Heritage Science

RESEARCH

Open Access

Sand dune movement and flooding risk analysis for the pyramids of Meroe, Al Bagrawiya archaeological site, Sudan

Abdelrhman Fahmy[1,2*], Salvador Domínguez-Bella[1], Javier Martínez-López[1] and Eduardo Molina-Piernas[1]

Abstract

The pyramids of Meroe are a significant archaeological place at the Al Bagrawiya archaeological site (Sudan) with hundreds of pyramids dating back to the kingdom of Kush (1070 BC–550 AD). In this area, winds, heavy rains, and flooding events are the main geohazards that need assessments and solutions because pyramids are subjected to an accumulation of sand dunes around them and the risk of flooding, affecting their durability. This research aims to assess the impacts of sand dunes on the stability of pyramid structures in addition to assessing the risk of flooding using satellite image observations, and damage and decay assessments of pyramid building materials were carried out through digital mapping. The results from satellite image analysis and monitoring showed that sand dunes along with heavy rains and flooding are the main decay factors, causing the collapse, disintegration, crumbling, alveolarization, loss of materials, and cracking of the sandstone ashlars, detecting an increase in deterioration, even considering only the last three decades.

Keywords Pyramids of Meroe, Al Bagrawiya archaeological site, Sand dunes, Wind, Flooding, Construction materials, Stone decay

Introduction

Several studies have been carried out on geoenvironmental and geohazard impacts on archeological sites and buildings. For instance, Stambolvo [1] explained the role of wind and rain in the deterioration of porous building materials, where water can penetrate stones by wind power and capillary suction to cause stone decay. Fitzner et al. [2] studied the conservation state of construction materials in the temples of Karnak and Luxor, and they categorized the damage as no visible, very slight, slight, moderate, severe, and very severe damage. They concluded that disintegration, detachment, and flaking degradation are degradation aspects due to salt weathering. Sandrolini et al. [3] used the available long record urban scale environmental data and finite element analysis to identify the decay sources and problems of the cathedral of Modena (Italy). They concluded that wind blowing to the facades resulted in tensile stresses and loads to the façade plane. Hemeda et al. [4] studied various environmental factors that structurally affected the pyramid of Snefru. Weathering, geotechnical, and seismic loads were the main damage factors for the pyramid. In addition, in the middle of Egypt, a geoenvironmental and geotechnical assessment of damage at the El-Ashmounein archaeological site was applied, where stone columns were broken due to flooding and seismic loads [5, 6]. Fahmy et al. [7] studied the impact of external environmental factors and intrinsic defects on the sustainability of Sahure's pyramid and showed that external factors such as earthquakes and climatic conditions are

*Correspondence:
Abdelrhman Fahmy
abdelrhman.fahmy@uca.es; abdelrhmanmuhammedfahmy@gmail.com
[1] Department of Earth Sciences, Faculty of Sciences, University of Cadiz, Campus Río San Pedro, 11519 Puerto Real, Spain
[2] Conservation Department, Faculty of Archaeology, Cairo University, Giza 12613, Egypt

the main external damage factors, while the clay content of the stone plays a damaging role as an intrinsic factor.

In fact, the challenges in relation to protecting cultural heritage need to be better understood to avoid further destruction of the cultural heritage landscape [8]. Severe climates can be considered a potential environmental problem for cultural and natural properties [9], causing partial or total collapse and sliding of archaeological buildings and findings in coastal and desert systems [10]. In this sense, sand dunes show considerable morphological diversity with active and inactive movements [11]. Wind could be an extra load on the dunes covering the buildings for a short or long time depending on wind power [12]. Therefore, windblown sand action can cause sand erosion in modern and ancient buildings [13]. On the other hand, floods are an unusual environmental hazard to the preservation of archaeological sites [14], and river floods are the most common type of natural disaster [15]. Flood events can cause irreversible destruction to archaeological sites and their built heritage [16]. For this, Fahmy [17] studied the impact of flooding on the Basilica Church at the El-Ashmounein archaeological site (Egypt). The results came across to the main reason for granite columns (freestanding columns) collapse displacement, and irreversible deformations is the repeated events of flash flooding which reached 3 m over the columns. Fernandes [18] studied the impact of heavy rains on the built heritage on Madeira Island, concluding that the trails near the canals were damaged by heavy rains and tourism activities were affected. In this context, Petra's afforestation, terracing, and construction of check and storage dams are considered solutions to protect the archaeological site from flooding by 70% [19].

In Sudan, Sweek et al. [20] carried out a conservation project for the Amun Temple because the architectural elements of the temple were affected by different kinds of decay mechanisms due to the poor quality of sandstone and heavy rains. Osman et al. [21] studied several properties of the Nubian formations and their geotechnical problems because these formations were the sources of construction materials in different archaeological buildings in Sudan. The governmental report of Sudan in March 2021 [22] mentioned different vulnerabilities that threaten the archaeological sites in Sudan. Among these vulnerabilities are natural encroachments such as strong winds, earthquakes, flash flooding, and Nile flooding. They explained that wind power could transport sand particles and weaken the sandstone building materials of archaeological buildings. In addition, the floods affected many archaeological sites, especially the Island of Meroe. Onderka and Vrtal [23] showed that the damage to the red brick and mud-brick structures in Wad Ben Naga's archaeological site is due to seasonal heavy rains. Fahmi et al. [24] studied the challenges of Sudanese heritage and mentioned that approximately 150 pyramids near the Nile River were affected during the recent flooding. Boozer [25] reported that the pyramids of Meroe were well preserved in the early 18th, nineteenth, and twentieth centuries but were subsequently damaged anthropologically. In this context, he discussed that Hinkel and Yellin (scholars) observed unrecorded and irreversible damage to many offering chapels in their architectural and relief elements. Moreover, the pyramid and chapel blocks were displaced at Meroe.

Remote sensing and satellite imaging observations have been used in archaeology for management and monitoring purposes. For example, Hadjimitsis et al. [26] said that satellite remote sensing and GIS analysis are tools for archaeological site observations and multianalysis of risk assessment. These tools preserve time and effort instead of in situ observation. Tapete [27] explained that remote sensing observations are extremely important in climate change issues, especially probable floods, drought, and other consequences in relation to water. In addition, he added that very high-resolution satellite images could help with damage mapping and assessment in archaeological sites. Angeli and Battistin [28] carried out a monitoring and assessment project for soil erosion and its impact on the buried archaeological heritage of Antonine Wall and Falerii Novi in Italy. Hu and Li [29] used GeoEye images and CORONA images with high resolution to reveal some archaeological ruins that were covered by sand dunes. In addition, we assessed other ruins affected by wind erosion and surrounded by sand dunes and nebkhas (aeolian landforms).

From the above literature review, very few studies refer to problems of flooding and sand dunes at Sudan archaeological sites. For this motive, the present study focuses on sand dunes and flooding risk assessment on the pyramids of Meroe. To achieve this, treated and untreated satellite images were used to monitor and assess the geohazard problems of sand dunes and flooding over the pyramids. Moreover, mapping and documentation for the decay forms of the pyramids of Meroe and the damage rate were performed to assess the durability conditions of the pyramids.

Al Bagrawiya Pyramids' studied area

The pyramids of Meroe at the Al Bagrawiya archaeological site were built approximately 200 km north of Khartoum, between the Nile River and the Atbara River (Fig. 1A) with coordinates latitude N 16°56.111', longitude E 33°42.852' [30]. The Al Bagrawiya archaeological site is a World Heritage Site with significant pyramid-shaped structures of the Meroe kingdom. Meroe was an ancient city in Sudan, and it was the seat

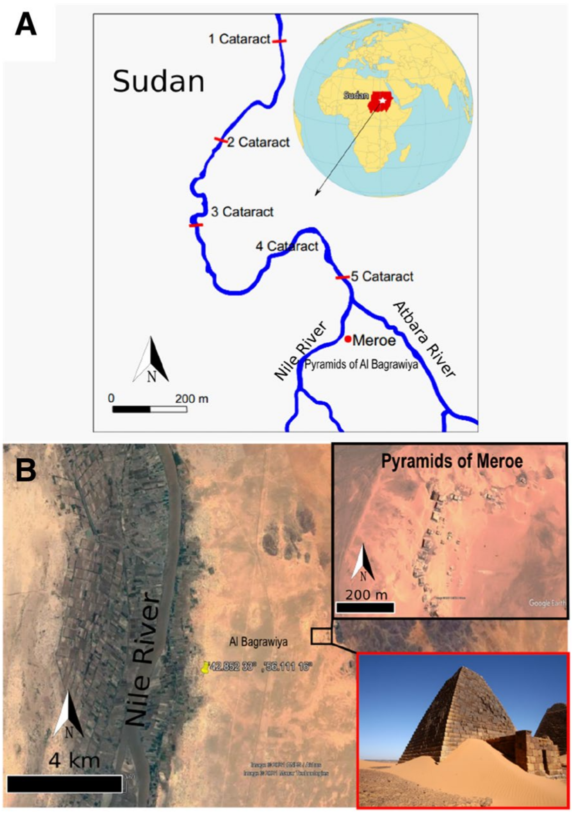

Fig. 1 **A** Map of Sudan and location of the pyramids of Meroe et al. Bagrawiya (red point). **B** The pyramids of Meroe et al. Bagrawiya and their general view

