplaceable monuments. The increase in reclamation and agricultural activities (Fig. 7) resulted in increasing irrigation and without an efficient drainage network, the water table rose and reached the subsurface foundations of preexisting structures of temples at Luxor accelerating the process of salt weathering (Figs. 4 and 9).

The hydrogeologic and climatic conditions combined with irrigation practices facilitated the weathering processes to take part in deterioration of archaeological sites at Luxor area. Before construction of the High Dam, the groundwater levels in the Nile Valley fluctuated depending on the water level of the Nile. During summer when evaporation was highest, the groundwater level was too deep to allow salts dissolved in the water to be pulled to the surface through capillary action. The disappearance of the annual flood and with heavy year-round irrigation, groundwater levels remained high with little fluctuation leading to waterlogging and capillary action. Soil salinity also increased because the distance between the surface and the groundwater table was small enough to allow water to be pulled up by capillary forces assessed by evaporation most of the year (Fig. 3), so that the relatively small concentrations of salts in the groundwater accumulated on the soil surface over the years (Fig. 6).

Since the climate in the study area is characterized by low precipitation and high evaporation during the major part of the year (Fig. 3), and the capillary zone extends to the surface, upward transport of salts occurs. The result of this is the accumulation of salts in the upper soil strata. The desert climate is characterized by extensive variations in temperature where it varies remarkably between days and nights. The high temperature of the day is able to draw the moisture out of pores towards the surface. When this water evaporates, the water soluble salts are concentrated on the surface of the stones. The low temperature of the night, especially at the stone surface, quite often plunges below the dew point. The condensed moisture then penetrates into the stone due to capillary action. There, it dissolves the salts, which crystallize again during the heat of the following day. This repeated dissolution and crystallization of the salts generates considerable stresses which can even damage the competent material (Fig. 6).

Many varieties of salt species are found in groundwater at the study area which react with country rocks including the archaeological foundations through capillarity and/or groundwater seepage. These salts (Table 1) are not in equilibrium but in a dissolution and/or dissolution–precipitation phases which are responsible for the different types of deterioration features of Luxor and Karnak temples resulting in dissolution of minerals of the building stones and/or precipitation and crystallization of new mineral species. The dissolution phase is responsible for dissolving the cementing materials of stones and moral paintings, weakness of stones and discoloring whereas the precipitation phase is responsible for salt efflorescence on stone surfaces and crystallization of salts between pore grains of building materials, walls, columns and moral paintings which exerts expansion during crystallization, tension and pressure forces leading to weakness of stones, exfoliation, stone bleeding, crushing, fracturing, decreasing the durability of monumental stones, and collapse of building stones (Fig. 6).

5. Recommendations

The following recommendations should be taken into consideration to mitigate the deterioration of the studied archaeological sites which could be grouped into two categories as follows:

5.1. Local strategies to protect the archaeological sites

5.1.1. Switching to less water-consumptive crops.
5.1.2. Using dewatering wells or subsurface drains to lower groundwater heads around the archaeological sites with the necessary safety precautions for avoiding land subsidence.
5.1.3. Constructing capillary barriers at antiquity sites to protect foundations.
5.1.4. Lining of irrigation canals to prevent seepage of water to surface layers.

5.2. Regional strategies to reduce seepage of excess water

5.2.1. Changing the irrigation methods in the study area from flood irrigation to more efficient methods such as sprinkler or drip.
5.2.2. Using a reliable drainage system through subsurface drains in the agricultural lands to lower the piezometric head in the upper layers of the aquifer and prevent capillary effects.
5.2.3. Using dewatering systems around the archaeological sites such as sheet piles, grout curtains and clay cut-off walls, drainage trenches, tiles, trench sumps, and sand point dewatering systems.

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