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Assessing the impact of Nile water level fluctuations on the structural stability of the Philae temples in Aswan, Egypt

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ABSTRACT

The ancient Egyptian temples at the Philae UNESCO World Heritage Site in Aswan face conservation challenges due to fluctuating water levels, which threaten their building material resistance. Following a summary review of the hydrological changes to the natural responses of the Nile caused by the construction of the Aswan dam, our research employs a novel approach, combining remote sensing data analysis, literature review, fieldwork, and multiple high-specification materials analyses, to assess the impact of these changes on the temples in Philae. The new data permit the identification of the most at-risk areas and inform the long-term monitoring and conservation of Philae. Our approach enhances understanding of the causes and effects of building material decay and underscores the urgent need for conservation strategies to mitigate ongoing water-induced deterioration. The research highlights the impact of human-induced hydrological changes, offering a case study that informs future climate change effects. It is clear that tough decisions will be required for the long term heritage conservation of the Philae temples in the face of modern infrastructural developments and climate change, and that cultural heritage management guidelines before and after dam construction is urgently required. The issues identified, are not unique to the Philae Temples so the results and recommendations are relevant to other World Heritage sites that are currently facing similar environmental and conservation challenges.

1. Introduction

The Philae area is a notable archaeological site with its most ancient structures dating to the reigns of Nectanebo I (370 BCE) and Nectanebo II (359 BCE). The majority of temples in this area were built from the 25th Dynasty. The site's significance derives from its sacred role as the preeminent cultic centre dedicated to the deities Isis and Osiris, leading to its initial UNESCO listing (1960) with further justification of the site's importance being developed by Kamel et al. (2020). The construction of the Aswan Dam in 1898, situated north of the archaeological site, resulted in the submergence of Philae Island and its monuments for nine months each year. In an effort to mitigate flooding hazards and for electricity production, the Egyptian government constructed another dam, the High Dam, in 1954, south of the Philae site (Tamborrino and Wendrich, 2017; De Keersmaecker, 2004). However, this new dam worsened the site's state of preservation since the temples remained in a state of permanent submersion and were subjected to daily fluctuations in water levels (UNESCO, 1960).

In response to the heightened threat to the long-term condition of the temples, in 1960 UNESCO initiated an international campaign to safeguard them from flooding. Over 50 countries contributed technical studies to determine the best preservation methods for each temple. The international collaboration on Philae's conservation underscores its global significance. Following comprehensive engineering, geological,

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and hydrological assessments, relocating the temples from Philae Island to Agilkia Island was deemed the best solution (Lemaitre, 2005; Aberta, 2019). Regrettably, the Osiris Temple, also known as the Abaton Temple in Bigeh Island, was not included in this extensive salvage operation. This temple remains submerged at its original location on Bigeh Island, near the original site of Philae Island. The continual fluctuations in the Nile's water levels have ongoing adverse effects on the Osiris Temple's structural stability and the existing graffiti, with its lower parts permanently underwater (Lacoste, 1961, Fahmy et al., 2025).

The effects on the Osiris Temple offer an interesting comparison to those Temples that were moved, though it is important to note that even the relocated Temples have been affected by continuing water level changes (UNESCO, 1960). The fluctuating water levels in the area have significantly impacted not only the Osiris Temple in Bigeh but also the enclosure walls of the temples in the Philae region. This ongoing issue necessitates a comprehensive study to evaluate the current state of these ancient structures and their preservation status.

In this context, the current research utilizes a novel mixed-method approach to monitor and assess the impact of water levels on the temples' building material durability in the Philae area. Satellite and aerial imaging, combined with temporal mapping, have been employed to track changes in water levels over time and their direct effects on the temples. These methods provide baseline data for specific time periods, allowing the identification of the most at-risk areas and develop

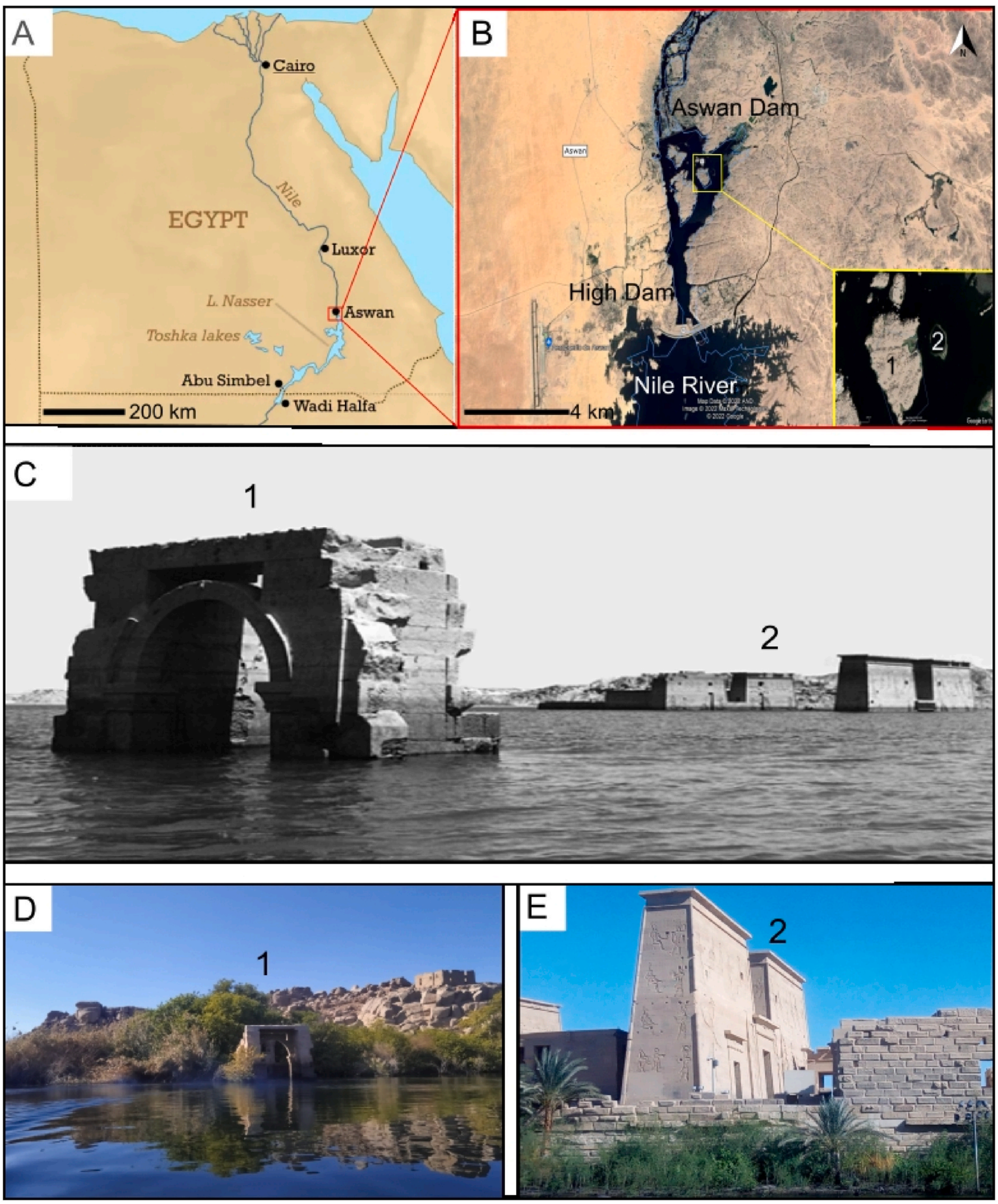

Fig. 1. (A) Map of Egypt and Aswan city highlighted with red square. (B) Google Earth map showing the Aswan city and study area. (1) Osiris Temple, Bigeh Island and (2) Isis Temple, Old location of Philae complex (Philae archaeological sites study area). (C) The previous impact of Nile water levels in 1960. From: https://en.unesco.org/mediabank/17130/(D and E) Current impact of Nile water levels on Osiris and Isis Temples. In E, (2) refers to Isis Temple on its current location on Agilkia island after the UNESCO rescue project. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

strategies to mitigate further damage. In addition to remote sensing methods, the research also focuses on the durability issues of the construction materials used in the temples. A series of tests, including surface roughness, uniaxial compressive strength, gloss, and colour measurements, have been conducted to evaluate the materials' physical properties and their deterioration over time. Microscopic examination has been carried out to understand the decay mechanisms of the sandstone used in the temples, under both saturated and unsaturated conditions. This examination is important for identifying how water exposure contributes to the degradation of sandstone, providing information about the decay challenges faced by these ancient Egyptian monuments.

2. Geographical and archaeological context

Philae is an island situated in the Nile River near Aswan, Egypt (Fig. 1A–E). It lies close to the significant geographical landmarks of the expansive Aswan Low Dam and the Old Aswan Dam, both important for the region's water management and irrigation systems. The island is located just downstream of the First Cataract of the Nile, a series of shallow rapids and rocky outcrops that historically marked the traditional boundary between Upper Egypt and Nubia (Drioton, 1960; Taher, 1963). In addition, Philae is recognized as a UNESCO World Heritage Site and remains a popular tourist destination. Efforts continue to preserve its historical and cultural significance through ongoing conservation projects. Access to Philae is typically by boat, and the site is one of Egypt's most evocative and visually stunning archaeological locations (Kockelmann, 2012; Ruggles and Cotte, 2010).

The island is positioned at approximately 24.0285° N latitude and 32.8832° E longitude (Fig. 1A and B). The desert climate is characterized by extremely hot summers, mild winters, and very low annual rainfall. The surrounding landscape includes rocky outcrops, sandy plains, and the lush, fertile banks of the Nile River. The small, rocky nature of Philae contributed to its selection for temple construction due to its isolation and defensibility (Fig. 1A). Archaeologically, Philae is renowned for its well-preserved temples and structures, primarily from the Ptolemaic and Roman periods. The most significant of these is the Temple of Isis, notable as the last operational pagan temple in the Mediterranean world. Philae was a major religious center dedicated to the goddess Isis, revered as the mother of Horus and the wife of Osiris. The island's temples remained an important pilgrimage site, attracting worshippers even after the advent of Christianity (Lyons, 1896). This transition is evident in the remains of Coptic churches found on the island, indicating the site's continued religious significance through time. The island's main structures include the Osiris Temple, the Temple of Isis, the Kiosk of Trajan, and various other chapels and shrines. These structures provide a glimpse of the religious practices and architectural prowess of ancient Egypt (Kockelmann, 2012). Excavations at Philae have uncovered numerous artifacts, including statues, inscriptions, and smaller temples dedicated to various deities. The rich history of the site spans several millennia, from the Pharaonic through the Ptolemaic, Roman, and into the early Christian periods (Lyons, 1896).

3. Materials and methods

3.1. On site observation

Qualitative field observations were conducted to monitor water level fluctuations of the Nile around the Philae temples, focusing on understanding their impact on the site's preservation. A comprehensive photographic archive was created, documenting the current state of the temples, including their structural fabric, material conditions, and visible decay patterns. Subjects of documentation included watermarks on the temple walls, areas of erosion, salt crystallization, biofilm development, and other weathering phenomena caused by prolonged exposure to fluctuating water levels.