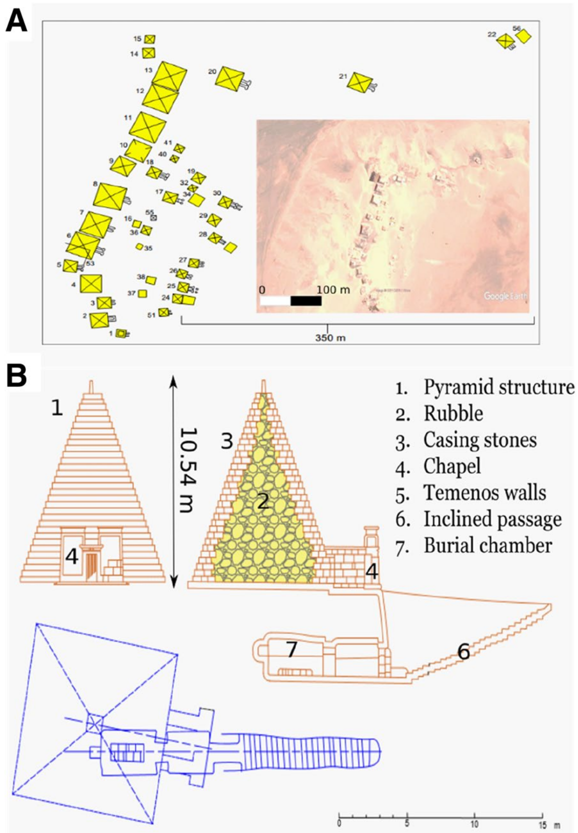

Fig. 2 **A** General map with plans for the pyramids et al. Bagrawiya (edited after [31]). **B** Elevation and plan view of Pyramid number 10 and its architectural and structural elements (edited after [30])

of the government and the royal palace [31]. The pyramids of Meroe back to the kingdom of Kush between the eighth century BC and fourth century AD and were devoted as a necropolis site for the kings and queens of Meroe (Fig. 1B). In addition, it contains more than 100 pyramids in the north, south, and west of Al Bagrawiya (Fig. 2A) [32]. In a comparison between the Egyptian and Meroitic pyramids, the inclination angle of the Meroe pyramids ranges between 68 and 81 degrees, while the Egyptian pyramid's inclination angle is lower than 52 degrees. Furthermore, the pyramids of Meroe are not as large as the Egyptian pyramids because the height of the Meroitic pyramids ranges between 10 and 30 m and the base ranges from 4.5 to 17.5 m. Some pyramids were constructed with sandstone blocks with a rubble-filled core in the earlier periods (Fig. 2B), but some other pyramids were covered by brick or coursed rubble and rendered by lime or gypsum mortar for painting [30, 33]. Additionally, pyramid number 10 contains different architectural elements, such as temenos walls, a chapel, an inclined passage, and a burial chamber, as shown in the plan and cross-section (Fig. 2B).

Geological and climate context

The geomorphological and geological features of Sudan vary from desert lands, hills, plutonic/volcanic formations, and valleys from various eras [34]. The Sudan plain consists of dark clays and red–brown sands [35]. The general geological column of Sudan is composed of coastal plain deposits, Nubian formations, Palaeozoic sandstone formations, and a basement complex (mainly Precambrian) [36]. Deposition of the fluvial and marine sediments overlying the amalgamated terranes, from the Cambrian onwards, was because of the erosion of the Trans- Gondwanan Mountain belt and subsequent recycling of the eroded detritus during later inversion tectonics (Fig. 3A) [37]. In addition, continued erosion and continental deposition resulted in the widespread formation of sandstones such as the Mesozoic Nubian Sandstone Formation [38]. The Nubian series (different kinds

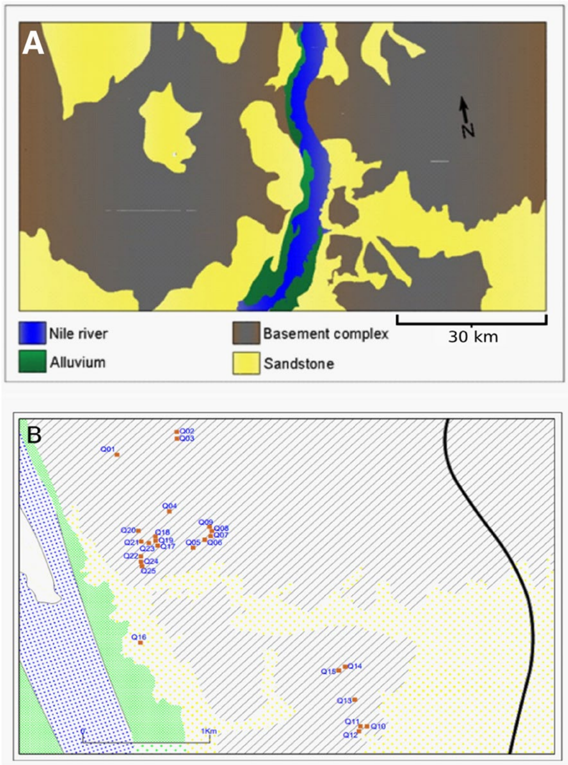

Fig. 3 A Lithological map of the study area. **B** Ancient Meroitic quarries in the northwest sector

of sandstones) is the main geological and geomorphological feature of the Meroe area. In addition, the basement rocks are unconformably present (Fig. 3A). Nubian sandstone is a Cretaceous formation similar to sandstone in Upper Egypt. It is characterized by a general absence of basal conglomerates. Consequently, it is poorly cemented and fragile except for the sandstone that occurred over the basement complex. Finally, basement rocks include igneous, metamorphic, and sedimentary rocks. In the sixth cataract, the basement rocks existed largely (large outcrop) [30, 34, 38, 39].

Many quarries have been used in the kingdom of Kush; ferruginous sandstone quarries (Nubian Formations) were used as raw materials to prepare stone blocks for pyramid construction [40]. Brigitte Cech [41] classified Meroitic quarries into five sectors (Fig. 3B): (1) Northwest Sector: Q01–Q25; (2) Northeast Sector: Q26–Q34; (3) Central Sector West: Q35–Q80; (4) Central Sector East: Q81–Q91; and (5) South Sector: Q92.

Meteorologically, this region lies within the zone of tropical continental climate with fluctuations in rainfall and temperature from south to north. Generally, the rainy season lasts 5–8 months in the southern and heavy rains for 1–3 months in the northern part of Sudan. The annual rainfall ranges from 100 to 600 mm, and temperatures can rise up to 43 °C [42]. The temperature in Sudan ranges from 26 °C to 32 °C annually, and since 1960, the temperature has increased from 0.2 °C to 0.4 °C per decade (Fig. 4) (https://climateknowledgeportal.worldbank.org). Rainfall patterns divide Sudan into five zones from north to south: (1) desert with 0–75 mm of precipitation annually; (2) semidesert with 75–300 mm; (3) low rainfall savannah on clay and sand with 300–800 mm; (4) high rainfall savannah with 800–1500 mm; and (5) mountain vegetation with 300–1000 mm of precipitation [43]. The archaeological site of Al Bagrawiya is situated in the zone of semidesert with 75–300 mm, as shown in the rainfall and flooding map of Sudan (Fig. 5). In this context, Salih et al. [44] mentioned that rainfall could be classified into five classes: (1) weak (W) is defined as 0.1–1.0 mm/day; (2) moderate (M) is > 1.0–10.0 mm/day; (3) moderately strong (MS) > 10.0–20.0 mm/day; (4) strong (S) > 20.0–30.0 mm/day; and (5) very strong (VS) > 30.0 mm/day.

Sand/dust storms are one of the main environmental events in Sudan [45]. They are related to arid and semiarid areas but can occur as long as there are dry sediments. The process of sandstorms involves three steps: (1) entrainment or emission of surface material; (2) transportation through the atmosphere; and (3) deposition [46]. Sherif [47] collected some sand particles from Atbara, which is adjacent to a recent study area of Al Bagrawiya, to characterize the sand particles. In this context, Khartoum and Atbara particle sizes are less than 0.3 mm, but Atbara's dust size contains a high percentage of larger particles. In addition, the majority of particles transported more than 100 km from the source are < 0.02 mm in diameter [46].

Furthermore, Sudan practices potential wind power, and the wind speed in Sudan at 50 m height varies between 5.1 and 7.1 m/s. According to the wind power analysis that had been carried out for 25 towns in Sudan, the wind speed at 90 m height varies between 8.96 and 8.73 m/s [48]. Most regions of Sudan are not subjected to hurricanes, although some thunderstorms with relatively high speeds for a short duration cover some areas in the center of Sudan during the rainy season [49].

Methodology

The scientific methodology depends on archaeological mapping for monitoring and risk assessment using Google Earth images and satellite images from the Spectro radiometer MODIS on NASA's Aqua satellite (NASA). SeaDAS has been used as a remote sensing tool to treat Earth images and satellite images. These treated

