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Geological and geotechnical risk assessment of Saqqara and Memphis morpho-archeological models, Western Nile Bank, Egypt.

By

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ABSTRACT

Saqqara and Memphis are Ancient Egyptian archaeological sites that are world heritage sites. Due to ongoing concerns from natural hazards and human activities, preservation is essential. This study proposes a comprehensive environmental management approach to minimize or prevent further damage to the monuments. This strategy is particularly important given the anticipated impacts of climate change and is based on a new risk assessment model. Most similar Egyptian archaeological sites are located in the Nile floodplain or on nearby hills and plateaus. Field observations developed two archaeological models: the "Saqqara hilly desert model" and the "Memphis flood plain model." Each model has distinct geomorphological and geoenvironmental characteristics. Key methods for categorizing risk levels in each model included bedrock investigation, foundation soils, environmental hazards, and detection of anthropogenic changes. The discussion focused on influential risk factors and 53their environmental consequences to determine the most suitable management approach. This study emphasizes damage prevention over traditional conservation and restoration methods for monuments. It advocates designing effective drainage systems, reducing air pollution, and utilizing geotechnical databases to mitigate risks like salt weathering, potential liquefaction, and wind erosion.

Keywords: Ancient Egyptian monuments, Saqqara- Memphis model, Geological risk assessment, Land use/land cover change, Conservation measures.

1) INTRODUCTION

The study area southwest of Cairo is home to significant monuments which are considered as vital human heritage globally. These monuments are distributed in four archaeological clusters: Saqqara, Abu Sir, Dahshur, located in high desert hills, and Memphis (Mit-Rahinah), the oldest Egyptian capital, situated in the cultivated Nile flood plain (Fig 1). Monument sites and materials face various geological and anthropogenic hazards. Key geological threats include salt weathering, sandstorm erosion, sand encroachments, soil liquefaction from earthquakes (e.g., the October 1992 Cairo earthquake), and flash floods. Future climate change is expected to exacerbate these hazards, especially flash floods, sandstorms, and salt weathering, which currently impact most ancient Egyptian monuments, including those in the study area. Most monuments face anthropogenic-environmental deterioration and damage from poor conservation practices and unplanned build-up aggressive encroachment, which affects Nile flood lands and increases land use pressure from tourism.

The study aims to develop a sustainable management strategy through risk analysis and assessment of the monumental sites and materials to mitigate their environmental problems. The area has faced complex and integrated damages and deterioration over its history, necessitating an investigation into the causative factors before proposing risk assessments. This research highlights the importance of damage prevention in conserving ancient Egyptian monuments. Geological and geotechnical risk assessments require data on archaeological sites, monumental materials (rocks and soils), and surrounding environmental profiles. Thus, the study focuses on environmental petrographical and geotechnical analysis of bedrock and monumental materials to determine the semi-quantitative risk assessment level for each archaeological site.

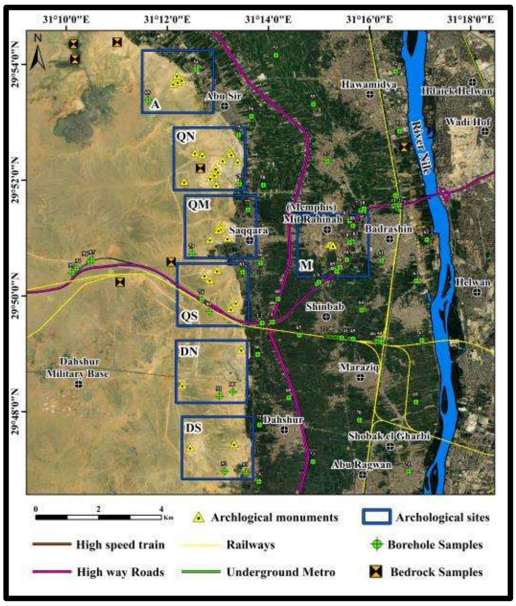

Fig 1: Location map of the study

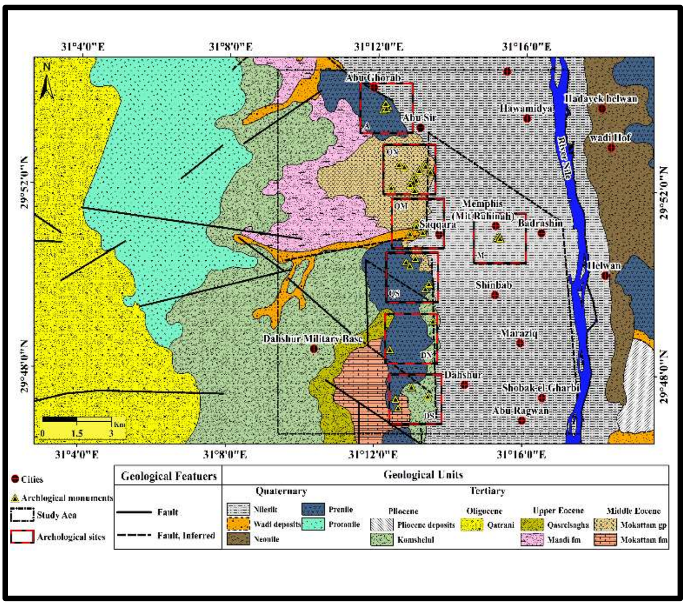

Fig 2: Geological map of the study area (data base: Geological Map of Egypt 1:500,000, Sheet NH 36 SW, Beni Suef) modified after Conoco (1987).

2) Materials and methods of the study

Various samples were collected, including rock samples from bedrocks of hilly archaeological sites and soil samples from boreholes in Nile sediments and desert hinterlands. Mapping of integrated remote sensing analysis and field investigation. Lithological differentiation utilizing multi-spectral satellite imagery, including band combination, band ratio, and supervised classification of Landsat 8 was carried out. Geological structures were mapped using high-resolution Landsat images. The remote sensing results were verified through detailed field investigations. The ALOS PALSAR RTC 12.5m DEM was used to create topographic contours and hill shades for geoenvironmental and land use/land cover mapping. Laboratory analyses included petrographic and mineralogical investigations of samples. Selected rock and soil samples underwent detailed mineralogical study using X-ray diffraction (XRD) analysis. Both powdered bulk samples and separated clay fractions (less than 2µ) were analyzed using Cu kα radiation and a Ni filter. Geotechnical information, including layer thickness and sieve analysis, was gathered to determine particle size distribution (Bouyoucos 1936), Atterberg consistency limits (Natural Water Content –WC %, Liquid Limit – LL %, Plastic Limit – PL %, Plasticity Index – PI%) together LL and Pl and Free swell were used to estimates the swelling properties and potentiality (Oloo, et al., 1987), SPT was used in-situ testing method for determining the penetration resistance of soil (Nixon, 1982). Direct shear was carried out to determine the shear strength parameters by measuring the resistance of a soil or rock mass to shearing ϕ, C (Gan et al., 1988; Wen-Jie et al., 2011) Unconfined

Compression Tests (Unconfined Compression Strength – UCS, and Dry Density – DD). The depth to the water table and the ground surface elevation were also measured and included in the analysis.