3.2. Water level change detection

Local water fluctuations in the study area between 2018 and 2021 were assessed using Google Earth imagery (Fig. 2) and comparisons between 1968 and 2022 (Fig. 3), satellite data images were generated from CORONOA satellite data (1105-2235Fore mission1968) and compared to Google Earth (GE) imagery. In addition, high-resolution satellite images from Google Earth Pro were selected for the years 2017, 2018, 2019, and 2020 to ensure temporal comparability and visibility of hydrological features and shoreline boundaries (Fig. 4). Although Google Earth imagery is pre-georeferenced, fixed anthropogenic structures such as temple foundations served as visual control points to confirm spatial consistency across time steps. Shorelines and vegetation boundaries were manually digitized in ArcMap 10.7 for generating change detection maps temporally by tracing the edge of visible water bodies and vegetation coverage on each GE image and each vector layer was stored in shapefile format, allowing overlay and comparison. Two water infiltration maps presented in Fig. 5 (B) were generated in QGIS. This modification highlighted the spatial extent and impact of water infiltration on the foundations and structural elements of the temples, allowing clearer visualization of the areas most affected by moisture encroachment.

Google Earth (GE) imagery proved valuable in this study due to its accessible, time-stamped historical archive, which enabled the detection of shoreline shifts and water fluctuations over time. GE data was not used in isolation. Field surveys and ground-truthing were conducted to validate image interpretations. The spatial resolution in this region was sufficient to identify key structural and hydrological features, especially in areas with restricted access or submerged remains. Lastly, given the logistical challenges and absence of continuous monitoring infrastructure, GE provided a practical and scientifically justified tool for establishing a baseline, while future studies may benefit from complementary high-resolution commercial imagery for long-term monitoring.

3.3. Building material sample selection

In order to characterize and evaluate the material properties and the extent of weathering impacts on the ancient building stones from the Philae temples, a comprehensive suite of analyses was conducted on highly weathered, both unsaturated and saturated, sandstone samples. The methods used are outlined below. Representative samples of highly weathered authentic building materials used in Philae were collected. These varied in size from 10 to 20 cm^3. Each sample was cut into three cubic specimens, each measuring 3 cm × 3 cm × 3 cm for testing and measurements needs.

3.4. Sandstone weathering assessment

A binocular microscope (USB digital microscope with stand), with magnification between 20 and 400 ×, and equipped with a digital camera of 1.3 Mpx was used to survey the morphological characteristics of the samples and to detect different kinds of degradation aspects. Following microscopical analysis, samples underwent a series of additional examinations, including roughness tests to assess surface texture, gloss to measure surface reflectance, and colorimetry to determine color properties and changes due to weathering.

The assessment of the temple building's surface conditions involved utilizing a digital microscope (DM) to detect minute surface details, thereby enabling a comprehensive understanding of the material's integrity. Complementing this, a glossmeter equipped with a Rhopoint detector (Novo-Gloss 60 Glossmeter) was employed to quantify the gloss or shininess of the building materials. This device operates on a scientific principle that involves recording the intensity of specularly reflected light at a precise angle of 60°, thus serving as a non-destructive technique (NDT) for evaluating surface conditions. The glossymeter's measurements are crucial as variations in gloss levels can reveal significant

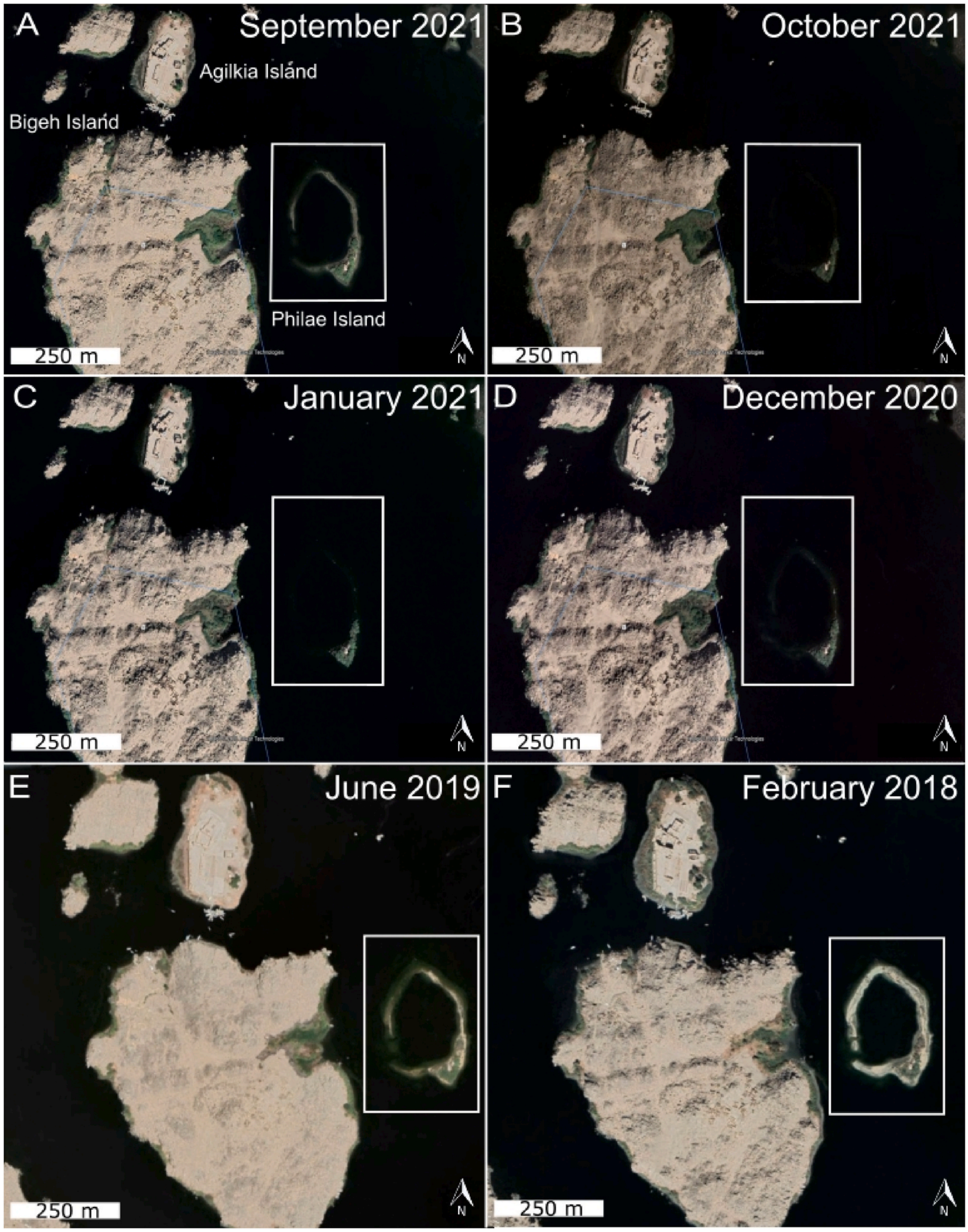

Fig. 2. (A, E and F) Google earth maps images that show the lowering of water level, as we can see the island boundary of Philae. (B, C, and D) Google earth images that show the rising of water levels.

changes in the material's surface, indicating potential degradation processes such as weathering, chemical reactions, biological growth, environmental impacts, and physical damage (Lisci et al., 2023; Borsoi et al., 2015). To capture these variations accurately, gloss measurements were systematically conducted at multiple points across both saturated and unsaturated samples of the construction materials. This approach ensures a thorough assessment of the surface conditions, contributing to the preservation and maintenance strategies for the temple's structural stability.

Analyzing chromatic and color variations in saturated and unsaturated sandstone is valuable in order to understand the weatherability process and environmental impact on the stone surfaces over the time (Sitzia et al., 2021). Spectral analysis was carried out using a portable spectrophotometer (**CM2600d, Konica Minolta**) on the collected samples of the saturated and unsaturated sandstone. The analysis was conducted on various representative spots on the stone surfaces to ensure spatial variability and heterogeneity. The spectral analysis is based on the interaction of light subjection on the selected spot. While some rays are specularly reflected, other scattered rays can be diffused, a phenomenon known as diffused reflectance. Both specular and diffuse reflectance is called total reflectance. SCI (total reflectance) methods were used and the readings were recorded utilizing it. Calculations of colorimetric parameters of Lab* were performed. In addition, chroma (color saturation and intensity) and hue values were calculated as well to quantify the changes in color appearance due to decay, weathering and alterations. Moreover, various color patches were obtained to show

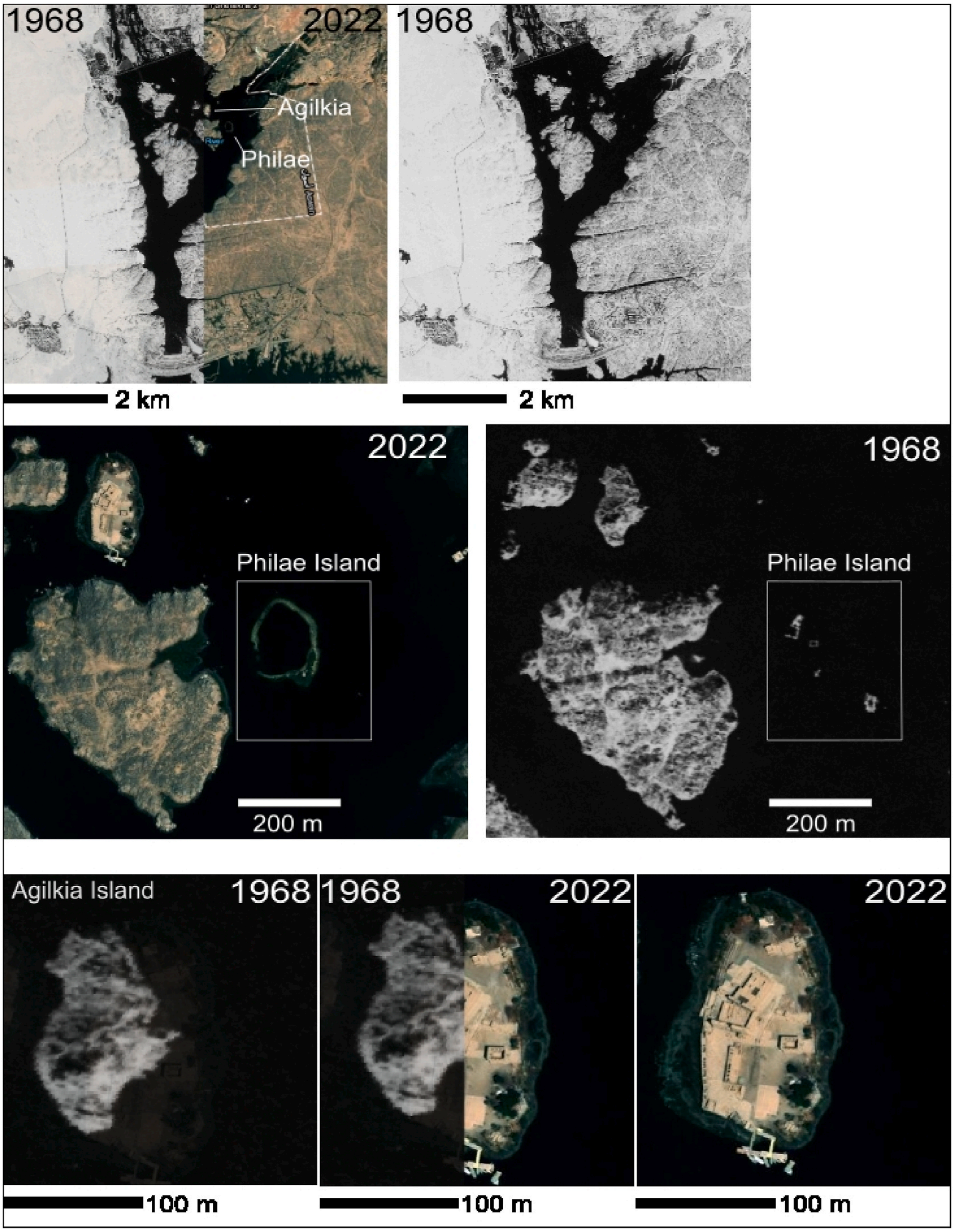

Fig. 3. Satellite images from 1968 (CORONA) and 2022 (Google Earth) showing water level changes and the relocation of the Philae temples from the submerged Philae Island to Agilkia Island.