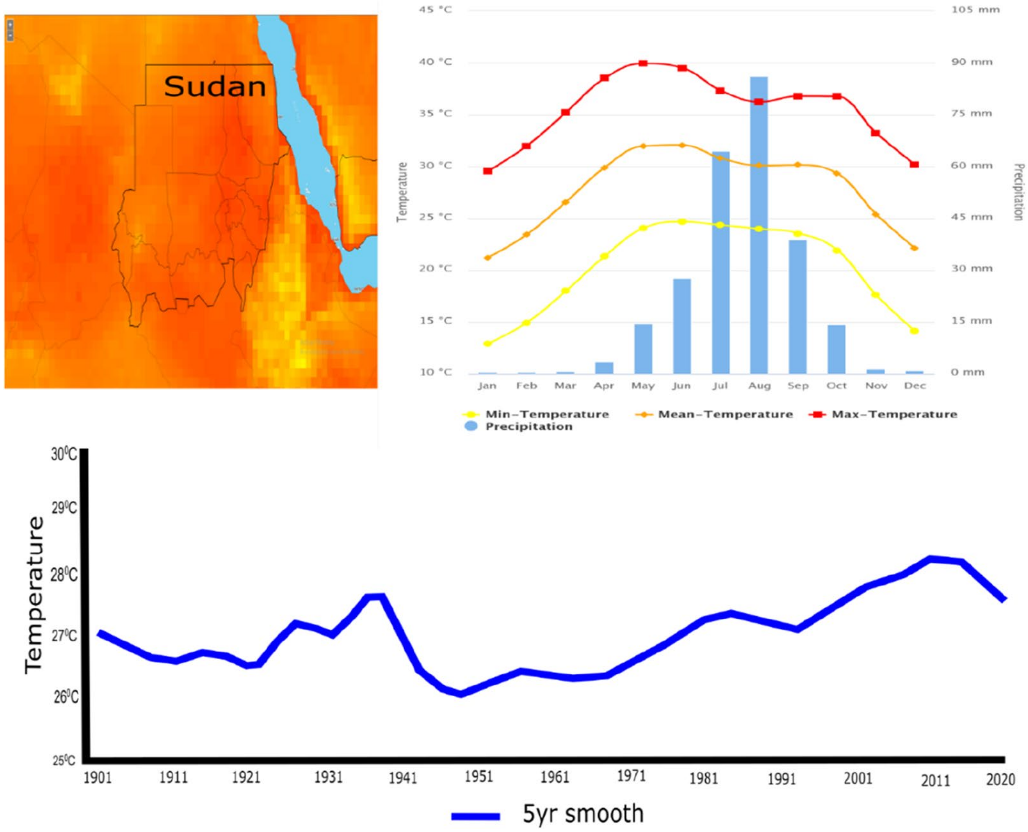

Fig. 4 Thermal map (upper left) and chart of temperature (upper right) over Sudan monthly. (Bottom) Historical temperature records from 1901 to 2020. Edited after: https://climateknowledgeportal.worldbank.org/country/sudan/climate-data-historical

satellite images were used to manage and monitor sand dune movement through high-resolution and detailed images during 2004, 2010, 2014, and 2021 according to available data in these years. Moreover, sandstorms, heavy rains, and flooding risks were observed and assessed through the Spectro radiometer MODIS on NASA's Aqua satellite images. Furthermore, decay deterioration mapping was carried out using digital engineering drawings to assess the actual preservation state and geohazard impacts on the pyramids of Al Bagrawiya and their building materials. For this, vulnerability rate and decay form specifications were carried out depending on fieldwork (observational recordings) and photographs were taken using the semiquantitive analysis method or/and ununified damage standard (for individual architectural and structural elements). Then, sketching for some selected architectural and structural elements for the pyramids was performed using AutoCAD 2020 through bench work.

Results and discussion

Destruction of pyramids

The pyramids of Meroe were constructed from Nubian sandstones. The sandstone blocks were prepared from various quarries from the Nubian formations around the area. The sandstone building materials of the pyramids are subjected to different kinds of damaging hazards and risks, probably as the main sand dune formation around the pyramids causing mechanical stresses and instability for the construction elements of the pyramids. Heavy rains and sandstorms are considered the main damaging factors for the construction materials of pyramids as well. Finally, flooding is a risk that threatens archaeological sites and pyramids in Sudan.

Sand dunes and wind impacts

A sand dune can be considered a loose sand hill formed in different sizes and shapes (barchans, longitudinal, transverse, parabolic, barchanoid, and star) due to wind flows, and the morphological feature of the sand dunes

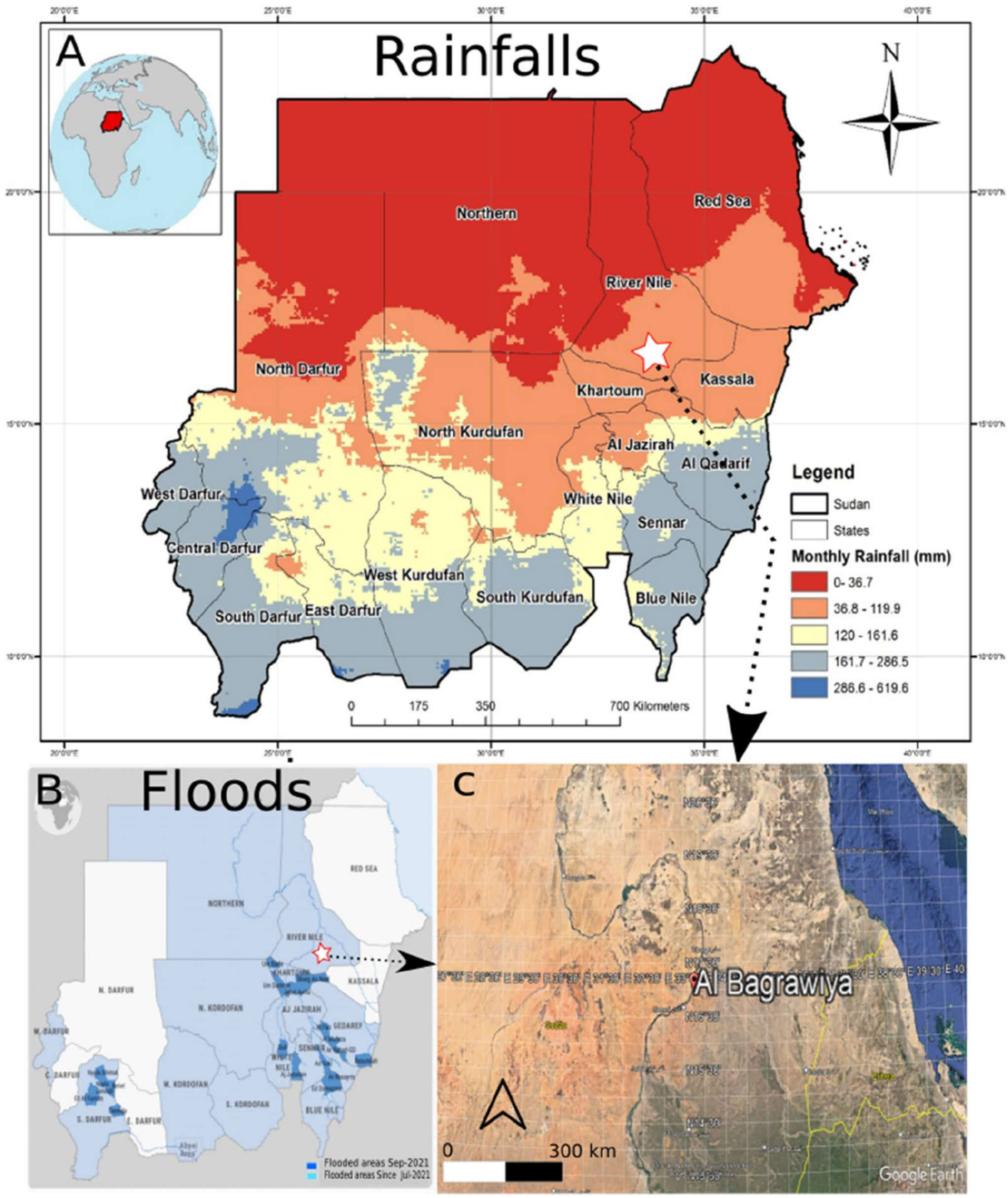

Fig. 5 **A** Map of Sudan's rainfall (after [43]). **B** Map of areas affected by flooding in Sudan (after [55]). White stars present the case study (**C**)

formed around the pyramids is a barchan shape (Fig. 6) [50]. Sudan experiences wind speeds at 90 m height varying between 8.96 and 8.73 m/s. The wind speed in the area around the case study is measured to be approximately 15.2 m (height), especially in the winter season. In this regard, sand could be transported at 6.7 m/s (speed). In the cases of sand storms, the carried sand measured to be 100 m (width) during 1 month of sand flowing, focused more on the northwest of Sudan [48, 50]. In this sense, sand dunes are the most serious and dangerous environmental problem in the northern part of Sudan and affect the archaeological sites in Sudan. For this, the strongest wind in Sudan is from December to April, and the calm wind is from June to October (Fig. 7). Google Earth images were collected and processed by software (SEADAS) to monitor the movements of the dunes around the pyramids from June 2004 until July 2021. During the last 15 years, the dunes increased from 1 year

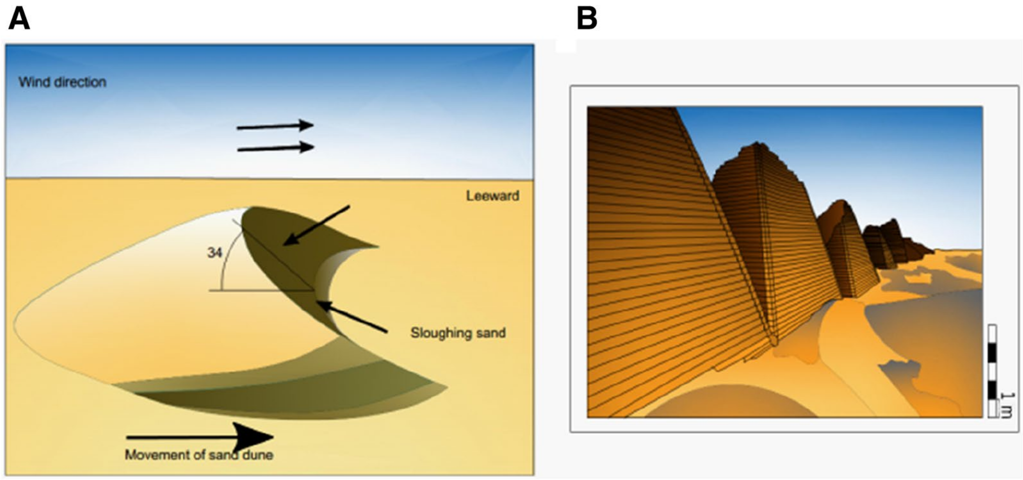

Fig. 6 **A** Barchan sand dune components and movement. **B** Schematic formation of barchan sand dunes around pyramids

to another and covered parts of the pyramids from one to three meters (Fig. 8).