3) Physiography and archaeological background

The study area covers approximately 200 km² in the southern Giza Governorate, northern Western Desert. It is bounded by latitudes 29° 55' 29" to 29° 45' 26"N and longitudes 31° 09' 20" to 31° 17' 43"E. The Saqqara-Memphis region is accessible via the Fayoum Desertic Road (northwest), Middle-Ring Road (center), and Cairo-Aswan Railway (east). Additionally, study area is currently undergoing construction activities such as building metropolitan areas, highways, and large projects. The area is characterized by diverse land uses (Fig 1). The study area includes some of the world's most significant ancient sites, featuring Memphis (the oldest capital of the Old Kingdom) and Saqqara (the oldest Egyptian cemetery). It is divided into four archaeological clusters: Saqqara, Memphis, Abu-Sir, and Dahshur. Each cluster contains multiple sites with core monuments (i.e., the buffer squares, Fig1). Memphis (site M) is located in the Nile floodplain, while the other clusters are situated in upper Eocene carbonate hills from North to South: Abu-Sir (A), Saqqara (QN, QM, QS), and Dahshur (DN, DS)

4) Results and Discussion

4.1 Geological and geotechnical characterization

4.1.1 Geological and geomorphological setting

Geomorphologically, the study area is characterized by Nile terraces (hills) and a cultivated floodplain where archaeological sites are distributed. The terraces are cut by faults and two major drainage channels that flow from the Western limestone plateau to the floodplain. Most monuments, including pyramids and temples, are situated on these hills, which rise 17 meters above the Nile valley. The building stones for these structures were sourced from nearby Eocene limestone quarries, and some tombs, such as those in the Serapeum, were carved from these Eocene rocks. The stratigraphic succession of the study area (e.g., Kusky et al., 2011; Hamdan et al., 2014) includes the Middle Eocene Mokattam group, Wadi Rayan and Observatory formations, Upper Eocene Qasr El-Sagha and Maadi formations, Oligocene Gebel Qatrani Formation, Pliocene Kom El Shelul Formation, undifferentiated Pliocene deposits, and Quaternary includes Nile-Silt, Wadi deposits, Neo-Nile deposits, Pre-Nile Deposits and Proto-Nile Deposits (Fig 2). The study area is characterized by various structural features including faults, grabens, horsts, and major fractures (Yehia 1985; Ghazala 2001). These faults have caused the upper Eocene Maadi Formation rocks, which are covered by Pliocene Kom El-Shelul sediments, to be down-faulted (Fig 2). The fault system facilitates the movement of groundwater and rainwater, especially through wadis between the archaeological sites QM and QS in the Saqqara hills (Fig 2). Additionally, Karstic solution features are frequently found within these faults and joints in the Saqqara hills. Petrographically, the top of the bedrock sequence at some archaeological sites (e.g., site-A and site-DN), is represented by sandy skeletal packstone-grainstone, composed of skeletal particles and bioclastics (Mollusca shell fragments) cemented by microsprite (Fig 3a).The Upper Mokattam Formation (Middle Eocene) is primarily foraminiferal lime-mudstone wackstone, Maadi / Qaser El Sagha Formation (Upper Eocene) is mainly sandy skeletal packstone-grainstone, with occasional intercalations of micritic silty mudstone beds. Pliocene Kom el-Shelul Formation is characterized by dolomitic lithic-quartz arenite (Fig 3b). The foraminiferal lime-mudstone wackestone forms the primary bedrock of the Saqqara hills and the monumental limestone blocks. The XRD analysis of the Maadi Formation sample reveals quartz, feldspars, calcite, and traces of dolomite ankerite (Fig 3c). The clay minerals in the separated clay size fractions are predominantly smectite, with some kaolinite and minor illipe. The Kom-ElShelul Formation's dolomitic lithic quartz-arenite is characterized by a heterogeneous texture and composition, featuring poorly sorted angular to subangular quartz grains and feldspar fragments, and cemented by idiomorphic dolomitic cement (Fig 3b).