the appearance of each color change in the color according to SCI method.

The roughness test is recognized as an NDT too and plays an important role in assessing the surface condition of archaeological construction materials (Vázquez and Alonso, 2015). This method is particularly valuable for evaluating the degradation state of stone surfaces, as variations in roughness characteristics can indicate weathering effects over time. Using a Perthometer M4P hosted by Rathgen research laboratory, Berlin, the test was performed on multiple points of both saturated and unsaturated sandstone samples collected from the Philae Temples. Each measurement was taken over a precise area of 1.5 mm^2, providing detailed insights into the surface texture. The primary goal of the test was to quantify specific parameters that describe the spatial distribution of peaks and valleys on the sandstone surfaces. These parameters included Arithmetic Mean Roughness (RA), Mean Roughness Depth (RZ), Maximum Height (Rmax), and Mean Peak Height (Rpm). The analysis of these roughness parameters allowed for a comprehensive assessment of the surface texture of the sandstone samples, highlighting the differences between saturated and unsaturated conditions and providing valuable information on the weathering and degradation processes affecting the building materials of the Philae Temples.

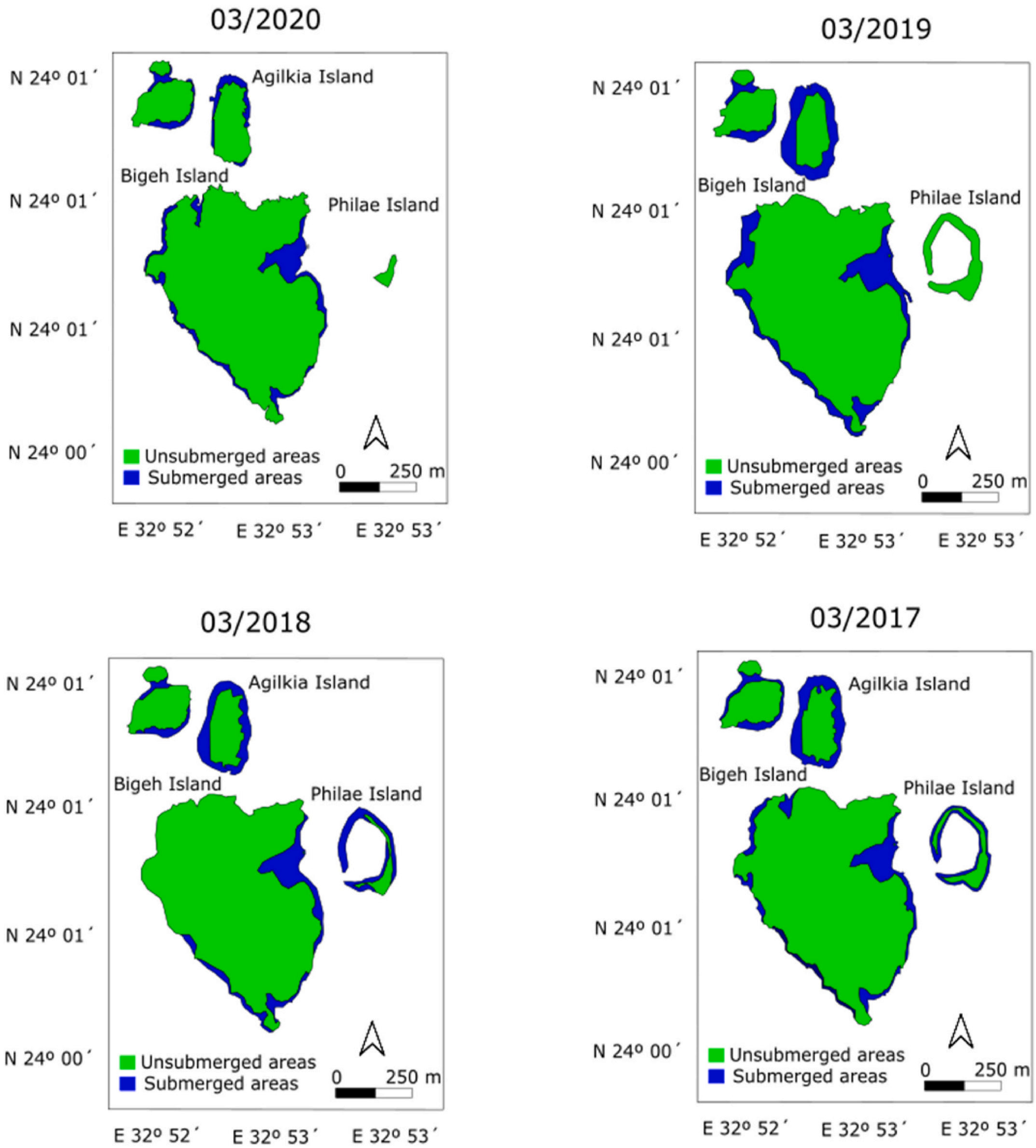

Fig. 4. Temporal analysis of water fluctuations in the Philae area between 2017 and 2020.

3.5. Uniaxial compressive strength (USC)

Mechanical strength was evaluated using a uniaxial compressive strength machine at the Faculty of Mechanical Engineering and Ship Technology (Gdansk University of Technology, Poland). The static compressive test was performed on testing machine INSTRON 8503 (500 kN) at a temperature of 20 °C.

4. Results and discussion

4.1. Hydrological context and problems with the Aswan Dams

It is well established that there have been significant fluctuations in the levels of the Nile throughout the Holocene, influenced by climatic changes, tectonic activity and other environmental factors (Krom et al., 2002; Stanley and Warne, 2003; Hassan, 2007; Peeters et al., 2024). The Old Aswan Dam, completed in 1902 by the British, was a pioneering effort to regulate such fluctuations, primarily to mitigate flooding and ensure more consistent water supply for irrigation. However, there was lack of long term and scientific records. One of the major physical changes was that the river upstream of the dam was transformed from a river to create Lake Nasser which is nearly 500 km long and 10 km wide. Despite being a significant engineering feat, the dam's capacity to manage the Nile's flow was limited (Cookson-Hills, 2013). This limitation prompted the construction of the High Aswan Dam upstream. This Dam was completed in 1970 and it is amongst the largest and most impactful dams in the world (Benedick, 1979). The High Dam not only enhanced flood control and enabled substantial hydroelectric power generation but also significantly increased the storage capacity of Lake Nasser, ensuring a more reliable water supply for agriculture and domestic use throughout Egypt. This strategic management of water resources has been crucial for sustaining Egypt's population and economy amidst fluctuating water levels and regional climate challenges (Strzepek et al., 2008).

Both the Old Aswan Dam and the High Aswan Dam, have experienced water infiltration and seepage. Water infiltration through or under the dam can lead to the rise of groundwater levels in the surrounding area. This rise in groundwater can affect the stability of the soil and the foundations of nearby temples and structures as well, potentially causing structural damage or destabilization. The High Aswan Dam and

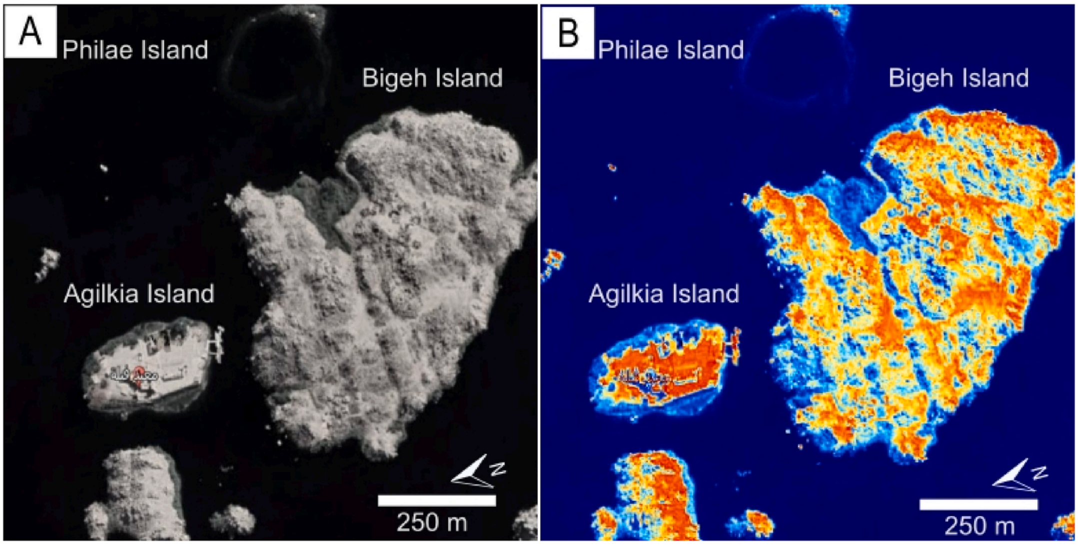

Fig. 5. (A) Grey scale aerial photography for the case study. (B) Modified aerial image in order to demonstrate the infiltration impact of the foundations and structures of the temples in the Philae archaeological site.

associated lake, despite its modern construction, also has seepage problems (Metwaly et al., 2006). Seepage can lead to the gradual weakening of the dam's foundation and surrounding soil. Such subsidence, can affect the stability of the land around the dam, including the areas where ancient temples and archaeological sites are located.