Figure 9 presents the risk analysis mapping for sand dune coverage around the pyramids. The rate of coverage from 2004 to 2021 increased, especially in 2010, 2014, and 2021. The area covered by sands around the pyramids is approximately 15400 m^2 with volumes of 15400, 30800, and 46200 m^3 and an estimated thickness of 1, 2, and 3 m, respectively. In this sense, Fig. 10 shows the rate of coverage for the sand dunes over the pyramids and was carried out to assess to what extent the pyramids have been covered by sand. The classification of coverage rate has been divided into three categories: uncovered, partially covered, and totally covered. In 2004, one pyramid was uncovered, 12 pyramids were partially covered, and 6 pyramids were totally covered by sand. In 2010, 3 pyramids were uncovered, 8 pyramids were partially covered, and 7 pyramids were totally covered. In 2014, one pyramid was uncovered, 14 pyramids were partially covered, and 4 pyramids were totally covered. Finally, in 2021, 7 pyramids were partially covered, 12 pyramids were totally covered, and there were no uncovered pyramids. From the previous observations, in 2021, the coverage of sands over the pyramids was higher than in other compared years, and the coverage rate of the sands over the pyramids depended on the wind power and its direction.

Moreover, there are different processes and mechanisms for sand dune impacts over the pyramids, especially during wind moving toward the pyramids. In the movement moments of sand, three processes of saltation, suspension, and sandblasting occur, which have a vital role in pyramid erosion and damage. Saltation/bombardment occurs when wind transports particles, mainly quartz, between 0.063 and 0.5 mm and usually at a height less than 1.5 m above ground level. Suspension is the transportation of particles for a long time, and the particle diameters are less than 0.063 mm. Sandblasting is a process whereby salt particles bombard soil aggregates, causing aggregate fragmentation and the release of fine particles [46]. Figure 11A explains the mechanism of saltation, transportation, suspension, and sandblasting of particles around the pyramids of Meroe. On the other hand, macro processes such as the accumulation of sand around the pyramids can represent an external force over the structure of the walls causing structural deformations, especially when the sands are mixed with water to be more compact with a high load (Fig. 11B). In this regard, wind erosion (encroachment) is the most dangerous geoenvironmental factor in Sudan that causes the degradation not only of archaeological buildings but also of soil degradation (dissertation) in arid and semiarid areas [51]. Likewise, wind speed is the main key in the decay of the building materials of the pyramid, especially when the potential energy of wind is more than 5 m/sec. In this context, recent studies in Sudan confirmed that the potential of wind energy exists in many areas with an average annual wind speed of more than 5 m/sec [52].

In addition, wind can transfer the heat and moisture inside the construction materials of the pyramids, increasing decay. Masaru et al. [53] mentioned that wind-driven rain loads might lead to moisture flow into the interior surfaces of buildings, increasing the humidity and heat transmission to the walls. The interaction of climatic factors such as variations in temperature and

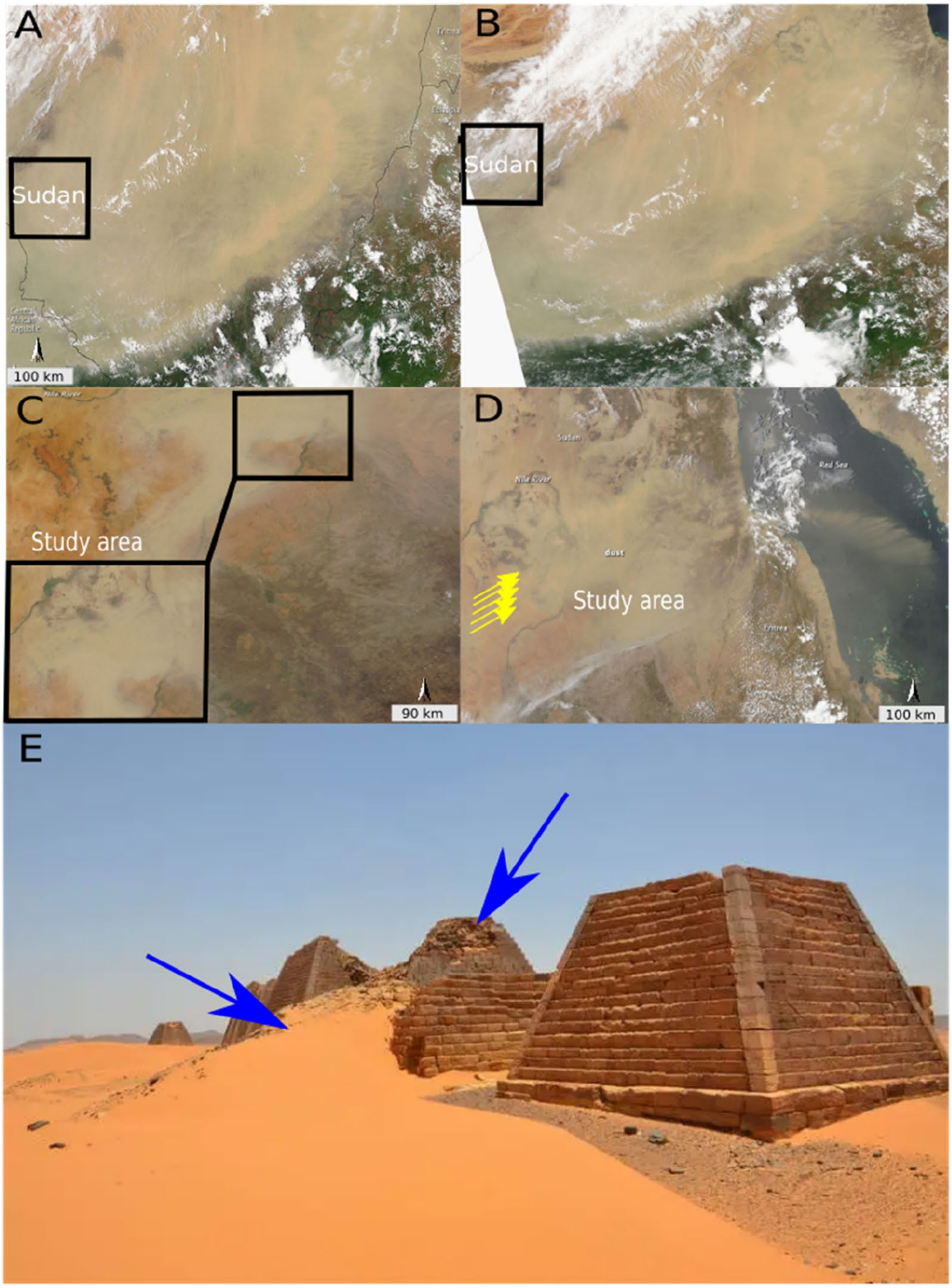

Fig. 7 **A** and **B** Captured satellite images for sandstorm over Sudan on 9 May 2009 (from https://earthobservatory.nasa.gov/images/38459/dust-storm-over-sudan). **C** and **D** A sandstorm over the archaeological site of Al Bagrawiya on 14 May 2013 (from https://earthobservatory.nasa.gov/images/81127/dust-storm-in-sudan). Yellow arrows in **D** refer to the wind directions. **E** General view of the pyramids of Meroe and the impact of the sand dunes on the building materials of the pyramids. Taken by Martchan/Shutterstock (https://www.theafricandream.net/sudan-forgotten-pyramids-are-more-than-egypt/)