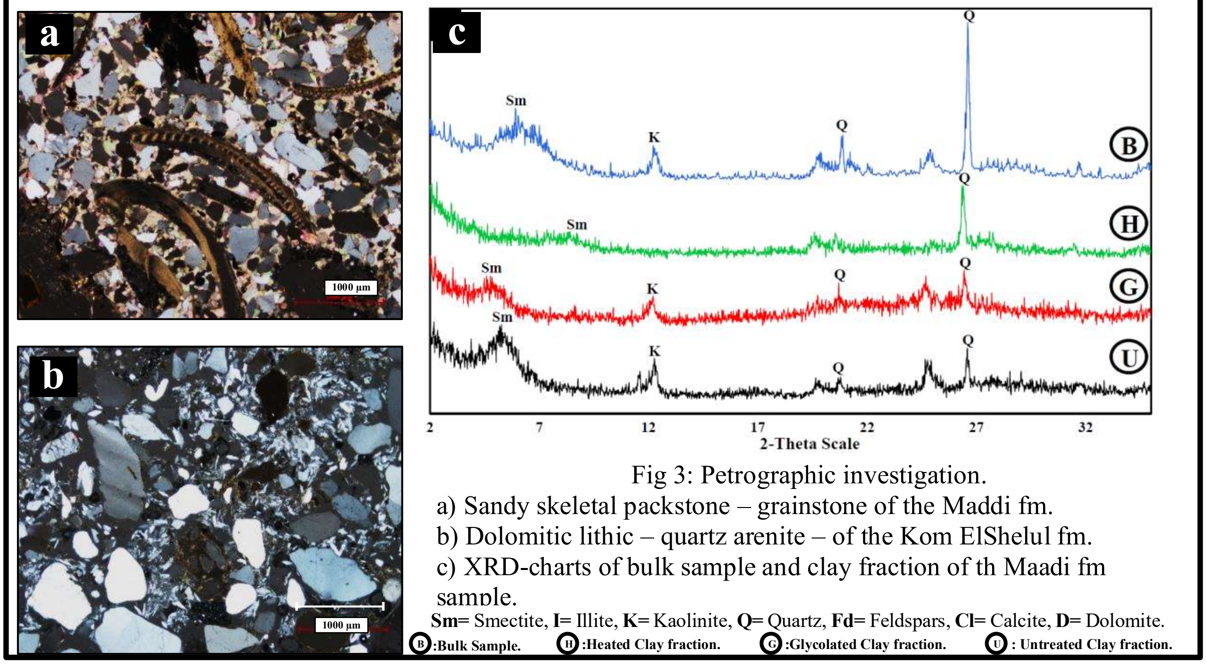

Fig 3: Petrographic investigation.
a) Sandy skeletal packstone – grainstone of the Maddi fm.
b) Dolomitic lithic – quartz arenite – of the Kom ElShelul fm.
c) XRD-charts of bulk sample and clay fraction of th Maadi fm sample.

4.1.2 Geotechnical characterization of Bedrock's sediments

Regarding geotechnical characterization of bedrock of the hilly model that contains (A, QN, QM, QS, DN and DS), the study was divided into two sections: evaluating bedrock sediments and assessing compacted rocks. It began with a sieve analysis to determine grain-size distribution, including gradation parameters such as D10, D30, D60, and D50 (Fig 4). The uniformity and curvature coefficients were also calculated. Additionally, mud proportions in the samples were measured to classify the sediment samples according to the Unified Soil Classification System (Table 1). The sand with gravel samples have D10 ranging from approximately 0.55 mm to 16 mm, averaging 7.8 mm. D30 varies from about 4 mm to 17.8 mm, with an average of 10.8 mm. D50 spans from approximately 10 mm to 20 mm, averaging 15 mm. D60 ranges from approximately 12.5 mm to 24 mm, with an average of 18.3 mm. Based on these parameters, the uniformity coefficient averaged approximately 15 and the curvature coefficient around 5 (Fig 4, Table 1). Mud percentages were determined for classification according to the Unified Soil Classification System. Sand and gravel samples have mud percentages ranging from 1.7% to 17%, averaging 6.2%. Most of samples were classified as well-graded sand and gravel (GW-SW), while some were poorly graded sand (SP). Silty sand samples had mud percentages from 17% to 24%, averaging 20%, and were classified as SM (Table 1). The N-spt of the tested samples was in the range of 46 to 48 with an average of 47 indicating dense to very dense Sand with an estimated relative density between 80% to 85% and angle of internal friction between 39.8° to 40.3° as shown in (Fig 5c$_{1\text{-}2}$). The γ_{max} of the two tested samples ranges from 1.94 to 2.13 gm/cm^3, and the California bearing ratio ranges from 13.7% to 32.4% (Fig 5a, b). For clayey samples, mud percentages ranges from 44% to 91% averaging 74.5%. Most were classified as high plasticity clay (CH), based on Atterberg's limits (Fig 6a). The uniformity and curvature coefficients were not calculated for most clayey samples due to pass% of sieve#200 exceeding 60% (Fig 4). The liquid limit ranges from 84% to 97%, averaging 90% (Fig 6a), and the plasticity index ranges from 47% to 60%, averaging 53%. These results indicate a very high swelling potential. The free swelling results ranges from 224% to 319%, averaging 270% (Fig 6b)

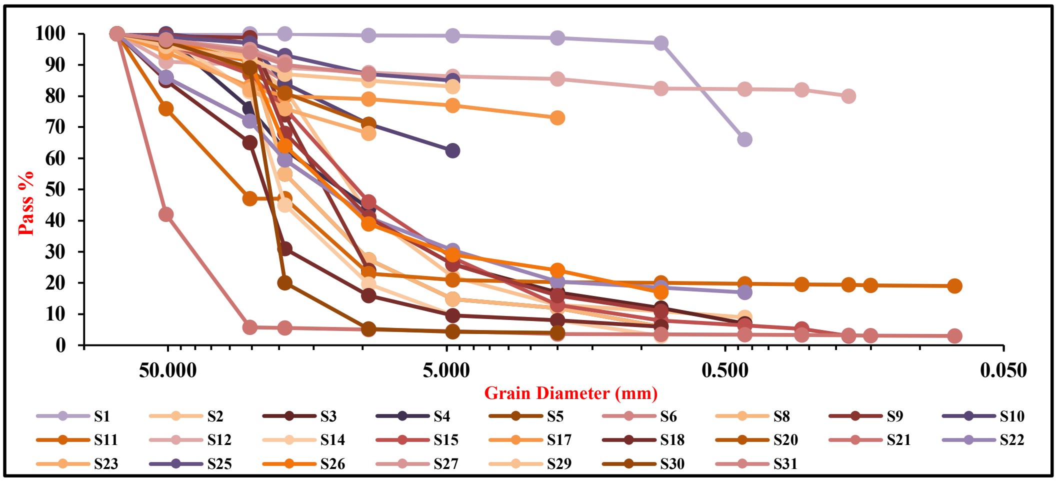

Fig 4: Grain size distribution curves of Bedrock's sediments.

Table 1: Grain size analysis of Bedrock's sediments.

BH No,	Nearest archaeological site	SP No,	Depth	Parameters and classification				
				(Cu)	(Cc)	D50	Mud content	Classification (USCS)
54	A	1	4	-	-	-	66	CH
54	A	2	17	22.581	1.758	11.6	9	SW
89	A	3	4	27.941	1.204	14	7	SW
75	QN	4	8	-	-	12.5	44	CL
75	QN	5	18	12.227	8.179	17.7	6	SP
78	QN	6	6	-	-	-	84.7	CH
78	QN	8	28	11.976	8.350	17.5	6	SW
77	QM	9	7	-	-	15	24	SM
77	QM	10	5	-	-	-	62.5	CH
79	QM	11	6	-	-	28.1	19	SM
79	QM	12	8	-	-	-	80	CH
81	QS	14	19	4.524	39.692	19.9	3.0	SP
76	QS	15	3	11.488	2.309	11	3	SW
80	QS	17	9	-	-	-	73	CH
90	DN	18	3	-	-	20.31	6.0	SP
91	DN	20	6	-	-	-	71	CH
93	QM-QS	21	8	-	-	54.7	3	GW
92	QM-QS	22	2	-	-	14.6	17.0	SM
92	QM-QS	23	13	-	-	-	68	CH
94	QM-QS	25	13	-	-	-	85	CH
95	QM-QS	26	7	-	-	14.2	17	SP
95	QM-QS	27	15	-	-	-	91	CH
96	QM-QS	29	11	-	-	-	83	CH
97	QM-QS	30	5	-	-	21.86	4.0	GP-SP
97	QM-QS	31	9	-	-	-	87	CH