The construction of the High Dam has altered the natural hydrology of the Nile River. The regulation of water flow and sediment transport has impacted the water table in the vicinity of the dam (Moussa, 2013). Changes in water levels and sedimentation can indirectly affect the surrounding temples by altering groundwater dynamics and potentially causing erosion or destabilization of temple foundations (Elba et al., 2017). Altered water levels and hydrology can also impact the surrounding environment, affecting the vegetation that helps stabilize the soil around temples and archaeological sites. This can lead to increased erosion and degradation of the temple complexes both biologically and mechanically. In addition, water infiltration and changes in groundwater levels can lead to structural damage to the ancient temples near both dams. This includes cracks in walls, foundations, and columns, compromising the durability of these historical structures.

While the Aswan Dams have brought significant benefits in terms of flood control, irrigation, and electricity generation (Monsef et al., 2015), issues of water infiltration and changes have impacted the stability and conservation of surrounding temples and archaeological sites. Today the Philae area experiences notable fluctuations in water level, ranging from 152 to 182 m above sea level, as reported by Moustafa and Moussa (2013). These fluctuations are closely tied to the annual cycles of the Nile River's discharge into Egypt. The discharge cycle typically exhibits two distinct phases 1) a rising stage starting from the end of July, peaking around mid-September, and 2) a falling stage from October through June (Abdel-Aziz, 2005). During years of high flooding, such as between 2003 and 2010, substantial changes in the riverbed's elevation were observed with increases reported from 1.5 to 3.5 m (Abdel-Aziz, 2005). These alterations directly impact the water flow dynamics and sediment transport across the riverbed.

Philae Island serves as an important marker for understanding these water level fluctuations. Even over relatively short timespans, the boundaries of the island have shifted noticeably in response to varying water levels. For instance, in February 2018, June 2019 and September 2021, lower water levels revealed distinct island boundaries, whereas in January and October 2021, higher water levels submerged these boundaries. Fig. 2(A–F) illustrates these dynamic water level changes, Philae Island's vulnerability to the Nile's annual flood cycles, and their impact its environmental stability and monuments. The Nile River's discharge phases, are important factors influencing the region's landscape and ecosystem.

Longer term comparisons of the Philae region were achieved using satellite-based analysis of historical CORONA imagery from 1968 and modern Google Earth (GE) imagery from 2022. The submergence of original Philae Island due to the construction of the Aswan High Dam and the formation of Lake Nasser can be seen in Fig. 3 (upper panel). In addition, the displacement of monuments from the now-flooded Philae Island to Agilkia Island, which remains above water as evidenced in the 2022 image Fig. 3 (middle panel). In the 1968 CORONA images, structures on Philae Island are visibly submerged or barely discernible, whereas in the 2022 images, Agilkia Island is clearly developed and hosts relocated monuments Fig. 3 (middle panel). Zooming in on Agilkia Island, the dramatic transformation from a largely empty island (full submersion) in 1968 to a fully developed archaeological site in 2022 is clear. This contrast is already apparent after the completions of UNESCO's 1980 Nubia Campaign Fig. 3 (bottom panel). These satellite imagery comparisons demonstrated the success of UNESCO's Nubia Campaign. They provide valuable data for tracking hydrological impacts, land use change, and long-term heritage site preservation in relation to full submersion risks, especially after 1980.Even now, water partially affects the upper levels of monument walls, with some structures remaining semi-submerged.

4.2. Sedimentation and erosion analysis

The accumulation of sediments in and around the Philae Temples in Aswan, especially on Agilkia Island, (where they were relocated due to the construction of the Aswan High Dam) has been a major concern for conservationists and researchers. The construction of the Aswan High Dam in the 1960s resulted in clear changes to the flow regime of the Nile River. The regulation of water flow and sediment transport downstream of the dam altered natural sedimentation patterns around Agilkia Island and the Philae Temples affecting the temple structures' stability and conservation (Benedick, 1979). Fine sediment deposition in the vicinity of the temples, can cause increased water turbidity and contaminants (Sharaky et al., 2016) and impacts submerged parts of the buildings e.g. the underwater part of Osiris Temple (Bigeh Island) (Fahmy et al., 2022b).

Between 1825 and 1902, the estimated suspended sediment load upstream of the Low Aswan Dam was about 200 million tons annually.

However, between 1902 and 1963, this load decreased by approximately 20 %, reducing it to 160 million tons per year. This reduction was due to changes in land use, water management practices, and the construction of additional water control structures (Banna and Frihy, 2009). After 1963, both the average water discharge and the suspended sediment load upstream of the Low Aswan Dam further decreased. Since the dam's construction, the water released downstream has averaged 55.5 billion cubic meters per year, roughly 35 % less than the discharge levels before the dam was built (Frihy and Lawrence, 2004). The dam's regulation of water flow and sediment transport likely influences sedimentation conditions at the site of the Philae Temples (Fahmy et al., 2022b). A direct impact of the dam on sedimentation patterns at the Philae Temples site could be observed, indicating that the dam plays an important role in shaping the sedimentation dynamics in this region (Biswas and Tortajada, 2011).

4.3. Temporal analysis of water levels variations and its impact on the temples

Satellite images were collected and analyzed for four years from 2017 to 2020. Fig. 4 shows four maps of the same region, each illustrating different features or changes over time. In 2017 and 2018, the water levels were low, in 2019 the water levels were very low but in 2020, the water levels recorded were high. The variations in water levels, as observed in the satellite images from 2017 to 2020 (Fig. 4), potentially have significant geochemical and mechanical impacts on temples, especially on their walls and foundations. The 2020 water level increase would have exerted hydrostatic pressure on the temple foundations, affecting the stability of the foundations, and potentially leading to erosion or weakening of the soil beneath the structures through water infiltration (Fig. 5 A and **B**). In addition, fluctuations in sediment load can indirectly influence dissolved oxygen levels in the water. This in turn indirectly affects geochemical conditions, and potentially pH, particularly when accompanied by temperature changes.

Understanding these impacts is important for developing preservation strategies in the face of changing environmental conditions. The temples were built from porous materials which, when saturated, makes the buildings susceptible to structural issues. Previous research exploring the potential impact of changes in water table levels and soil moisture on building structures highlighted how such changes can induce differential movement and structural damage (Toll et al., 2012). It also demonstrated how moisture movement through capillary action (capillary rise) can deteriorate structures made from monumental sandstone. This deterioration occurs through two main processes 1) the dissolution of cementing minerals, which reduces the stone's strength, and 2) the recrystallisation of dissolved salts, which can lead to the expansion of the stone, thereby causing further damage through spalling of the surface (Torraca, 1981). Conversely, during periods of low water levels (2017 and 2019), the soil around the foundation may dry out and shrink. This can cause settlement or subsidence, affecting the even distribution of weight on the foundation and potentially leading to cracks or structural damage.

Other issues caused by high water tables, include moisture seeping into the walls resulting in dampness and promoting the growth of molds

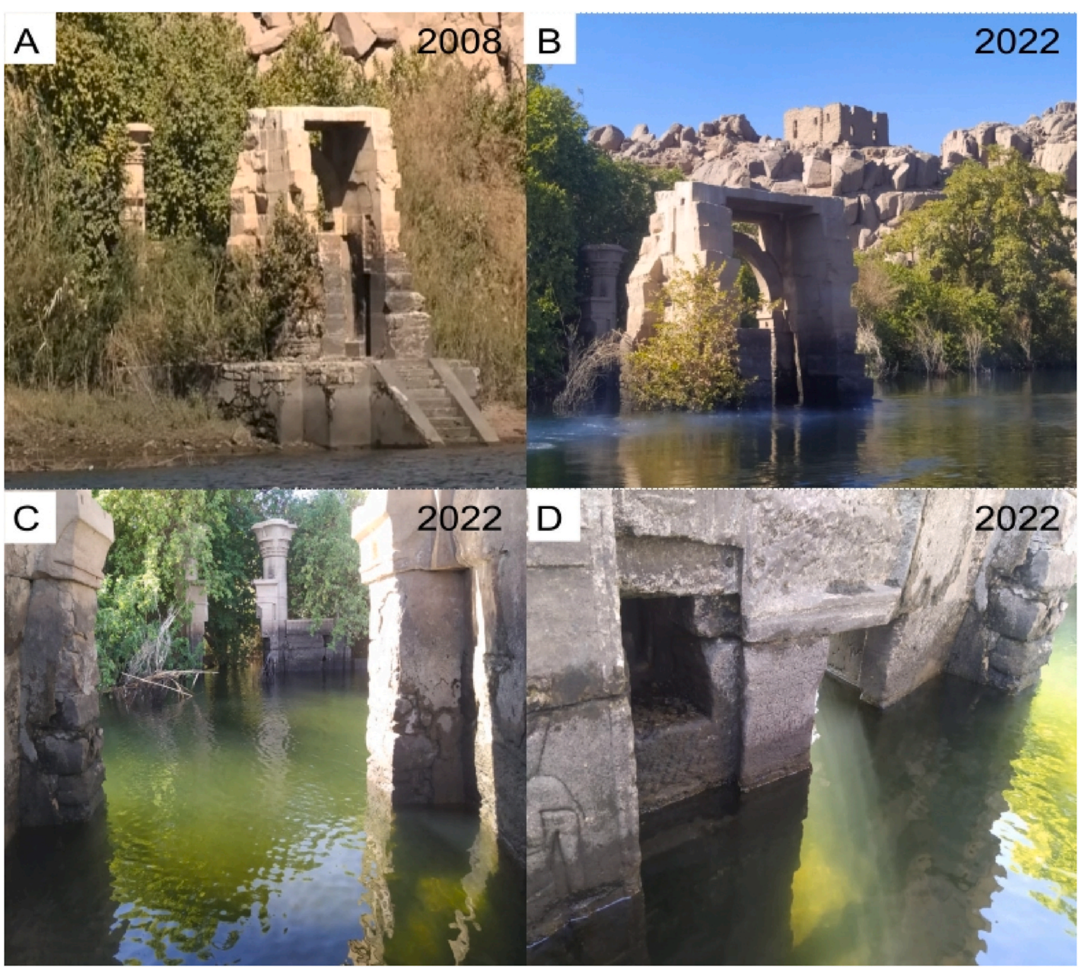

Fig. 6. Water level variations of the Nile water. (A) Lowering case of the Nile water. (B) Rising case of the Nile water. (C and D). The building materials decay due to the water level fluctuations.

and fungi (Wahab et al., 2013). Depending on the geochemistry of the water, chemical reactions with the stone may affect the stability of building materials. During low water level periods of accelerated weathering is likely. This includes erosion due to wind-blown particles or direct exposure to sunlight, especially if the temples construction materials are mostly porous sandstone (Fahmy et al., 2022a). Over the course of several years, repeated cycles of wetting and drying can exacerbate structural weaknesses in the temples. Additionally, cracks formed during dry periods can be widened during wet periods as materials expand with moisture absorption.