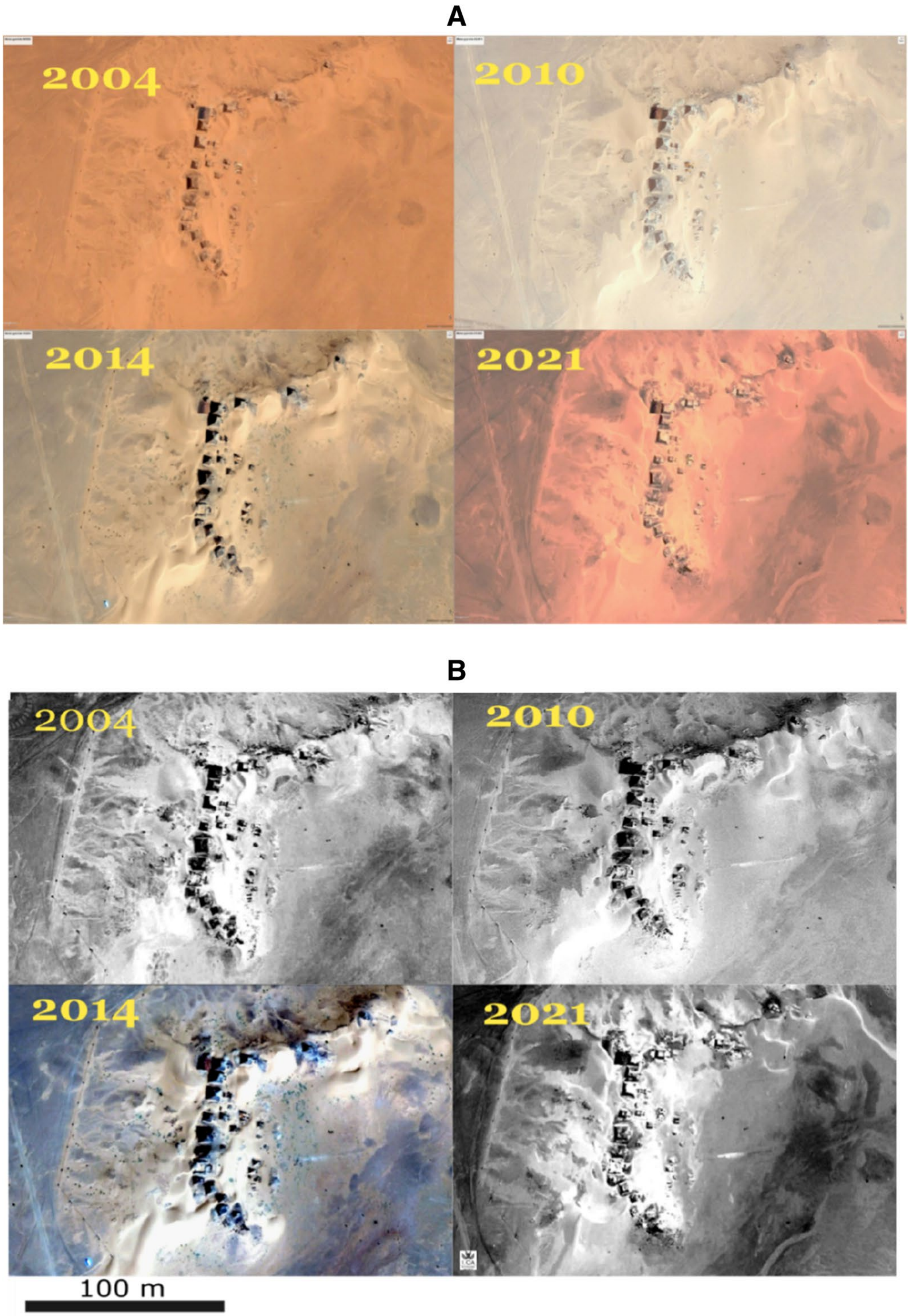

Fig. 8 **A** Images for monitoring the movement of sand dunes around the pyramids from Google Earth. **B** Treated images to clearly see this movement around the pyramids. Images from 2004 to 2021 are in grey colour, except for 2014, which is in RGB colour

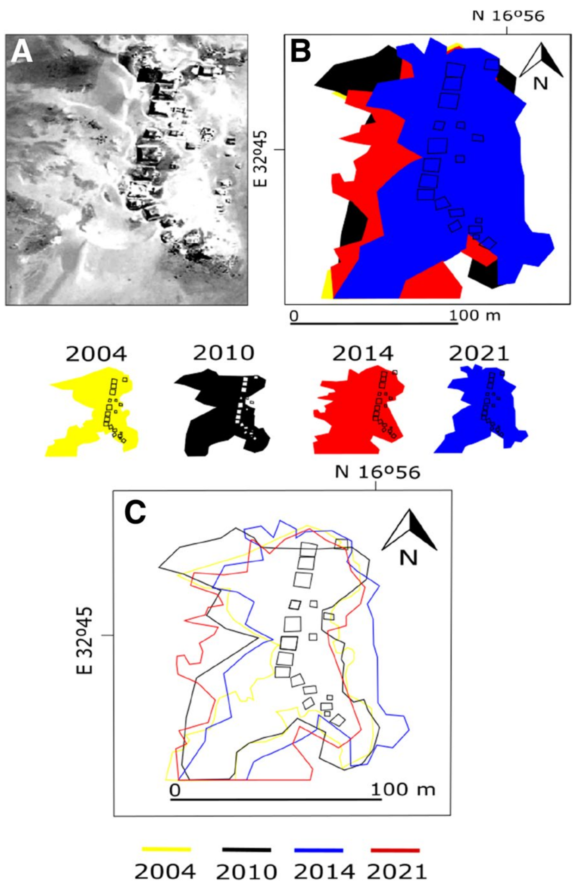

Fig. 9 **A** Base map for the studied area. **B** Coloured estimation for sand dune coverage around the pyramids and their variations from 2004 to 2021. **C** Linear outlines for the variations in sand dune coverage from 2004 to 2021

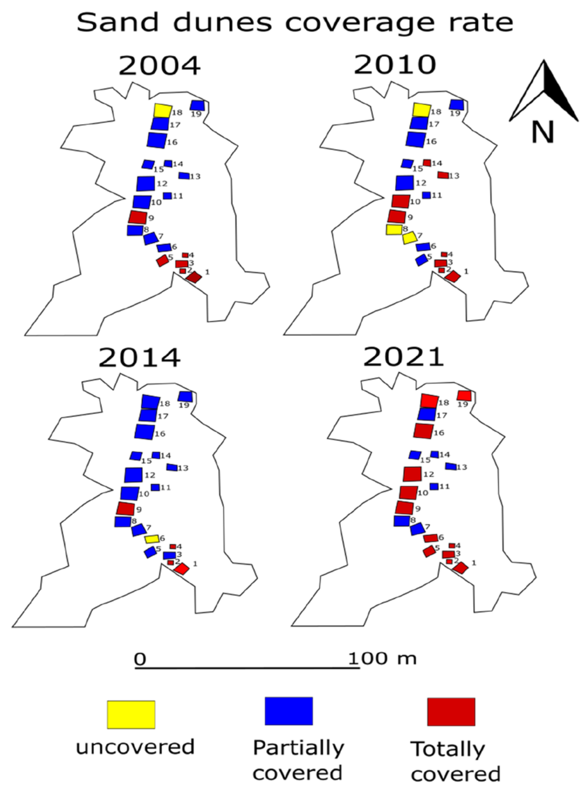

Fig. 10 The coverage rates of the accumulated sands over the studied pyramids in 2004, 2010, 2014 and 2021

humidity along with wind could cause acceleration and more damage to the construction materials of the pyramids. In this sense, Moncmanová [54] confirmed that decreasing and increasing temperatures could cause differential thermal conductivity between the outer layer and inner core of the stones, which will lead to fine cracks, spalling, and lack of strength.

Heavy rains and flash flooding risks

Sudan is subjected to flash floods and heavy rains yearly from July to September. Many destructions are happening to houses, people, and infrastructures. In 2007, during the season of flooding, Sudan was subjected to the worst heavy/intense rains, which affected so much of the infrastructure and the archaeological sites in Sudan (Fig. 12). According to the Sudanese report on 12 August 2021, heavy rains and flooding affected six locations in the River Nile state, including Atbara, Shendi, Al Matama, Barbar, Abu Hamad, and Ad Damar, from 7 to 10th August 2021. The floods led to vast destruction of the new houses and built heritage where the flood rate exceeded the risk level. (Fig. 13A and B) [55]. In this regard, [23] displayed damage to the red brick and mud-brick structures in Wad Ben Naga's archaeological site due to seasonal heavy rains and flooding. The Sudanese report on 16 September 2021 confirmed that floods affected many archaeological sites, especially the island of Meroe. In addition, they mentioned that the water levels of the Nile River have risen above flooding risk levels at the Khartoum, Atbara, Shendi, and Ed Diem stations. Water levels reached 17 m, which was 50 cm above the flooding risk level [55].

Damage rate and decay patterns of the pyramids

Risk analysis for the damage rate over the pyramids was carried out to identify the state of conservation for each pyramid in the study area. The damage is classified into three categories: slightly, moderately, and severely damaged. Figure 14 presents the damage rate of the pyramids over several years. In 2004, 3 pyramids were slightly

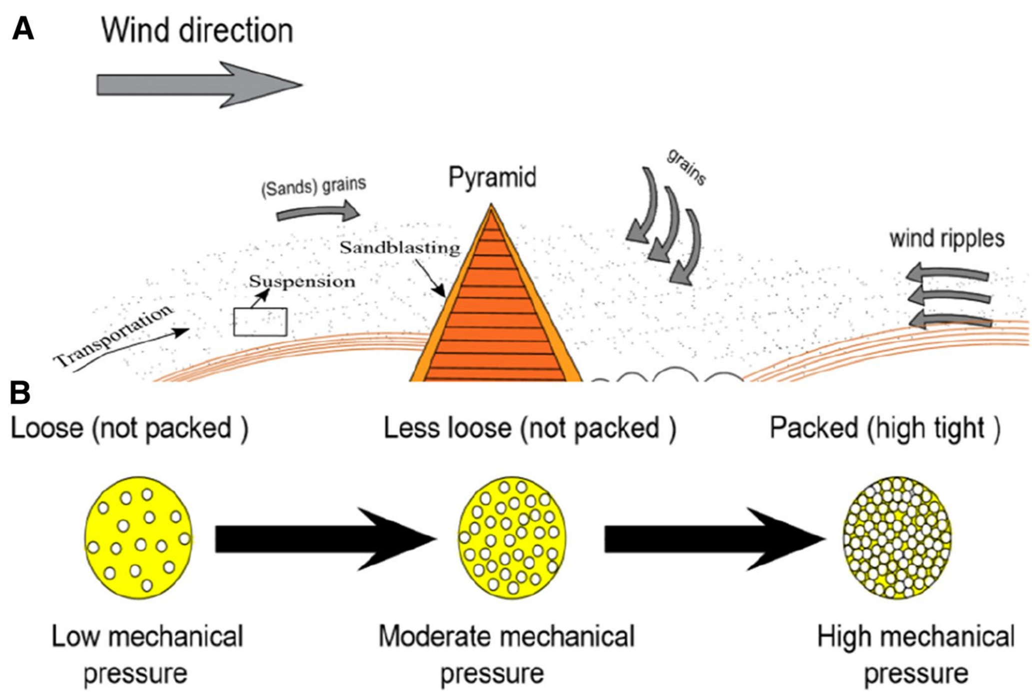

Fig. 11 **A** Mechanism of sand accumulation around the pyramids. **B** Three possible phases for the sands as external forces on pyramid structures

damaged, 7 pyramids were moderately damaged and 9 pyramids were severely damaged. In 2010, 2 pyramids were slightly damaged, 5 pyramids were moderately damaged and 12 pyramids were severely damaged. In 2014, one pyramid was slightly damaged, 6 pyramids were moderately damaged, and 12 pyramids were severely damaged. In 2021, 4 pyramids were moderately damaged, and 15 pyramids were severely damaged. From the previous observations, in the last two periods in 2014 and 2021, the damage rate increased due to the increasing activity of wind power and climate change.