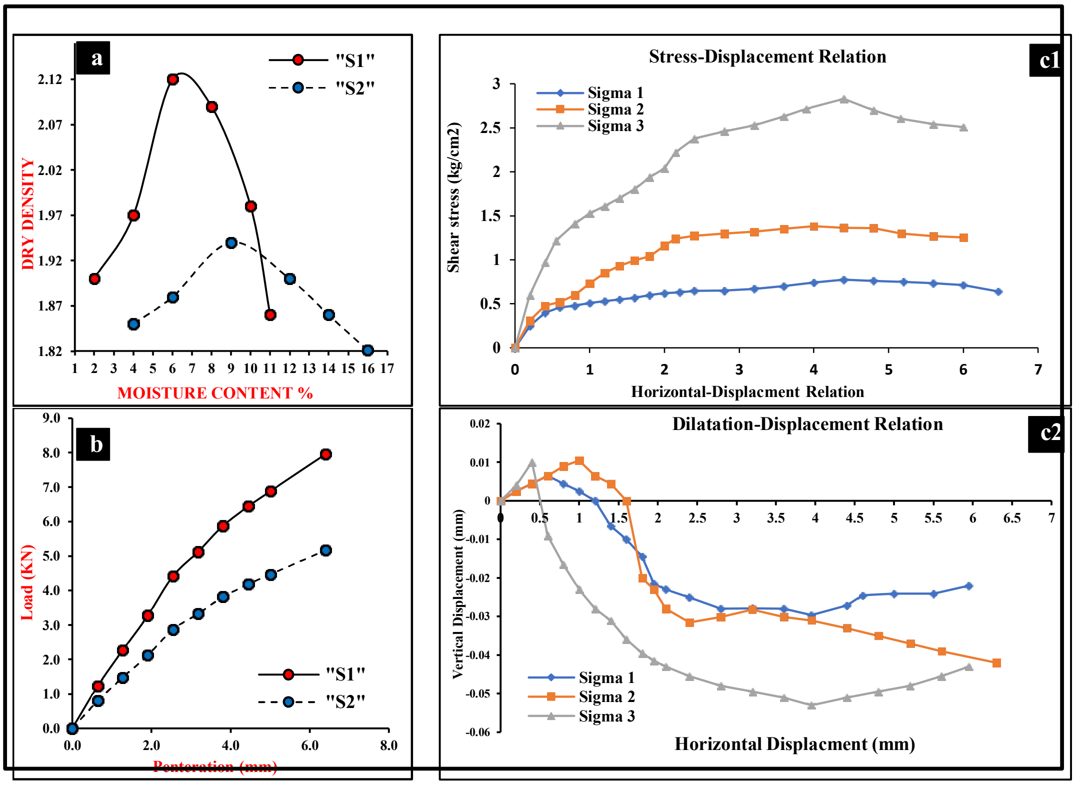

Fig 5: Shear parameters of sand-samples:

a) Modified proctor test charts of sand sample (no,1 and no,2).
b) CBR test charts of sand sample (no,1 and no,2).
C) Direst shear test charts of sand sample (no,1).

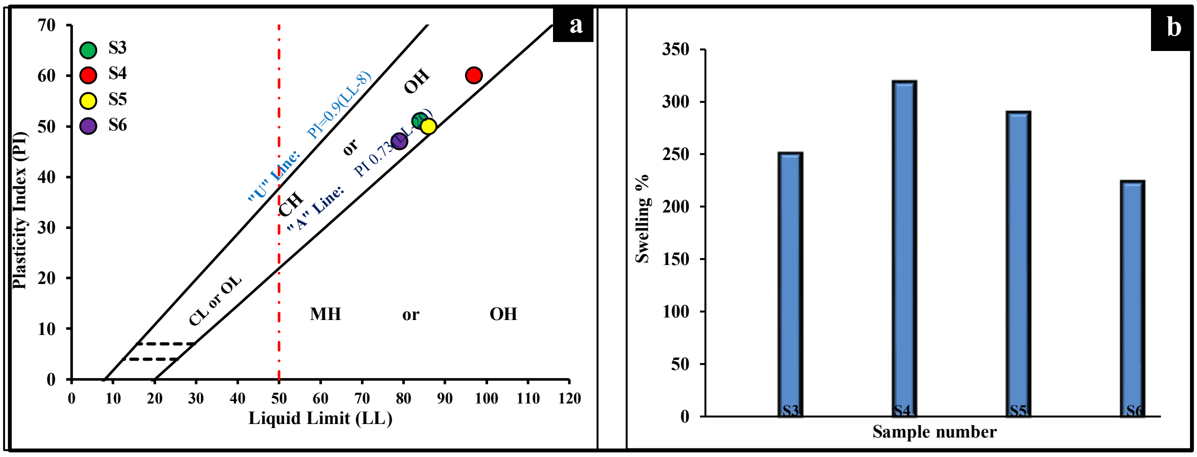

Fig 6: Swelling and plasticity properties of clayey samples:

a) Plasticity chart of clayey sample (no, 3-6).
b) Free swelling test chart of clayey sample (no, 3-6).

These values are exceptionally high, indicating a very high swelling potential. The consistency can be classified as hard based on unconfined compressive strength results exceeding 4 kg/cm² and its moisture content. The geotechnical properties of the compacted rocks forming the bedrocks of the desert hilly Saqqara model (A, QN, QM, QS, DN and DS) were assessed by comparing the engineering properties of the Mokattam Formation and the Maadi Formation limestones. The study focused on unit weight, unconfined compressive strength, abrasion, and absorption percentage to determine which formation exhibits superior quality. the results, summarized in (Table 2), show that the Mokattam

Formation generally outperforms the Maadi Formation in all assessed properties. The lower quality of the Maadi Formation may be due to the intercalation of shale within its limestone.

Table 2: Comparison between Mokattam Formation and Maadi Formation limestone.