Fig. 6 illustrates the impact of fluctuating Nile River water levels on the structural and architectural stability of the Osiris Temple (Bigeh Island). Fig. 6 (A) captures the temple as it appeared in 2008, during a period when the water level was low and temple's structure and foundation state is clearly observed. In contrast, Fig. 6 (B) shows the temple during a period of high-water levels. The increased water level

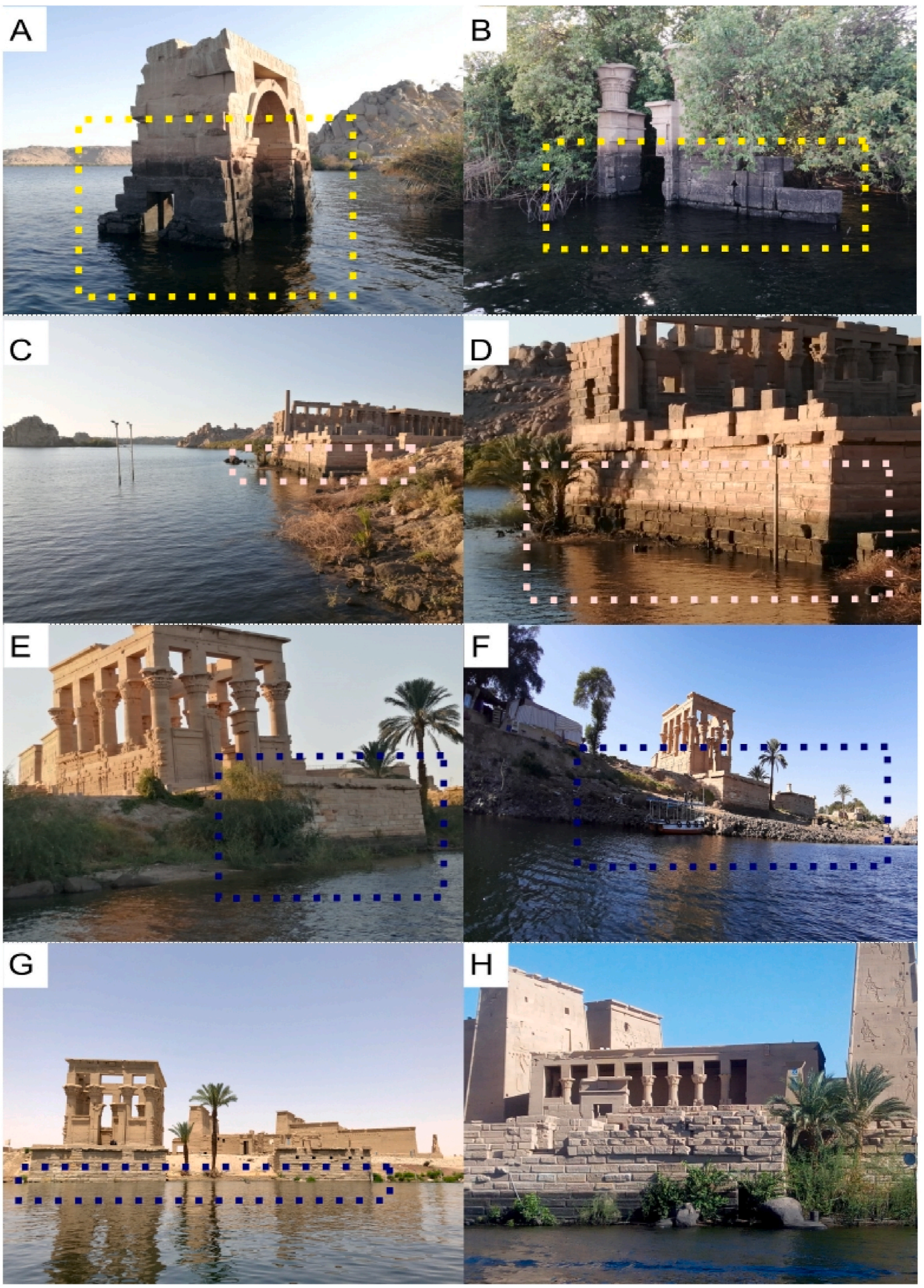

Fig. 7. (A–B) water level fluctuations influence on the structural elements of the temple of Osiris. (C–H) water level fluctuations influence on the foundations and walls of the Philae temples.

significantly submerges parts of the temple, highlighting the vulnerability of the structure to prolonged water exposure. Fig. 6 (C and **D**) focus on the degradation and damage that have occurred over time due to these fluctuating water levels. Fig. 6 (C) presents a detailed view of the erosion and structural wear on the lower sections of the temple, which have been directly impacted by the repeated rise and fall of the river. In addition, Fig. 6 (D) further emphasizes this damage, showcasing areas where the stone and other materials have deteriorated, leading to visible cracks and structural instability and defects.

The effects of water fluctuations are not limited to the temples, vary within the catchment and are multi-causal. Obviously, the Nile undergoes seasonal water level changes, typically peaking in late summer and receding during winter. Lake Nasser is characterized by unpredictable and extensive water level changes reaching up to 17 m. The Aswan Reservoir (Philae area) experiences lower annual amplitude but more consistent diurnal variations of around 3 m due to dam operations (UNESCO, 1960). This significantly influences the composition and distribution of riparian vegetation along the reservoir's shores (Badry et al., 2019). Multiple interconnected habitats, including shoreline zones, dendritic inlets (khors), and granite islands that host the UNESCO World Heritage Site, are directly impacted by the fluctuating water regime. Water level fluctuations across the Nile and its associated impoundments have also been shown to have a significant influence on the development and sustainability of macrophyte communities (Springuel and Murphy, 1991).

4.4. In situ observation and structural deficiencies

Construction materials of the temples that are in permanent contact with water can be severely affected by water infiltration. Water is considered an external force and strong solvent for the disintegration and decomposition of sandstone (George, 1896; Afifi and Bricker, 1983; Sleater, 1973; Zhang et al., 2022; Meng et al., 2022). The presence of water in the pores of a stone is the direct cause of decreasing stone resilience because the water in the pores can soften the bonding strength of the stone (Fahmy et al., 2022). Sandstones that contain clay mineral constituents, either scattered throughout the matrix or filling voids, can play a vital role in the degradation of the stone (Jiménez-González, 2008). Accordingly, clay minerals with water content and with other salty fluids can cause swelling that results in structural breakdown (Veniale and Lodola, 2008; Mercadal et al., 2024). Initial observations indicate that the architectural and structural elements of the temples at the Philae archaeological site are significantly impacted by water load. Multiple degradation patterns such as disintegration, blackening, scaling, and cracking are apparent. Fig. 7(A–G) illustrates how water level fluctuations influence the architectural and structural elements of the temples. The impact of water level fluctuations on structural integrity, instability and biotic crust creation is compounded by soil accumulation and vegetation growth (Cassar et al., 2018). Moreover, surface loss occurs due to flaking and delamination, further accelerating the deterioration of temple structures. In light of these challenges, comprehensive conservation efforts are imperative to mitigate further damage to the temple complexes.

4.5. Microscopic examination

Microscopic examination was conducted using a (USB portable digital microscope) to assess the condition and degradation rate of the sandstone surfaces used in the Philae temples under unsaturated and saturated conditions. In Fig. 8(A) (unsaturated condition), the grains appear tightly packed and relatively uniform in size. The surface looks clean with minimal visible porosity. The grains appear well-bonded with no significant signs of severe weathering or degradation. In Fig. 8(B) (saturated condition), there is a noticeable increase in visible porosity compared to Fig. 8(A). The grains appear more loosely packed, indicating either swelling or dissolution of the binding materials. Signs of degradation such as pitting or grain detachment are evident, due to the impact of water saturation.

In Fig. 8 (C) (saturated condition) materials are darker and more heterogeneous, exhibiting an increase in grain dislocation and roughness compared to the unsaturated condition. Evidence of degradation, including minor cracks and increased surface roughness is also clear. A cross-section of the sandstone (Fig. 8 (D) (saturated condition), reveals a clear boundary between the saturated and unsaturated zones. The

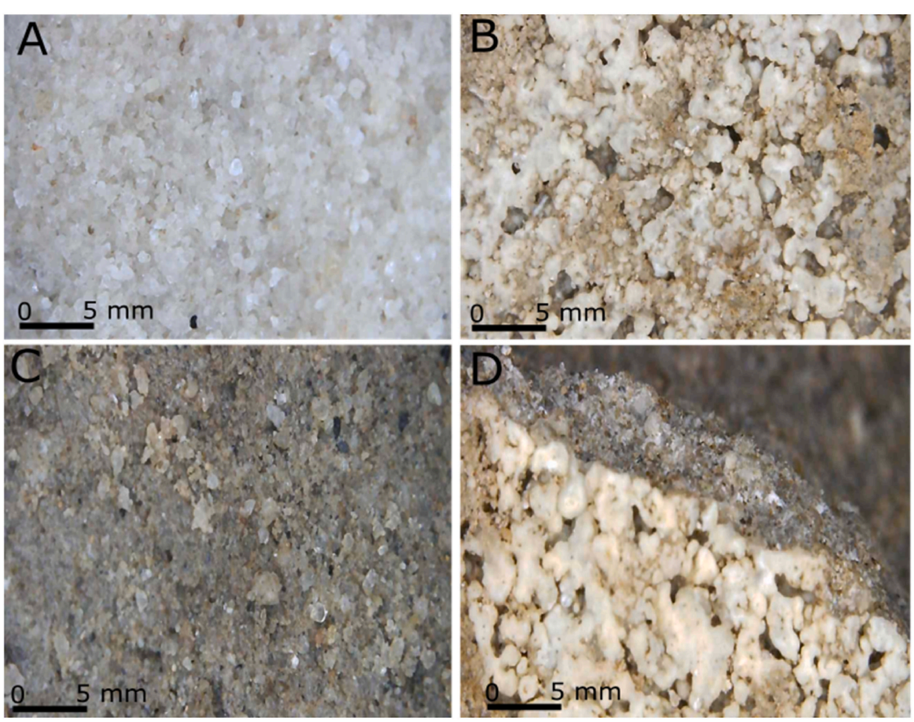

Fig. 8. Unsaturated (A) and saturated (B–D) sandstone surfaces under the digital microscope.

saturated zone has a more porous and weathered appearance, with visible degradation at the boundary interface. The outer surface is more eroded, indicating ongoing degradation due to water exposure.

The grain dislocation and porosity increase in the saturated samples demonstrating that chemical weathering and binding material loss by water has altered the structure of the material in a manner that will directly impact the stone's durability. The appearance of pitting and cracks in the saturated samples seen in Fig. 8 (B and **C**) is indicative of ongoing mechanical and chemical degradation. In addition, the boundary layer seen in Fig. 8 (D) highlights the effect of prolonged water exposure, which leads to a weakened outer layer and a relatively intact inner layer. Overall, the saturated samples seen in Fig. 8 (B and C and D) show more visible signs of degradation compared to the unsaturated sample of Fig. 8 (A), indicating that water saturation accelerates the degradation process.