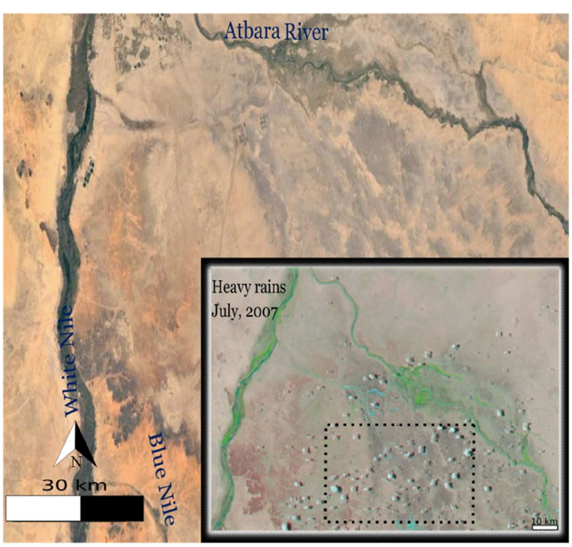

Fig. 12 Aerial satellite image to show the heavy rains over the case study in July 2007. From https://earthobservatory.nasa.gov/images

Figure 15A–F shows the most dominant deterioration patterns over the construction material of the pyramids of Meroe at the Al Bagrawiya archaeological site, such as collapsing, crumbling, buckling, disintegration, alveolarization, loss of materials, and cracking. In this sense, Fratini and Rescic [56] confirmed that the abrasive effect of wind is an important factor that causes the alveolarization of ancient building materials. In this arid area, the wind has a significant potential for causing failures for the blocks of the pyramid and can cause wall collapse and detachment of the casing stones, in addition to out-of-plane buckling [57]. Cracks and disintegration could be caused by the expansion and contraction of the construction materials in accordance with the heating and cooling effect of temperature and wind power [58].

Conclusion

The present study showed two geoenvironmental factors that threatened the preservation state of the Al Bagrawiya Archaeological Sites in Sudan. For this, the current study explained the impact of sand dunes and their role in the

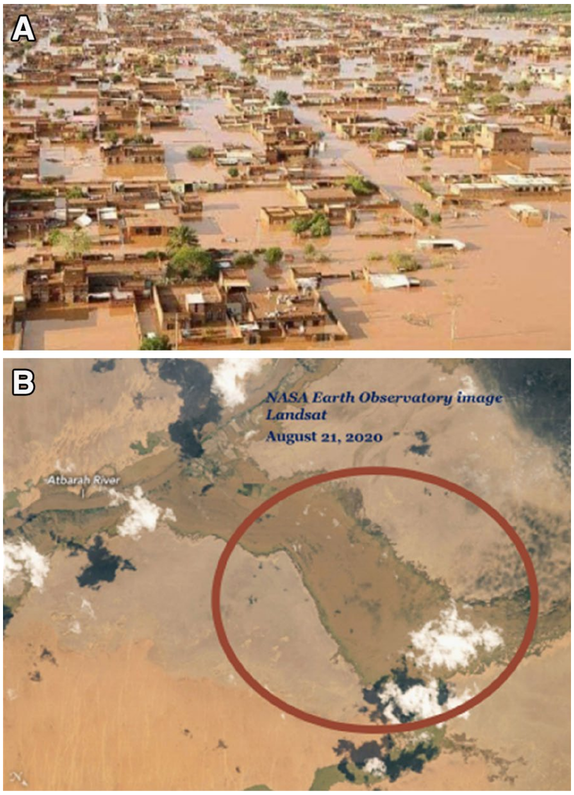

Fig. 13 **A** The impact of flooding in Sudan. From: https://dailynewsegypt.com/2020/09/06/egypt-dispatches-urgent-aid-to-flood-hit-sudan/. **B** Satellite image of the flooding over Atbara and near the Al Bagrawiya archaeological site. From: https://earthobservatory.nasa.gov/images/147288/record-flooding-in-sudan

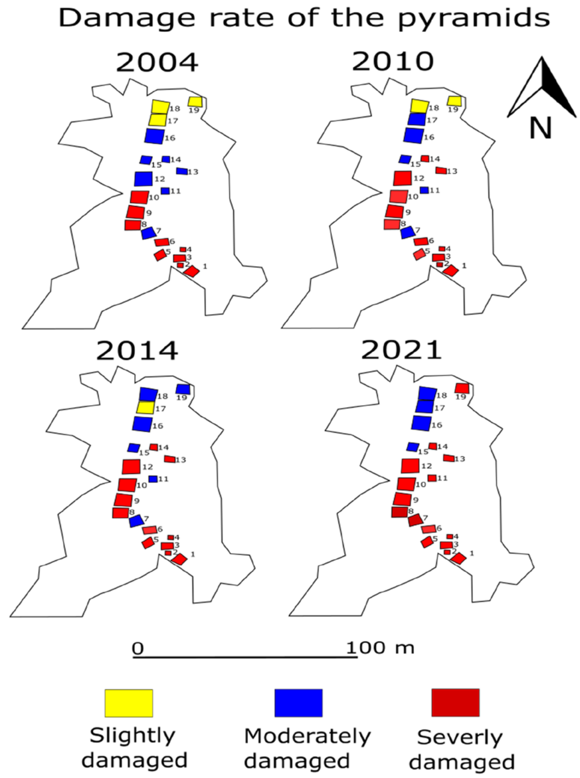

Fig. 14 Damage rate for the pyramids in 2004, 2010, 2014 and 2021

degradation of the construction materials of the pyramids. In addition, wind power is considered an erosive factor for the sandstone blocks of the pyramids. Furthermore, the research presented the threats of flooding of the Nile River on the archaeological sites of Al Bagrawiya.

Sand dunes played a significant role in the destruction and degradation of the building materials of the pyramids of Meroe. In this regard, satellite images showed that the sand dunes are Barchan type, which increased each year due to the accumulation of sand during the strong wind and sandstorms that cause damage and degradation to the pyramids. Wind is considered a deterioration key et al. Bagrawiya, the archeological site that led to sand dune formations and abrasion of the building materials for the pyramids.

Sand dunes and wind loads resulted in decay and destruction patterns of the building materials of the pyramids, such as total collapse, disintegration, loss of materials, crumbling, cracks, and buckling. Flooding from heavy rains and rising Nile River water is considered a potential threat at the Al Bagrawiya archeological site and its pyramids. In 2020 and 2021, the water levels reached 17 m beyond the safe flooding rate, which gives us a red alarm to take all precautions to carry out preventive protection for archaeological sites from probable damage from flooding.

Future studies with multianalytical techniques are needed regarding the chemical and physical impact of sand dune components (quartz, gypsum, clay, etc.) on the construction building materials of these pyramids. In addition, restoration, conservation, and site management plans are highly recommended for safeguarding this important archaeological site and its built pyramids.

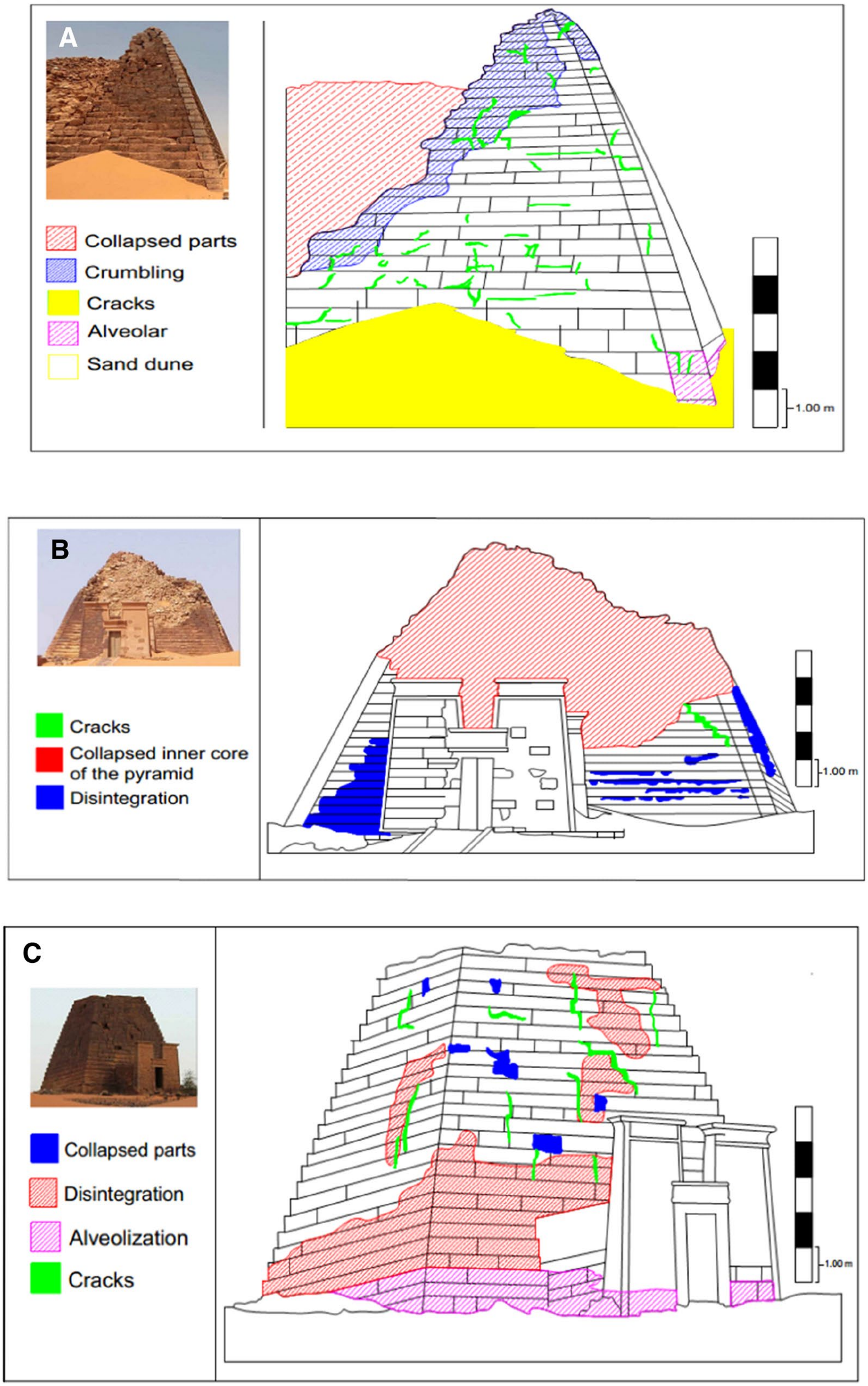

Fig. 15 **A**–**F** Degradation maps for the construction materials for the pyramids of Meroe