Sp no,	Rock unit	U.weight	UCS	Abrasion%%	Absorption%
7	Mokkatam limestone	2.4	148.2	42.5	2.27
8	Mokkatam limestone	2.42	162.7	44.6	2.25
9	Maadi limestone	2.35	98.7	56.3	4.52
10	Maadi limestone	2.38	112.4	58	4.39

4.2 Environmental hazards impacts

4.2.1 Earthquake hazards

The seismic activities are concentrated to the south of the study area, which is more prone to earthquake hazards. The epicentral locations and magnitude of included earthquakes in the study area and surroundings have been presented by (Alrefaee and Abd el-aal, 2017). The distribution of earthquake magnitudes in the study area is shown in (Fig 7). The region between the middle Saqqara archaeological site (QM) and Memphis (M) is highly prone to earthquakes. Earthquakes can trigger landslides and ground instability by increasing shear stress and causing liquefaction. Soil texture, depth, and infiltration rate significantly affect earthquake impacts on structures. Groundwater-saturated sandy soil in the Nile floodplain may amplify shock waves and increases liquefaction intensity.

4.2.2 Groundwater rise and soil salinity.

Groundwater rises in the Nile floodplain, including cultivated lands, urban areas, and archaeological sites of Memphis (M) (Fig 7), causes a significant environmental damage. This rise negatively impacts soil, human health, and infrastructure, especially when groundwater is rich in sulfate and chloride salts. Floodplain soil is prone to waterlogging due to soil levels. Infrastructure like concrete foundations, bars, pipes, and submerged structures can be severely corroded and weakened by the high salt content. The study area faces threats from sandstorm erosion and sand encroachment, especially around the cultivated Nile floodplain and hilly archaeological sites. Thunderstorms cause these sandstorms by increasing wind speed over wide areas. These storms, often linked to rainstorms, raise the risk of flash floods and wind erosion in monumental sites. Sand accumulates on the foothills of pyramids and temple walls were observed (Fig 10a-b). Additionally, shifting sand buries and blocks roadways, while sand accumulation on cultivated land borders leads to increased soil erosion and decreased soil fertility.

4.2.3 Sandstorms and sand encroachment hazard

4.2.4 Flash flooding hazard and Paleo-drainage analysis

The analysis of the drainage systems in the study area and surroundings (Fig 8) shows that the dendritic drainage pattern is too large to have formed under current arid conditions. These systems likely developed during the wetter Pleistocene pluvial period. With the onset of aridity, many channels became dry and abundant. The dry wadis of these paleo-drainage systems created sub-basins that generally run from the western and eastern high plateaus into the Nile floodplain, with some running parallel to the Nile's main channel (Fig 8). Seven regional sub-basins (sub-basins 1-7, Fig 8) were identified, with only sub-basins 1, 4, and 5 contributing to the hilly archaeological sites. The water points delineated in Fig 8 are expected to receive maximum runoff during heavy rainstorms due to climatic changes. The most susceptible sites are linked to the main Paleo-channel of stream order 5 within sub-basin No. 5 (Fig 8). The hilly area south of the QM archaeological site and north and east of the QS site is likely to face hazards during heavy rainstorms. Additionally, the relatively impervious calcareous bedrocks in these areas may increase runoff risk, negatively impacting the Saqqara archaeological sites (QM and QS).

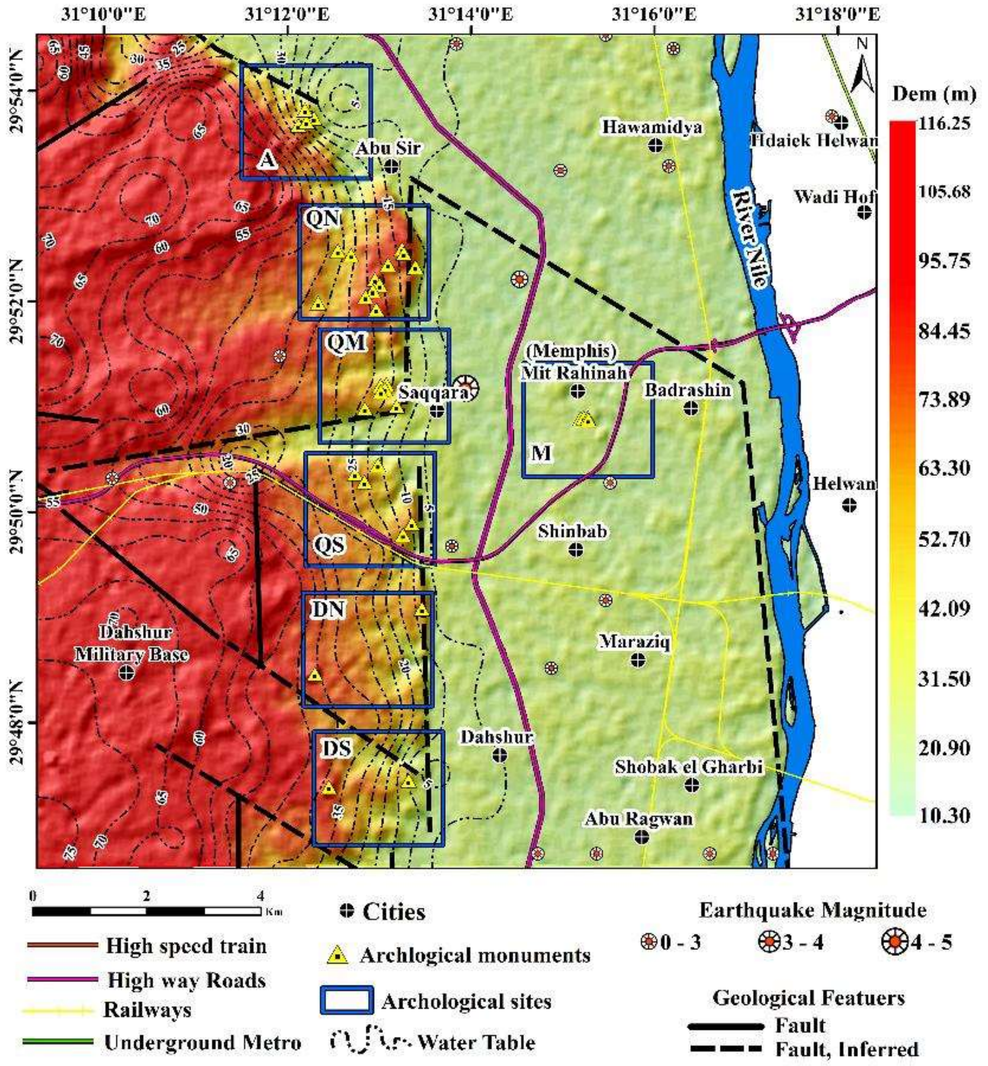

Fig 7: DEM image showing the distribution of water table and earthquake magnitude, (Earthquake magnitude After (Alrefaee and Abd el-aal, 2017)).