4.6. Gloss measurements

The primary objective was to assess the surface condition and damage rate by measuring the gloss units (GU) of both saturated and unsaturated areas on the sandstone surfaces. The gloss test was performed using a gloss meter, which measures the reflection of light off a surface, quantified as GU. Sandstone samples were collected from the site, ensuring a representative selection of both saturated and unsaturated areas. The samples were cleaned and prepared according to standard procedures to ensure accurate measurement. Measurements were taken on both the saturated and unsaturated areas of the samples (Fig. 9).

The results showed that the GU for unsaturated areas ranged between 0.4 and 0.2, and for saturated areas, it ranged between 0.0 and 0.3. The unsaturated areas' gloss readings of 0.4 to 0.2 GU indicate a relatively low level of surface gloss, which is typical for natural stone surfaces that are dry and not intensely weathered. The variation within this range reflects slight differences in surface texture or composition due to environmental factors or/and inherent material properties. The gloss readings of 0.0–0.3 GU for saturated areas are indicative of increased surface roughness and decay. In this sense, lower gloss values, approaching 0.0 GU, demonstrate high surface degradation due to prolonged exposure to moisture leading to chemical weathering or physical erosion. The unsaturated surface is generally in better condition, with minor variations in gloss indicating slight surface irregularities.

The higher end of the gloss range (0.4 GU) reflects relatively smoother surfaces, whereas the lower end (0.2 GU) indicates areas with more texture or minor wear. While the saturated surface shows signs of wear and decay overall, the lower gloss values (0.0 GU) allow the identification of areas of high roughness and degradation, while values up to 0.3 GU indicate lower degradation but still some degree of surface compromise. The difference in GU between saturated and unsaturated areas refers to the impact of moisture on the sandstone surfaces. A decrease in gloss from 0.4 (unsaturated) to 0.0 (saturated) indicates a higher rate of damage in areas exposed to moisture (Fig. 9). The presence of readings as low as 0.0 GU in saturated areas underscores severe surface degradation.

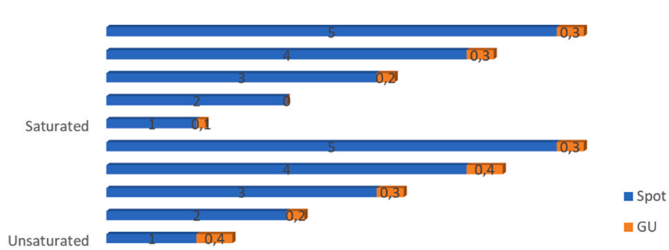

Fig. 9. Gloss unit levels for the unsaturated and saturated tested spots.

4.7. Colour measurements

The assessment of sandstone surfaces under unsaturated and saturated conditions reveals significant differences in colorimetric properties, indicating surface degradation due to water absorption and environmental impact. Measurements of lightness (L), green to red component (A), and blue to yellow component (B) show notable variations between the two states (Table 1). Unsaturated surfaces exhibit L values ranging from 51.9 to 75.6, while saturated surfaces have L values from 43.5 to 74.0, indicating that saturation causes the surfaces to darken (Fig. 10). This reduction in lightness points to a less reflective and potentially more degraded surface. The A values shift from −1.0 to 1.6 in unsaturated samples to −3.3 to 0.0 in saturated samples, indicating a move towards green. The B values, ranging from −6.8 to −2.6 in unsaturated areas and 6.8 to 31.1 in saturated areas, show an observed shift towards yellow. These changes imply that water interacts with the minerals in the sandstone, altering its color characteristics (Fig. 10). In addition, the increased roughness caused by degradation would increase surface roughness and therefore surface absorption of light resulting in darker tonality.

The color changes are further supported by variations in RGB values and Hue angles between unsaturated and saturated surfaces (Table 1). Saturated areas display a broader range of RGB values, particularly in the blue component, which is considerably lower in some spots. The shift towards lower lightness (L), green (negative A values), and yellow (positive B values) in saturated conditions indicates a substantial color alteration. These shifts likely result from the water absorption impacting both the visual and physical properties of the sandstone. Consequently, the darker, more intensely colored surface with noticeable green and yellow hues indicates surface degradation (Fig. 10), potentially affecting the aesthetic and perceived quality of the sandstone construction materials in Philae. In this context, the colorimetric measurements emphasized the impact of saturation on the sandstone's color properties and highlighted the detrimental effects of water exposure on the building material.

4.8. Surface roughness test

Saturated and unsaturated samples were analyzed to identify patterns and characteristics of their roughness profiles (Table 2) (Fig. 11). The green and yellow profiles (2 and 3, saturated) are marked by sharp peaks and valleys, along with frequent and high-amplitude fluctuations (Figs. 11 and 12). These profiles reflect a surface with significant irregularities and high roughness, indicative of highly textured or uneven, weathered surfaces. By contrast, the red profile (1, saturated) displays moderate fluctuations with less frequent and lower amplitude peaks and valleys compared to the yellow profile (Fig. 11). This indicates moderate roughness, with the peaks and valleys being more uniform and less severe. Unsaturated surfaces also exhibit different roughness characteristics. The magenta profile (3, unsaturated) features smaller, more consistent fluctuations, indicating a relatively smooth surface with minor roughness which has not been subjected to severe weathering processes (Fig. 11). Similarly, the cyan profile (2, unsaturated) shows low amplitude but more frequent, gentle fluctuations, signifying low surface roughness indicating less degradation compared to other profiles. The blue profile (1, unsaturated) has very low amplitude and infrequent fluctuations, making it the smoothest of the sandstone profiles. The black profile, is the control surface, being a standard baseline of plastic cylinder (Fig. 11). It is the smoothest surface among all tested samples being a highly polished surface exhibiting minimal roughness. Understanding the number and amplitude of peaks and valleys in these profiles offers insights into the surface's texture. High peaks and deep valleys typically indicate a rough surface, with the amplitude of the fluctuations reflecting the severity of surface irregularities (Fig. 12). Finally, higher amplitudes reflect a greater roughness, while the frequency of fluctuations indicates the uniformity of the roughness.

Table 1
Colorimetric measurements results for the unsaturated and saturated tested areas for sandstone surface.

Condition	spots	L	A	B	R	G	B	Chroma	HUE
unsaturated	1	74.3	1.5	−2.9	182	181	187	3.26	297.3
	2	75.6	−1.0	−2.6	181	186	190	2.79	249.0
	3	51.9	1.6	−3.1	123	122	129	4.12	292.8
	4	61.0	1.0	−6.8	142	146	158	6.87	278.4
saturated	1	43.5	−3.3	7.1	101	103	90	7.83	114.9
	2	51.1	−1.1	6.8	124	121	109	6.89	99.2
	3	74.0	−0.0	14.8	192	180	154	14.80	90.0
	4	46.5	−2.4	31.1	122	109	56	31.19	94.4

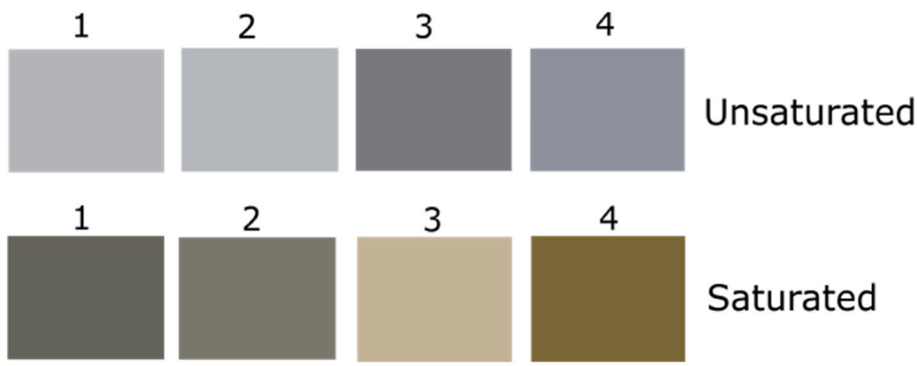

Fig. 10. Colour change patches for the sandstone building materials under unsaturated and saturated condition. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Table 2
Results of perthometer/profilometry test for unsaturated and saturated areas. Legend: LT = Total lengths of measured surface, in mm; RA = Arithmetic Mean Roughness, in μm; RZ = Mean Roughness Depth, in μm; Rmax = Maximum height, in μm; Rpm = Mean Peak Height, in μm.

condition	spots	LT	RA	RZ	Rmax	Rpm
Standard (plastic cylinder)		1.5	0.43	2.38	2.84	1.32
unsaturated	1	1.5	2.32	8.25	15.68	2.78
	2	1.5	0.66	3.55	6.32	2.34
	3	1.5	0.95	5.44	18.56	1.66
saturated	1	1.5	5.95	25.34	42.88	12.03
	2	1.5	3.28	14.88	28.32	8.22
	3	1.5	8.45	37.24	66.56	17.28

4.9. Mechanical and petrophysical properties

Compressive strength values obtained for the sandstone samples are 3.760 MPa (saturated) and 5.904 MPa and 6.095 MPa (unsaturated) (Fig. 13A). These values indicate that the sandstone is relatively weak, especially when considering that the typical compressive strength of unweathered, high-quality sandstone ranges from approximately 20 to 200 MPa. The significantly lower compressive strengths observed in these samples reflects several potential factors that could have contributed to the weakening of the rock. One possibility is that the sandstone has undergone extensive weathering, which can break down the mineral grains and weaken the rock structure. Additionally, high porosity, poor cementation, and unfavorable mineral composition could also be contributing factors to the reduced strength.

The failure modes observed in the compressive strength tests of the sandstone cubes were carefully documented and illustrated (Fig. 13 B and **C**). The progression of damage typically began with clean, sharp brittle fractures, which often resulted in multiple jagged pieces. As the load increased, vertical cracks running parallel to the applied load were observed, splitting the cube into two or more pieces. Subsequently, diagonal fractures appeared at approximately 45° to the direction of the load. Further loading led to the development of multiple vertical cracks,

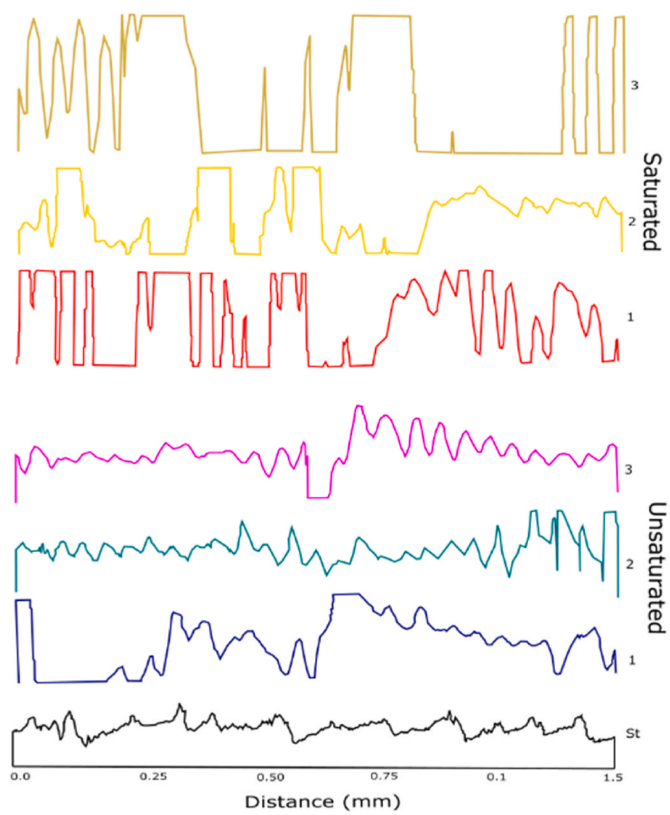

Fig. 11. Fingerprints of the surface roughness characteristics of the unsaturated and saturated sandstone surfaces in comparison to a plastic standard cylinder.