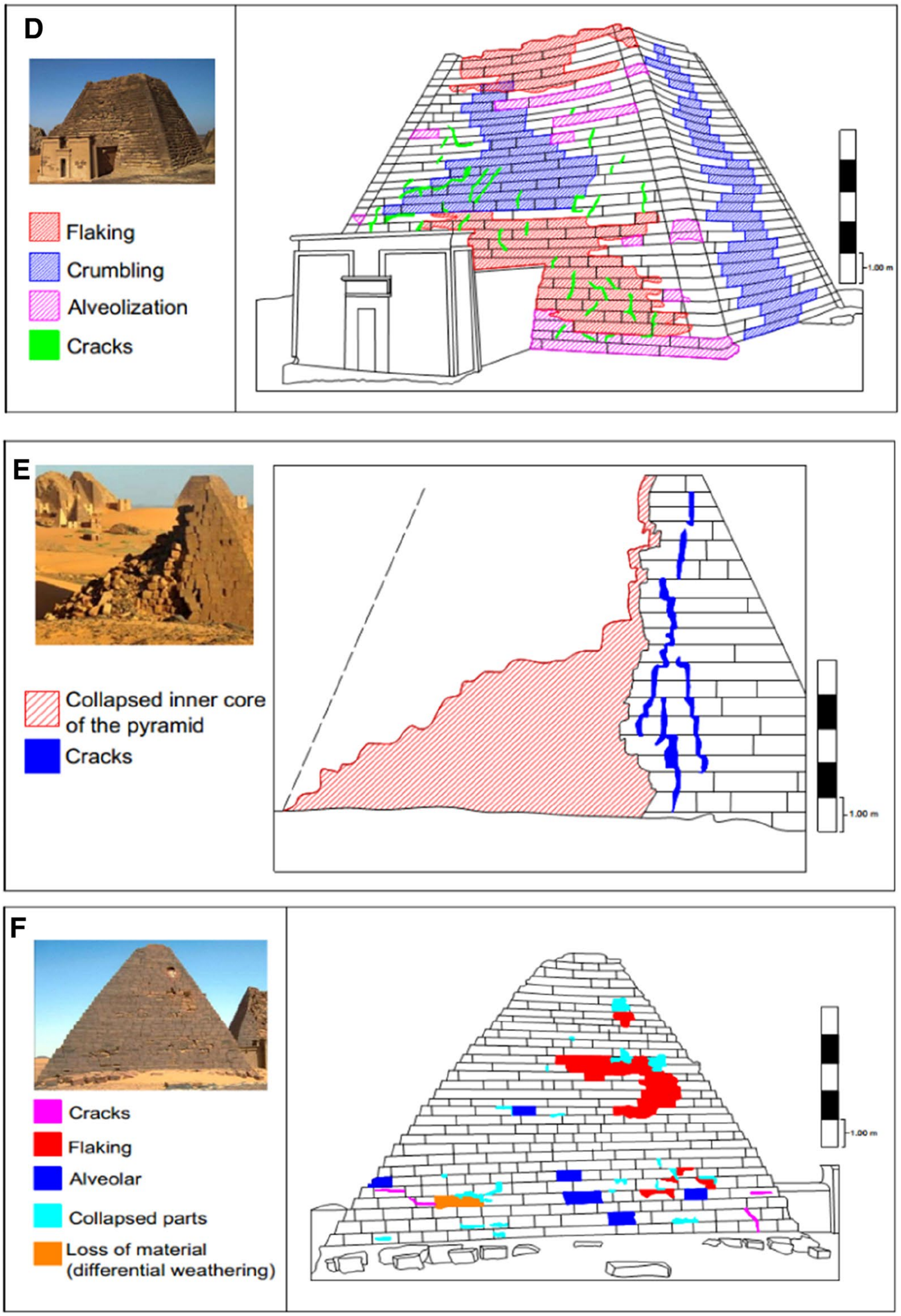

Fig. 15 continued

Acknowledgements
A. Fahmy acknowledges UGEA-PHAM and HUM-440 at the University of Cadiz for their given facilities to carry out this research. E. Molina Piernas acknowledges co-funding from the European Social Fund (D1113102E3) and Junta de Andalucía.

Author contributions
AF wrote the main manuscript. SDB, JML, EMP supervised and reviewed the article.

Funding
Funding for open access publishing: Universidad de Cádiz/CBUA. Not applicable.

Availability of data and materials
Not applicable.

Declarations

Competing interests
The authors declare no competing interests.

Received: 7 March 2023 Accepted: 20 June 2023
Published online: 27 June 2023

References

1. Stambolov T. The deterioration and conservation of porous building materials in monuments. 1976. https://www.iccrom.org/sites/default/files/2018-02/1976_stambolov_deterioration_eng_21362_light.pdf. Accessed 12 Feb 2023.
2. Fitzner B, Heinrichs K, Bouchardiere DL. Weathering damage on Pharaonic sandstone monuments in Luxor - Egypt. Build Environ. 2003;38:1089–103. https://doi.org/10.1016/S0360-1323(03)00086-6.
3. Sandrolini F, Franzoni E, Sassoni E, Paolo P. The contribution of urban-scale environmental monitoring to materials diagnostics: a study on the Cathedral of Modena (Italy). J Cult Herit. 2011;12:441–50. https://doi.org/10.1016/j.culher.2011.04.005.
4. Hemeda S, Fahmy A, Sonbol A. Geo-environmental and structural problems of the first successful true pyramid, (Snefru Northern Pyramid) in Dahshur, Egypt. Geotech Geol Eng. 2019;37(4):2463–84. https://doi.org/10.1007/s10706-018-00769-x.
5. Hemeda S, Fahmy A, Moustafa A, El HMA. The Early Basilica Church, El-Ashmonein Archaeological Site, Minia, Egypt: geo-environmental analysis and engineering characterization of the building materials. Open J Geol. 2019;09:157–86. https://doi.org/10.4236/ojg.2019.93011.
6. Fahmy A, Molina-Piernas E, Martinez-López J, Domínguez-Bella S. Salt weathering impact on Nero/Ramses II Temple at El - Ashmonein archaeological site (Hermopolis Magna). Egypt Herit Sci. 2022;10:125. https://doi.org/10.1186/s40494-022-00759-6.
7. Fahmy A, Molina-Piernas E, Domínguez-Bella S, Martínez-López J, Helmi F. Geoenvironmental investigation of Sahure's pyramid, Abusir archeological site, Giza, Egypt. Herit Sci. 2022. https://doi.org/10.1186/s40494-022-00699-1.
8. Delaney A, Devaney FM, Martin JM, Barron SJ. Monitoring survey of Annex I sand dune habitats in Ireland. Irish Wildlife Manuals, No. 75. National Parks and Wildlife Service, Department of Arts, Heritage and the Gaeltacht, Dublin, Ireland. 2013. https://www.npws.ie/sites/default/files/publications/pdf/IWM75.pdf
9. Stancheva M, Ratas U, Orviku K, Palazov A, Rivis R, Kont A, Peychev V, Tõnisson H, Stanchev H. Sand dune destruction due to increased human impacts along the Bulgarian Black Sea and Estonian Baltic Sea Coasts. J Coast Res. 2011;64:324–8.
10. Barbaro G, Foti G, Chiara G. Beach and dune erosion: causes and interventions, case study: kaulon archaeological site. J Mar Sci Eng. 2022;10(1):14. https://doi.org/10.3390/jmse10010014.
11. Wilson P. Sand dunes and archaeology. J Ir Archaeol. 1995;9:24–6.
12. Tsoar H, Cohenzada A, L. The conflict between urban planning and the preservation of sand dunes—the case of the Big Dune in the city of Ashdod, Israel. City Environ Interact. 2020;5:100034. https://doi.org/10.1016/j.cacint.2020.100034.
13. Ra L, Bruno L. Windblown sand action on civil structures: definition and probabilistic modelling. Eng Struct. 2019;178:88–101. https://doi.org/10.1016/j.engstruct.2018.10.017.
14. Ortiz R, Ortiz P, María J, Auxiliadora M. A new approach to the assessment of flooding and dampness hazards in cultural heritage, applied to the historic centre of Seville (Spain). Sci Total Environ. 2016;551–552:546–55. https://doi.org/10.1016/j.scitotenv.2016.01.207.
15. Drdácký MF. Impact of floods on heritage structures. J Perform Constr Facil. 2010;24:430–1. https://doi.org/10.1061/%28ASCE%29CF.1943-5509.0000152.
16. Iosub M, Enea A, Minea A. Flash flood impacts on the cultural heritage in Moldova region, Romania. Case study: Jijia valley. 19th International Multidisciplinary Scientific GeoConference SGEM. 2019; 30 June - 6 July, pp.839–846. Available from: https://doi.org/10.5593/sgem2019/2.2/S11.103
17. Fahmy A. Geo-environmental and seismic response analysis of free-standing stone columns at El-Ashmonein archaeological site- Minia-Egypt. With practical applications for restoration and preservation. Master thesis. 2019. http://research.asu.edu.eg/handle/123456789/177612. Accessed 14 Feb 2023.
18. Fernandes F. Built heritage and flash floods: hiking trails and tourism on Madeira Island. J Heritage Tour. 2016;11:6631. https://doi.org/10.1080/1743873X.2015.1082574.
19. Al-Weshah RA, El-Khoury F. Flood analysis and mitigation for Petra area in Jordan. J Water Resour. 1999;125:3. https://doi.org/10.1061/(ASCE)0733-9496(1999)125:3(170).
20. Sweek T, Anderson JR, Tanimoto S. Architectural conservation of an Amun temple in Sudan. JCMS. 2012;10(2):8–16. https://doi.org/10.5334/jcms.1021202.
21. Osman MA, Ali EM, Elhaj OB. A study on geotechnical properties of weak rocks in Sudan abstract. J Build Road Res. 2014;17:13–27. https://doi.org/10.53332/jbrr.v17i.597.
22. Government of Sudan Report: Sudan Rapid Post Disaster Needs and Recovery Assessment (Rapid PDNRA). 2021. https://www.gfdrr.org/sites/default/files/Sudan_RPDNRA-English_HighRes.pdf. Accessed 14 Feb 2023.
23. Onderka P, Vrtal V. Preliminary report on the nineteenth excavation season of the archaeological expedition. Ann Naprstek Mus. 2021. https://doi.org/10.37520/anpm.2021.012.
24. Fahmi M M, Ahmad Y, Hashim H. The Challenges for preserving glorious heritage of sudan: status and solutions. **2022**; 9(2), 25–38. https://www.informaticsstudies.org/index.php/informatics/article/download/334/434. Accessed 16 Feb 2023.
25. Boozer AL. A historiography of archaeological research at Meroë, Sudan. AncWest East. 2017;16:209–48. https://doi.org/10.2143/AWE.16.0.3214940.
26. Hadjimitsis DG, Agapiou A, Themistocleous K, Alexakis DD, Sarris A. Remote sensing for archaeological applications: management, documentation and monitoring. In: Diofantos G, editor. Remote sensing of environment—integrated approaches. London: IntechOpen; 2013.
27. Tapete D. Remote Sensing and Geosciences for Archaeology. Geosci. 2018. https://doi.org/10.3390/books978-3-03842-764-3.
28. De Angeli S, Battistin F. Archaeological site monitoring and risk assessment using remote sensing technologies and GIS. Collection: geography, planning and tourism. Monograph Chapter 12. Cheltenham: Edward Elgar Publishing; 2021. p. 145–54.
29. Hu NK, Li X. Sand dunes, mobility, and cultural heritage. IOP Conf Ser Earth Environ Sci. 2017;57:012028. https://doi.org/10.1088/1755-1315/57/1/012028.
30. Ahmed SM, Welspy D. The Archaeological Sites of the Island of Meroe. Nomination file: World Heritage Centre. Online Report. 2019. https://whc.unesco.org/document/168998. Accessed 17 Feb 2023.
31. Yellin J. Meroitic royal chronology: the conflict with Rome and its aftermath: Sudan & Nubia. Sudan Archaeol Res Soc. 2015;19:2–15.
32. Riedel A, Wolf P. Meroe, Sudan. Archaeological Investigation, Conservation and Site Management at the Meroe Royal Cemeteries/Sudan – The Qatari Mission for the Pyramids of Sudan. The years 2015 and 2016.