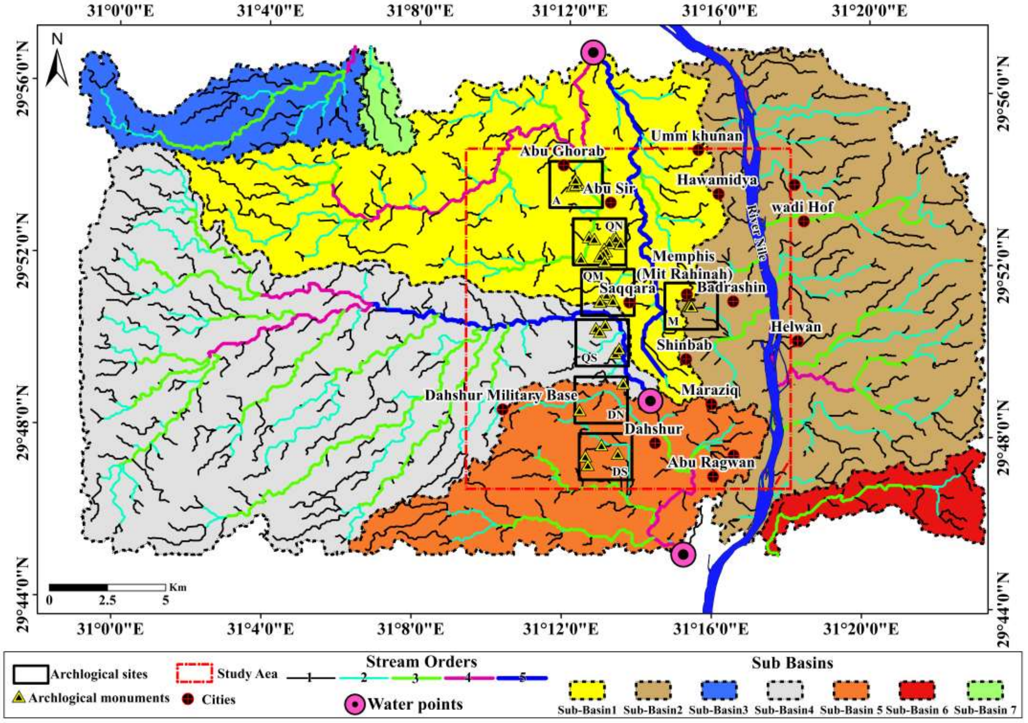

Fig 8: Drainage analysis and distribution of sub-basins, stream order and water points of the study area based on DEM and applications of Arc GIS.

4.2.5 Anthropogenic hazard in the Nile floodplain.

Anthropogenic activities in the Nile floodplain, including cultivation, urbanization, and scattered brick industries around the Memphis (M) archaeological site, have been documented over time. Change detection maps, using satellite images from 1985, 2003, and 2024, were created to monitor these activities and their impacts on archaeological and monumental sites (Fig 9). Change detection results

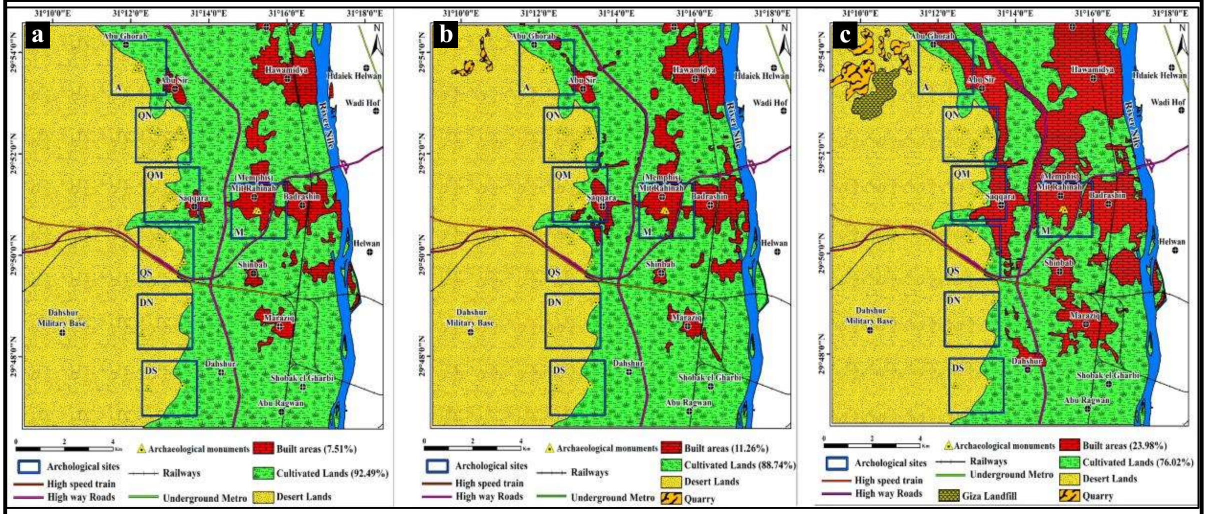

Fig 9: Change detection of the study area (Desert land% to Cultivated Lands%) from year 1985 to 2024.
a) Year 1985. b) Year 2003. c) Year 2024.

show a progressive loss of natural Nile floodplain cultivated lands. There was no significant increase in urban areas from 1985 to 2003, but urbanization grew progressively from 2003 to 2024 (Fig 9). Urban areas are mainly near main roads, irrigation canals, and riverbanks. Uncontrolled urbanization led to a dramatic drop in cultivated lands and the deterioration of the Memphis archaeological site. The area also faces threats from high population density and sewage leakage, causing salt weathering, subsidence, and damage to buildings and infrastructures.

4.3 Deterioration features of archaeological monuments

4.3.1 Chemical weathering forms

Chemical weathering features include salt efflorescence, karstification staining, and discoloration, with salt weathering being the most dominant. Notable examples include carbonate stones from temple walls in Memphis (M) (Fig 10c), Abu Sir pyramids, and tombs and ceilings in Saqqara. These sites exhibit varying degrees of salt efflorescence, resulting in different levels of damage and deterioration hazards (Fig 10d). Salt weathering requires moisture and salt from various sources, which causes expansion and dissolution of salt crystals on or near the monument surface, leading to deterioration and destruction (Fig 10e). Karstic surfaces in monuments form due to the acidity of rainwater and the composition and texture of carbonate bedrocks and building stones. Carbon dioxide in rainfall dissolves softer calcareous materials and allochems in rocks, affecting exposed parts like the Mit Rahina and Saqqara pyramids.