which created column-like fragments. Extensive pulverization and crumbling occurred next, producing a large number of small fragments. In some cases, cone-shaped fractures radiated from the centre of the face

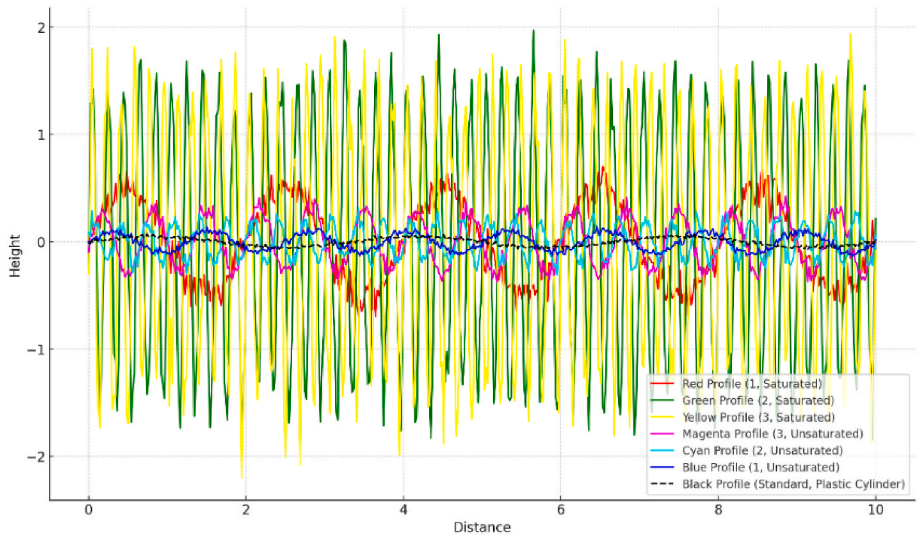

Fig. 12. Representative chart for the tested profiles demonstrating the fluctuation and amplitude differences.Distance (mm) and Height (μm).

opposite to the applied load. Finally, localized bending or buckling of the stone was observed, which is more typical in elongated specimens.

These failure modes provide valuable insights into the mechanical behaviour of the sandstone under compressive loading. The presence of multiple fracture types and extensive fragmentation highlights the brittle nature of the sandstone and its susceptibility to various forms of mechanical failure. This detailed understanding of the sandstone's behaviour under stress can help inform future studies and practical applications involving this material. The mechanical weakness and lack of durability of this sandstone can be attributed to its petrophysical properties, including an average density of 2 g/cm^3, a high porosity of 21.5 %, and significant water absorption by total immersion at 10.15 % (Fahmy et al., 2022b). The relatively low density indicates that the sandstone condition is not very compact, while the high porosity reflects the substantial amount of void space within the material, both of which contribute to its reduced strength and structural resistance. Furthermore, the high-water absorption rate highlights its susceptibility to weathering and degradation when exposed to moisture, further compromising its durability.

5. Conservation challenges and mitigation

The semisubmerged temple at Philae, along with other structures in the region, face conservation problems due to fluctuating water levels in the Nile. These fluctuations, driven by seasonal variations, dam operations, and broader climatic changes, contribute to structural instability, erosion, and biological colonization. Prolonged exposure to moisture leads to salt crystallization, weakening stone surfaces and accelerating material decay. Additionally, the repeated wetting and drying cycles result in mechanical stress, which further compromises the durability of these ancient structures. Addressing these challenges requires a combination of continuous monitoring, structural engineering solutions and advanced water management strategies.

There are multiple solutions to safeguarding cultural heritage affected by rising water levels, flooding or increased precipitation, and this topic has become one of significant debate in the context of climate change and "immovable" heritage (Sesana et al., 2019; Murdock, 2023; Nguyen et al., 2023). In order to establish baseline data, model different hydrological scenarios and identify areas at risk, remote sensing data are increasingly employed and allow diachronic value estimations of environmental and landuse change (e.g. Souissi et al., 2019; Farhadi et al., 2022; Nguyen et al., 2023). Historical records are valuable in such models because they permit impact and future-trend assessments. It was beyond the scope of this study to develop a Multi-Criteria Decision-Making GIS model, but examination of the historical data provides a useful first step towards this. In considering long term mitigation protocols, it is approaches like this, that would provide a comparatively low-cost method to explore engineering solutions, discuss options with communities and estimate costs ahead of any ground-based interventions. Since every site is different, it would be sensible to integrate studies like this with associated community consultations so that local experience and knowledge can be incorporated into models and the lived impact of proposed mitigation strategies is adequately considered (see Orlove et al., 2022; UNESCO, 2021).

One of the most effective engineering approaches to mitigating water-related deterioration is the construction of protective barriers, such as cofferdams (Partial Retaining Walls), revetments and engineered seawalls (Petronijević and Petronijević, 2022; Sanitwong-Na-Ayutthaya et al., 2023). These barriers function as physical shields that prevent water from directly reaching the temple's foundations and lower architectural elements. Their design must be informed by a detailed hydrodynamic analysis of the Nile's water flow patterns and sediment transport characteristics. Materials used in these barriers should be selected for durability, ensuring minimal impact on the surrounding ecosystem and keep the structural stability of monuments safe. Additionally, periodic maintenance will be required to reinforce their structural stability and adapt to any shifts in water levels over time. Nature-based solutions (NbS) can also be integrated into a diversified portfolio of water management strategies (e.g. Opperman and Galloway, 2022). This method offers a promising approach to managing rising flood or water level risks in river systems by utilizing natural or modified ecosystems to mitigate floodwaters while simultaneously providing environmental and social benefits.

In Fig. 14(A–D), the historical and proposed evolution of hydrological and conservation interventions at the Philae monuments are presented. Fig 14 (**A**) illustrates the critical state of the monuments following the construction of the High Dam in the 1960s, where rising water levels of Lake Nasser submerged the temples seasonally, threatening their structural stability (UNESCO, 1960 and 1968). In addition, Fig 14 (**B**) shows the current condition, where the Philae monuments have been relocated to Agilkia Island on higher ground (+122 m), reducing direct submersion risk, but still being exposed to water level fluctuations and potential seepage. Fig 14 (**C**) presents a proposed mitigation strategy that includes installing protective barriers (cofferdams or cut-off walls) around the monuments in conjunction with improved hydrological management of the High Dam to stabilize water levels and prevent erosion. Fig 14 (**D**) demonstrates the enhanced protection state after implementing both structural barriers and

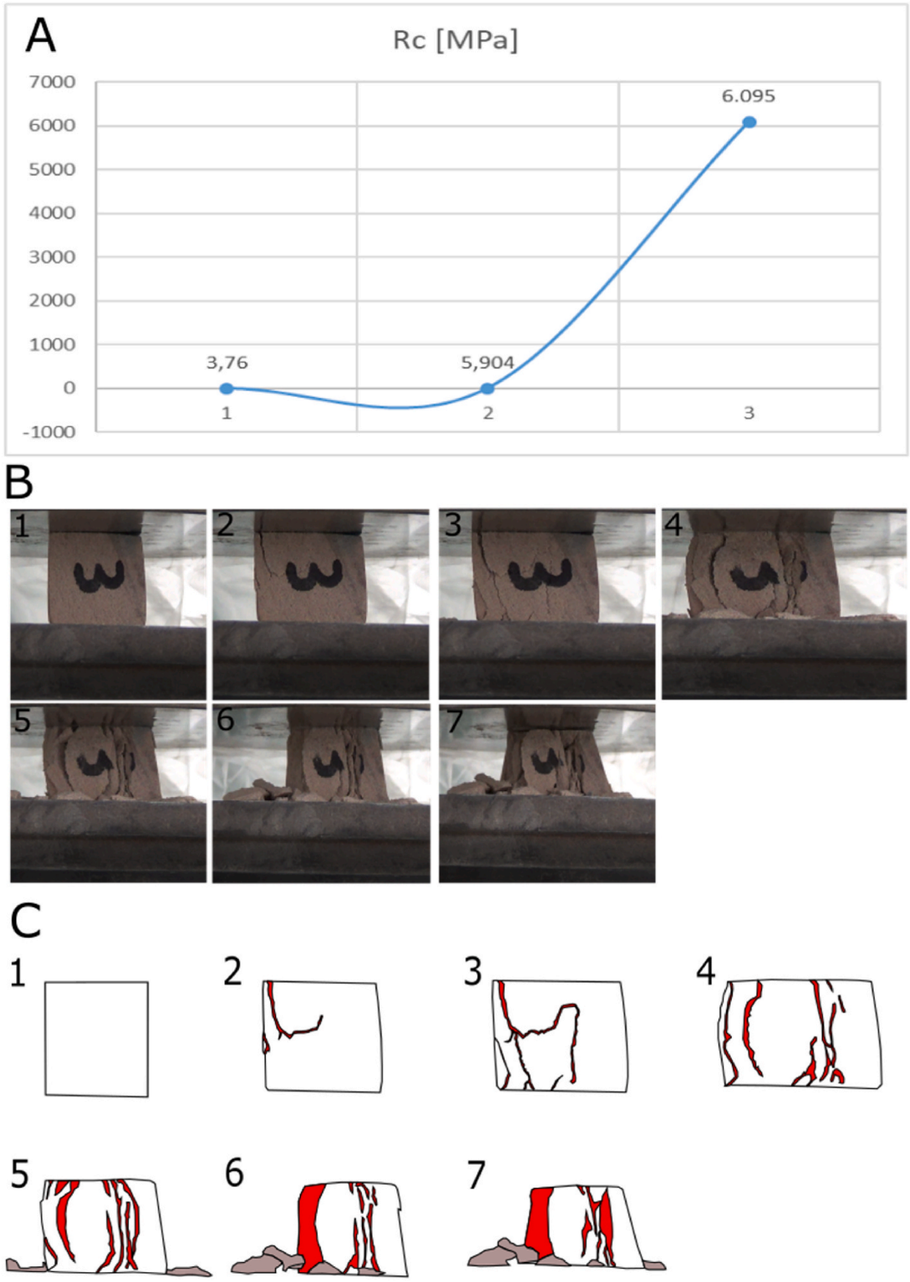

Fig. 13. (A) Compressive strength results for the unsaturated and saturated sandstone cubes. (B and C) Modes of failure for sandstone cubes under compressive load.