e-Forschungsberichte, S. 2018;152–157. http://www.sudarchrs.org.uk/wp-content/uploads/2019/07/SARS_SN20_Riedel-et-al.pdf. Accessed 21 Feb 2023.
33. Hinkel FW. The royal pyramids of meroe. architecture, construction and reconstruction of a sacred landscape, Sudan & Nubia. Sudan Archaeol Res Soc. 2000;4:11–26.
34. Ahmed AH. Mineral deposits and occurrences in the arabian-nubian shield. New York: Springer Cham; 2022. p. 521.
35. Worrall GA. A simple introduction to the geology of the Sudan. Sudan Notes Rec. 1957;38:2–9.
36. Whiteman AJ. Geology and scenery of Sudan. Sudan Notes Rec. 1966;47:137–44.
37. Fielding L, NajmanY Millar I, Butterworth P, Ando S, Padoan M, Barfod D, Kneller B. A detrital record of the Nile River and its catchment. J Geol Soc. 2016;174(2):301–17. https://doi.org/10.1144/jgs2016-075.
38. Williams M. Geology and soils. In the Nile Basin quaternary geology, geomorphology and prehistoric environments. CUP. 2019. https://doi.org/10.1017/9781316831885.005.
39. Abujaball MM. Sedimentary Facies & Depositional Environment of Shendi Formation, Al-Musauwarat/Umm Ali Area, Sudan. Master thesis. 2019. Available from: http://dspace.iua.edu.sd/bitstream/123456789/5235/1/introd.pdf
40. Humphris J, Bussert R, Alshishani F, Scheibner T, Humphris J, Bussert R. The ancient iron mines of Meroe. Azania Archaeol Res Afr. 2018;53(3):291–311. https://doi.org/10.1080/0067270X.2018.1515922.
41. Cech B. The Quarries of Meroe, Sudan. UCL Qatar series in archaeology and cultural heritage. Doha: Hamad bin Khalifa University Press; 2018. https://doi.org/10.5339/uclq.2018.9789927118883.
42. World Bank. Sudan. Online report. 2021. https://www.climatecentre.org/wp-content/uploads/RCCC-ICRC-Country-profiles-Sudan.pdf. 1–9.
43. Siddig K, Stepanyan D, Wiebelt M, Grethe H, Zhu T, Berlin H. Climate change and agriculture in the Sudan: impact pathways beyond changes in mean rainfall and temperature. Ecol Econ. 2020;169:106566. https://doi.org/10.1016/j.ecolecon.2019.106566.
44. Salih AAM, Ahmed N, Tjernström M, Zhang Q. Characterization of the Sahelian-Sudan rainfall based on observations and regional climate models. Atmos Res. 2018;202:205–18. https://doi.org/10.1016/j.atmosres.2017.12.001.
45. UNEP. More action needed on sand and dust storms. Online report. 2017. https://www.unep.org/es/node/331. Accessed 23 Feb 2023.
46. UNEP, WMO, UNCCD. Global Assessment of Sand and Dust Storms. United Nations Environment Programme, Nairobi. Online report. 2016. https://wesr.unep.org/redesign/media/docs/assessments/global_assessment_of_sand_and_dust_storms.pdf. Accessed 24 Feb 2023.
47. Sharif S M. Dust Storms in Sudan: intensity and particles; characteristics. Online document. 2014. 26–29. https://www.researchgate.net/publication/262602280_Dust_Storms_in_Sudan_Intensity_and_Particles_Characteristics. Accessed 27 Feb 2023.
48. Khadam AMA, Hamouda EA, Doud KR. Wind power harnessing in sudan, opportunities and challenges wind power harnessing in Sudan, Opportunities and Challenges. UofKEJ. 2016;6(2):1–6. https://doi.org/10.13140/RG.2.2.22530.68802.
49. Wahab. Probability distribution of extreme wind speeds in Sudan. J East Afr Stud. **2001**; 47(39). https://pdfcoffee.com/wind-in-sudanpdf-3-pdf-free.html. Accessed 28 Feb 2023.
50. Ghrefat H A. The geology of sand dunes. Nova Science Publishers, Inc. ch4. 2021. https://www.researchgate.net/publication/287244680_The_geology_of_sand_dunes. Accessed 01 Mar 2023.
51. Ayoub AT. Extent, severity and causative factors of land degradation in the Sudan. J Arid Environ. 1998;38(3):397–409. https://doi.org/10.1006/jare.1997.0346. Accessed 03 Mar 2023.
52. Gamri T. Sand dunes: mechanisms, impacts and control measures in the Sudan sand dunes: mechanisms, impacts and control measures in the Sudan. ENRIJ. 2021;5(3):1–16.
53. Masaru A, Janssen H, Roels S. Impact of wind-driven rain on historic brick wall buildings in a moderately cold and humid climate: numerical analyses of mould growth risk, indoor climate and energy consumption. Energy Build. 2009;41(1):101–10. https://doi.org/10.1016/j.enbuild.2008.07.011.
54. Moncmanová A. Environmental factors that influence the deterioration of materials. Billerica: WIT Press; 2007. p. 1–25. https://doi.org/10.2495/978-1-84564-032-3/01.
55. OCHA. Sudan. Situation Report. 2021. https://reliefweb.int/sites/reliefweb.int/files/resources/Situation%20Report%20-%20Sudan%20-%2019%20Sep%202021.pdf. 13(13): 1–21.
56. Fratini F, Rescic S. The stone materials of the historical architecture of Tuscany. Geol Soc Spec Publ. 2016;391:71–92. https://doi.org/10.1144/SP391.5.
57. Maraveas C, Fasoulakis Z. Wind-induced failure analysis and retrofit of an existing steel structure. Open Civ Eng J. 2018;8:271–91. https://doi.org/10.4236/ojce.2018.83021.
58. Zanke AS. Building cracks: causes and preventions. IJEST. 2020;5(8):165–9. https://doi.org/10.33564/IJEAST.2020.v05i08.025.

Publisher's Note
Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.