4.3.2 Physical weathering forms

The primary deterioration forms in carbonate bedrocks are cracking, exfoliation, erosion, abrasion, and structural instability. At sites like the Serapeum Tomb (QM), cracks and joints are frequent, sometimes filled with secondary materials that form darker, resistant deposits. Common deposits include calcite, halite, and gypsum, which accumulate along these cracks and joints and between the building stones (Fig 10f). Temperature variations, both daily and seasonally, along with indoor/outdoor differences, cause exfoliation in archaeological sites. Softer materials erode more than harder ones, resulting in uneven weathering that lead to structural instability, including collapse and missing blocks (Fig 10b).

4.4 Integrated causative and controlling factors.

The deterioration of archaeological and monumental sites is caused by various factors including climate, geology, environment, and land use. Earthquakes and heavy rainfall driven by climate change exacerbate these issues. Bedrock type, soil profile, distance from the epicenter, tectonic activities, soil properties, and groundwater level all influence the risk of soil liquefaction. Population pressure and human activities are driving groundwater rise, salt weathering, wind erosion, and earthquake impacts. Seepage from drained water and septic tanks accelerates salt weathering at Memphis (Mit Rahina) floodplain sites via capillary action. Traffic on roads and railways in urban and cultivated areas further destabilizes building foundations and deteriorates monumental materials. Tourism activities, temperature, and humidity variations impact the deterioration of monuments in the Saqqara cluster. Salt weathering needs moisture (e.g., atmosphere moisture and rainfall) and salt from various sources such as building materials, bedrocks, and subsoil salinity. In the study area, which is an arid region, irregular rainfall combined with high evaporation and humidity accelerates the weathering process. Evaporation of carbonate solutions can lead to karstified surfaces on monuments. In arid climates, wind erosion and abrasion cause deterioration.

The Western Desert, which includes the study area, is susceptible to climate change, affecting archaeological sites based on temperature, precipitation, wind patterns, and human intrusion as well.

Climate change may cause more cyclonic storms, resulting in intense rainfall and runoff through old drainage systems (Ducassou et al., 2009). Runoff levels are influenced by soil infiltration, which is determined by soil permeability and the exposure of carbonate-shale bedrocks. Sand sheets near monumental sites could naturally reduce the risk of flash floods.

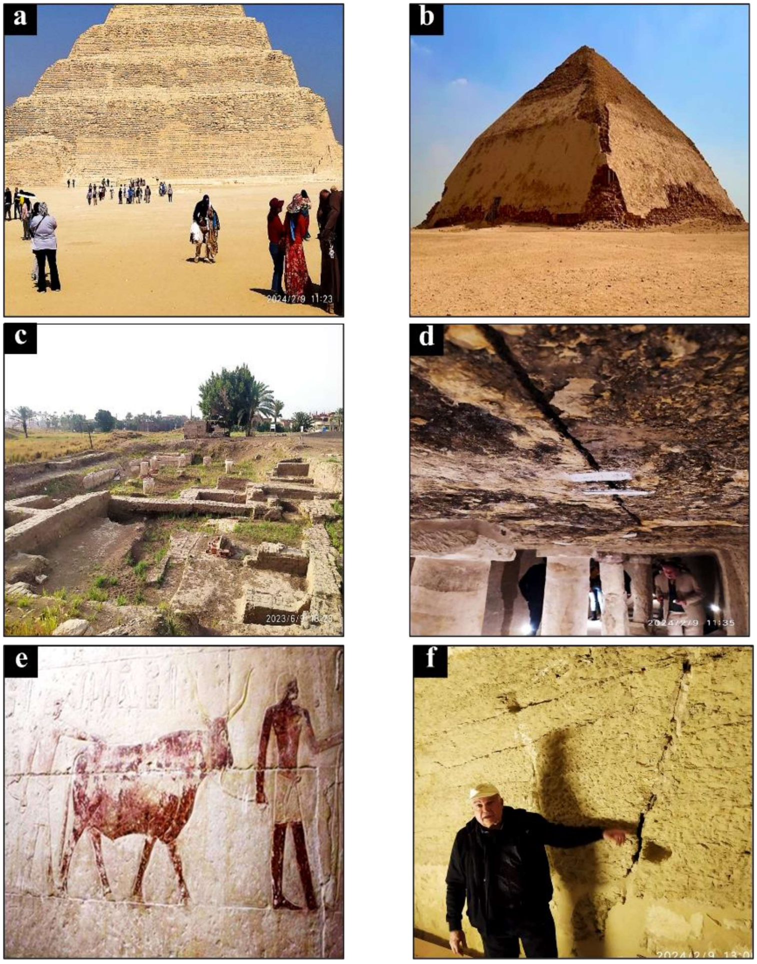

Fig 10: Archaeological and monumental sites, and deterioration phenomenon.

a) The step pyramid of Djoser (QN), with Burial chamber lies at the bottom of the shaft in the center at a depth of 28m.
b) The Bent pyramid in Dahshur (DS), unusual form, which changes angel halfway up, reflecting evolution of construction.
c) The remains of the temple of the goddess Hathor are buried under the silt layers of the Nile and prone to groundwater rise in Mit Rahina(M).
d) Cracks in the ceiling of the inner corridor of the step pyramid of king Djoser (QM).
e) Deterioration of colors and drawings in one of the rooms of Kagemni tomb (QS).
f) Cracks affecting the upper Mokattam bedrocks inside the Serapeum tomb (Qm).