Nature-Based Solutions (NBS) such as vegetative buffers or soil-absorbing systems to manage infiltrated water in the subsoil, thus preserving the monuments from both surface and groundwater threats. This progression reflects a hybrid strategy combining engineering and environmental approaches to secure heritage assets in changing hydrological contexts.

Beyond physical barriers and natural solutions, hydrological management systems offer an effective way to regulate water levels and reduce the impact of water rising. This method includes the installation of strategically placed pumps, drainage networks, and water diversion channels to redirect excess water away from the vulnerable structures. The use of subsurface drainage systems can help lower the groundwater table, minimizing capillary rise and salt deposition within the stone matrix. These interventions must be carefully integrated into the site's wider landscape to avoid unintended consequences such as soil erosion or changes to the sedimentation regime in adjacent areas. Prior to installing engineering solutions and hydrological management, it would be advisable to model them virtually during different seasons/scenarios. Consultation with local communities would allow local knowledge to be incorporated in modelling scenarios. Effectiveness and impacts of different models could then be evaluated, discussed with communities and the preferred option agreed.

The development of comprehensive guidelines for cultural heritage management before and after dam construction is a challenge and needed to mitigate the often-irreversible impacts such projects can have on archaeological sites, historical landmarks, and cultural landscapes. Dam construction frequently leads to the submergence or destruction of heritage assets. Without established frameworks ahead of works, such losses can occur without proper recording, preservation, or community consultation. Standardized guidelines would ensure a consistent and ethical approach to identifying, evaluating, and safeguarding both tangible and intangible cultural heritage, while also integrating heritage protection into broader environmental, development planning and improving the conservation and risk management practices

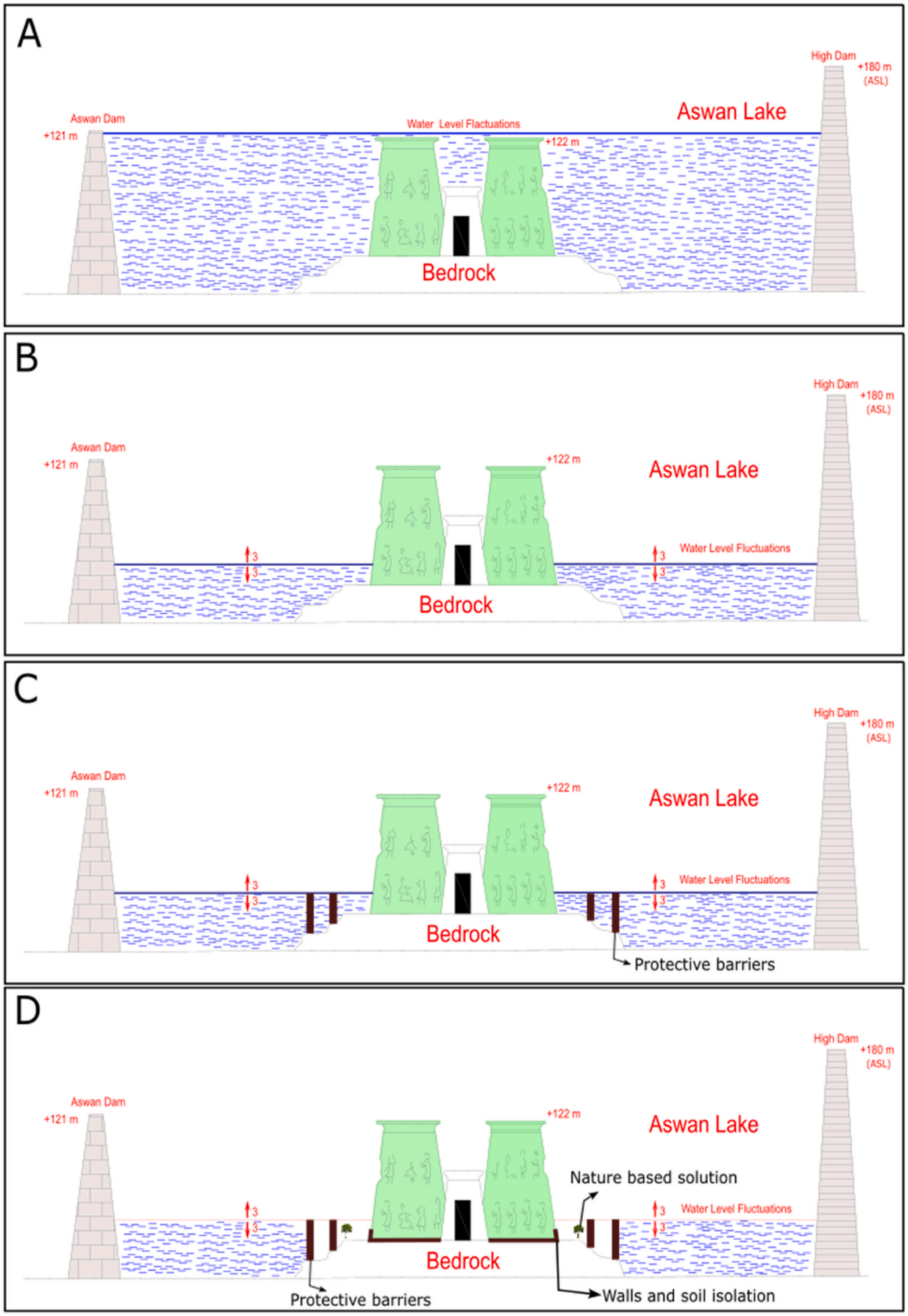

Fig. 14. Progressive hydrological and conservation scenarios for the Philae Monuments in relation to the Aswan High Dam. (A) Submersion of the original Philae site following the construction of the High Dam in the 1960s, leading to seasonal flooding. (B) Current situation showing the relocated Philae Monuments on Agilkia Island at a higher elevation (+122 m), reducing but not eliminating water-related risks. (C) Proposed mitigation approach incorporating protective structural barriers and controlled hydrological management of the High Dam to stabilize water levels. (D) Final scenario integrating both protective barriers and Nature-Based Solutions (NBS) to manage subsurface water infiltration and enhance long-term resilience of the site.

(Perez-Alvaro, 2023; Perez-Alvaro et al., 2025).

Guidance needs to address both the direct impact of construction and inundation, as well as indirect impacts like changes in land use and increased development (Cunliffe et al., 2012). The controversial nature of dam interventions and their heritage impacts is amply demonstrated by the OrientDams project initiated in 2015 in the Middle East and North Africa (MENA) region. While dams provide benefits like electricity, irrigation, and industrial development, they also cause significant damage, including the submersion of archaeological sites, displacement of people, and loss of fertile land. The OrientDams project seeks to quantify the loss of archaeological heritage due to the construction of these dams along the Euphrates, Tigris, and Nile rivers, highlighting the lack of adequate safeguarding measures and the necessity for better preservation strategies (Marchetti and Zaina, 2020). Similar interventions at Angkor World Heritage site risk worsening land subsidence and endangering monument stability. Here, InSAR technology combined with ground-based measurements for monitoring potential hazards and assessing conservation needs aided in preparedness for future threats (Chen et al., 2019).

6. Conclusions

This study has demonstrated the impact of water exposure on the sandstone surfaces of the Philae Temples and presents the deterioration mechanisms affecting these UNESCO monuments. Through multiple analysis of temporal water level variations, sedimentation and erosion patterns, colorimetric changes, gloss measurements, surface roughness profiles, and mechanical strength, the research highlights the important factors contributing to the degradation of the temples' sandstone and its preservation.

The study found that the construction of the Aswan High Dam has considerably altered sedimentation patterns around Agilkia Island, where the Philae Temples were relocated. The dam has reduced the natural sediment load and changed the water discharge rates, leading to increased sediment accumulation around the temple structures. This accumulation can destabilize the foundations and contribute to the degradation of submerged parts of the temples. Additionally, temporal analysis of water level fluctuations from 2017 to 2020 revealed significant variations, with lower water levels in 2017–2019 and a high-water level in 2020. These fluctuations exert hydrostatic pressure on temple foundations, which lead to erosion and weakening of the soil, and cause cycles of wetting and drying that exacerbate structural weaknesses.

Colorimetric, gloss, and surface roughness analyses revealed clear differences between unsaturated and saturated sandstone surfaces. Unsaturated areas showed higher lightness and gloss values (0.4–0.2 GU), indicating smoother, less degraded surfaces, while saturated areas had lower lightness and gloss (0.3–0.0 GU), referring to increased surface roughness and degradation. A shift toward green and yellow hues in saturated conditions implies possible mineral alteration due to moisture. Roughness tests confirmed greater surface irregularity in saturated samples, and mechanical strength tests showed reduced compressive strength (3.760 MPa vs. 5.904–6.095 MPa), emphasizing the weakening effect of water on the sandstone.

The study's results highlighted the urgent need for effective water management in preserving sandstone structures within Philae site. Water exposure, as evidenced by the observed differences in color, gloss, surface roughness, and mechanical strength, significantly accelerates the degradation of stone materials. To mitigate these damaging effects, it is essential to implement a comprehensive conservation strategy that combines both preventive and responsive measures. We propose installation of physical protective barriers to shield stone surfaces from direct contact with moisture, as well as the development of advanced water management systems tailored to the site's specific environmental conditions, but suggest modelling and community consultation would be required ahead of implementation. Improving site drainage infrastructure is vital to prevent water accumulation around or beneath sandstone elements, while regulating groundwater and surface water levels can help reduce capillary rise and long-term saturation. Moreover, integrating moisture sensors and other monitoring tools enables continuous assessment of environmental conditions and material response, allowing conservation teams to detect early signs of deterioration and intervene promptly. Protective coatings or treatments, when compatible with the original materials, may also offer added resistance to water infiltration without compromising the stone's durability or breathability.

Public awareness and collaboration with local stakeholders, site managers, dams' managers and interdisciplinary experts and conservators will enhance the sustainability of these efforts. The issues identified in this case study, such as water-induced deterioration, are not unique to the Philae Temples. Many World Heritage sites are currently facing similar environmental and conservation challenges. Such challenges are only likely to increase with climate change. The results emphasized the need for national and international guidelines to manage cultural heritage sites both pre- and post-dam construction. Accordingly, this research not only enhances the understanding of water-induced deterioration but also provides a framework for assessing and safeguarding endangered archaeological sites worldwide.

Finally, future scenarios studies are needed to assess the long-term (2050–2100) impact of changing environmental and infrastructural conditions on the structural and material stability of the monuments. Such protocols would help streamline assessment processes, reduce delays due to unexpected discoveries, and prevent costly project redesigns. Early documentation and preservation efforts not only serve to protect cultural assets but also develop community trust. Sustainable development of this kind respects cultural identities and community values. In the long term, it should be possible to balance economic progress with the conservation of heritage assets, which can themselves generate significant economic benefits for communities.

CRediT authorship contribution statement

Abdelrhman Fahmy: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Laura Basell:** Writing – review & editing, Supervision. **Salvador Domínguez-Bella:** Writing – review & editing, Supervision. **Eduardo Molina-Piernas:** Writing – review & editing, Supervision.

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Declaration of competing interest

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Further reading

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