4.5 Geo-environmental risk assessment model

The assessment of risk to archaeological sites and monumental materials is intricate due to various deterioration factors. For the Memphis and Saqqara morpho-archaeological models, risk categories were established by evaluating five groups of parameters (Table 3). This evaluation involved twenty parameters derived from both natural and anthropogenic influences (Table 3). The spatial distribution and integrated evaluation of parameters across various archaeological sites (A, QN, QM, QS, DN, DS, and M) associated with the Saqqara and Memphis models led to the creation of semi-quantitative geological, geotechnical, and environmental risk assessment levels. This assessment model is designed to be flexible, enabling modifications to the risk evaluations as the archaeological sites evolve and their unique characteristics are considered. The risk level increases for monumental elements situated in lower topographic positions due to elevation differences between the Nile terraces (hills) and the Nile floodplain morpho-archeological models. The Memphis (M) monuments are considered to be at the highest risk compared to the Saqqara monuments, which positioned at higher elevations and thus less affected by groundwater rise. This risk evaluation is based on geotechnical properties, including structural discontinuities and the calcareous and swelled clay contents in the bedrock types. The risk level is highest in rocks with shale intercalation and high fractures. Nile silt with swelled clays and high plasticity also imply a high-risk level. In clastic rocks, the risk increases with higher clay and silt content. Risk evaluation takes in consideration the spatial distribution and magnitude of environmental hazards and their negative impacts. For example, liquefaction and groundwater rise in the Nile floodplain increase risk levels for the Memphis monuments. Risk for land use and human activities is based on the spatial contributions of cultivated land, built-up areas, and tourism activities, along with their potential negative impacts. The risk level evaluation of monumental deterioration parameters considers the intensity and percentage of salt weathering, karstification, wind erosion, and exfoliation features. The semi-quantitative risk level is numerically defined from 0 to 10. These values are categorized as low, medium, high, and very high-risk levels (Table 3). The geo-environmental risk assessment (Table 3) shows significant differences between the Saqqara model and Memphis model. The Memphis model is classified as high to very high risk, while the Saqqara model is classified as medium to very low risk. The Saqqara model can be divided into medium to high-risk zone including the middle archaeological site (QM), low to medium-risk zones include Abu-Sir (A), Dahshur South (DS), and Saqqara South (QS) and very low to low-risk zones include Dahshur North (DN) and Saqqara north (QN).

Table 3: Assessment of the risk level for the Saqqara and Memphis morpho-archaeological models.

Risk Parameters			Saqqara model *						Memphis model **
			Abu-Sir	Saqqara			Dahshur		Mit-Rahinah
			A	QN	QM	QS	DN	DS	M
Geomorphological parameters	1	Nile terraces (hills)	4	4	5	5	4	4	-
	2	Nile floodplain	-	-	-	-	-	-	9
Geological & Geotechnical Parameters	3	Low Mokattam Fm	-	-	-	-	-	2	-
	4	Upper Mokattam Fm	-	5	4	1	-	-	-
	5	Maadi Fm	2	-	-	-	-	-	-
	6	Qaser el-Sagha Fm	-	-	-		2		-
	7	Kom el-Shelul	-	-	-	1	1	3	-
	8	Pre-Nile Sediments	2	-	-	2	2	1	-
	9	Wadi deposits	-	-	2	-	-	-	-
	10	Nile Silt	2	1	3	1	1	2	9
Environmental hazards parameters	11	Earthquake	4	2	8	3	2	4	9
	12	Ground water rise	-	-	-	-	-	-	9
	13	Sandstorm	5	4	8	6	4	5	3
	14	Flash flood	-	-	7	-	-	-	-
Land use parameters	15	Agriculture	2	1	3	1	1	2	9
	16	Built-up	-	-	-	-	-	-	9
	17	Tourism	4	4	8	4	4	4	2
	18	Roads & traffic means	1	-	3	1	1	1	6
Deterioration parameters	19	Chemical weathering	2	2	4	2	2	2	9
	20	Non-Chemical weathering	5	4	8	6	4	5	6
Average of risk level			3	3	5	3	2	3	8

* Medium-Risk category

** High-Risk category

Risk Categories	0-2	3-5	6-8	9-10
	Low	Medium	High	Very High

4.6 Integrated management procedures

To reduce vulnerability to geohazards, human intervention, and deterioration processes, and to protect archaeological and monumental sites, integrated mitigation measures should be followed based on geo- environmental risk analysis (Table 3). New urban areas and infrastructure should not be constructed in earthquake-prone areas and existing settlements in the Nile floodplain around the Memphis site should be protected with suitable materials and engineering designs. Existing buildings should include safety cut-off valves and reinforced tanks for gas, petrol, and water vessels to mitigate the impact of earthquakes. A sensitive monitoring system should be established to track deformation in buildings, monumental sites, and groundwater fluctuations. Accurate de-watering calculations can prevent ground subsidence of ground underneath buildings and archaeological sites. To minimize groundwater fluctuations, accurate de-watering calculations can prevent ground subsidence of ground underneath buildings and archaeological sites. To mitigate wind erosion and sand accumulation around roads and archaeological sites, it is recommended to create green belts using treated sewage water around these areas and outside the Saqqara hills. To preserve archaeological sites and keep them for as long as they were for thousands of years, three zonation levels are proposed based on risk levels (Table 3). The first zone is the inner core, containing monumental elements, where any activities that cause vibration or leaching are prohibited. The second zone is the middle buffer zone within the site's boundaries (Fig 1), where touristic activities should be restricted, especially around the Memphis site in the Nile floodplain. To manage risks caused by anthropogenic activities, the third zone is the outer buffer zone, extending about half a kilometer from the archaeological site boundary. Risk analysis in this zone is crucial for preventing negative impacts and ensuring proper procedures and monitoring. Human activities in this zone should be authorized and supervised by qualified professionals. The deterioration features of the sites should be regularly evaluated and documented to implement effective mitigation measures. These measures include regulating visitor numbers, pathways, and the timing and frequency of visits to minimize dust, humidity, and gas emissions within all buffer zones.

Conclusion and Recommendations

Currently and throughout millennia, the magnificent ancient Egyptian monuments have continually faced damage and deterioration. Saqqara-Memphis complex has experienced continuous damage due to environmental conditions and the inherent properties of construction materials. Urban expansion near agricultural areas has increased risks. To assess these risks, a regional geomorphological survey recommends using morpho-archaeological models: Flood Plain Memphis and Hilly Desert Saqqara. The morpho-archaeological models for Egyptian historical sites along the western Nile Bank help evaluate environmental impacts. Each model has unique geological and geotechnical characteristics that influence its risk levels. Natural and human-induced hazards, such as weathering, sandstorm erosion, and liquefaction, damage the monuments, with salt weathering being the most severe, particularly at Memphis model. A geo-environmental risk assessment is crucial for developing a preservation plan to safeguard these sites from further damage. The proposed management plan should incorporate a public awareness program to foster effective cooperation among governorates, local and central authorities, visitors, and citizens. Additionally, the recommended environmental management plan is essential for protecting both the monuments and archaeological areas from damage.

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