GIS Odyssey Journal

2021 • Volume 1 • Number 2

https://doi.org/10.57599/gisoj.2021.1.2.103

Lidia Żuk[1], Sonia Tomczak[2], Luka Mamić[3]

‘THE SKY IS NOT THE LIMIT’ – GIS ANALYSIS OF SENTINEL-2 IMAGERY FOR HERITAGE PROTECTION AND MANAGEMENT

Abstract: This article aims to demonstrate the potential of Sentinel-2 and GIS for heritage monitoring, protection and management. Applications of remote sensing in heritage strategies have been explored for decades. However, new possibilities were opened up with the launch of the European Union's Earth Observation Programme Copernicus. Systematic and frequent global coverage of land surface offered by one of its products – Sentinel-2, provides an almost instant insight into sudden events and long-term processes that affect heritage around the world. Following new developments in remote sensing, GIS provides tools to integrate data for their effective processing, analysis, interpretation and dissemination of results. We will explore the potential and limitations of those datasets and tools using UNESCO World Heritage sites from Sudan as case studies. In particular, we will tackle issues related to interpretation of changes around heritage sites, attempt to estimate their recent conditions and identify existing and/ or potential threats.

Keywords: GIS, archaeological heritage protection, satellite imagery, Sentinel-2, UNESCO sites

Received: 27 December 2021; accepted: 30 December 2021

---

[1] Adam Mickiewicz University in Poznań, Faculty of Archaeology, Poznań, Poland, ORCID ID: 0000-0002-8475-746X, email: lidkazuk@amu.edu.pl

[2] Nicolaus Copernicus University in Toruń, Doctoral School of Humanities, Theology and Arts, Toruń, Poland, ORCID ID: 0000-0002-6933-1487, email: soniatomczak@gmail.com

[3] University of Zagreb, Faculty of Geodesy, Zagreb, Croatia, ORCID ID: 0000-0001-9877-0174, email: lmamic@geof.hr

Introduction

There can be little doubt that archaeological heritage is undergoing dynamic processes that can be observed in different parts of the world. Natural hazards and cultural phenomena pose serious threats to the preservation and integrity of that heritage. Moreover, the rapidity of those changes requires frequent observations to monitor negative tendencies and develop effective strategies for their protection. Remote sensing has been long recognised as a powerful tool in heritage protection and management (e.g. Beck et al., 2007; Lasaponara & Masini, 2008; Cowley, 2011). Its growing importance in the last decade is reflected in publications by leading specialists in archaeological remote sensing that demonstrate broad ranges of applications and also open up new directions (Tapete, 2018a; Verhoeven et al., 2021). Among many factors, its increasing role is attributed to the technological development of sensors for data capture and the accessibility of new remote sensing and Earth Observation data (Tapete, 2018b). The European Union's programme Copernicus is one of a number of recent advances in the field of Earth Observation Programmes. According to the European Space Agency (ESA), it aims to provide timely and quality information, ensuring autonomous and independent access to reliable information around the globe (Martimort et al., 2007). Moreover, the high frequency of image acquisition from Sentinel missions offers an almost instant insight into sudden events: their development, extent, effects and aftermath. Therefore, it seems a ready-made solution to challenges in heritage strategies that are posed by global changes. However, its potential has not yet been adequately explored. As noted elsewhere, there is a noticeable preference for very high resolution (VHR) optical imagery that are mainly obtained from commercial providers (Tapete, 2018b). Applications of Copernicus products in archaeological studies still seem to be rare (see Tapete & Cigna, 2018; Abate et al., 2020). We will attempt to address this gap by exploring the potential of the optical dataset provided by Sentinel-2.

In pursuit of an autonomous heritage monitoring system

Initially, the idea behind the assessment of Sentinel-2 for heritage monitoring was relatively straightforward. We attempted to select a few well-documented archaeological sites that were recently reported as being affected either by natural or cultural threats. Using established methods of satellite data processing or an approach to available data characterized as “beg, borrow and steal” to use a phrase from Cowley et al. (2021), we aimed to estimate the impact of such events on archaeological structures. We assumed that starting from known, well-recognized and documented cases will help establish potential and limitations of Sentinel-2 dataset. Obvious candidates for such analysis are UNESCO World Heritage sites. According to UNESCO policy, party States are obliged to regularly report on the state of conservation of World Heritage properties which allows to assess the conditions of those sites. Thousands of reports and decisions taken by the World Heritage Committee since 1979 have been published as a part of the State of Conservation (SOC) Information System, which is, according to UNESCO, “one of the most comprehensive monitoring systems of any international convention" (https://whc.unesco.org/en/soc/). Those reports were also used in statistical analysis of the state of conservation of World Heritage properties between 1979-2013 which is to date probably the most comprehensive overview of factors affecting cultural and natural heritage around the world (Veillon, 2014).

However, while browsing through statistical analysis at the SOC, one cannot overlook an interesting gap in the number of properties examined and reported each year. There are no reports for 2020 although in 2019 and 2021 a considerable number of properties was examined (166 and 255 respectively) (Fig. 1).

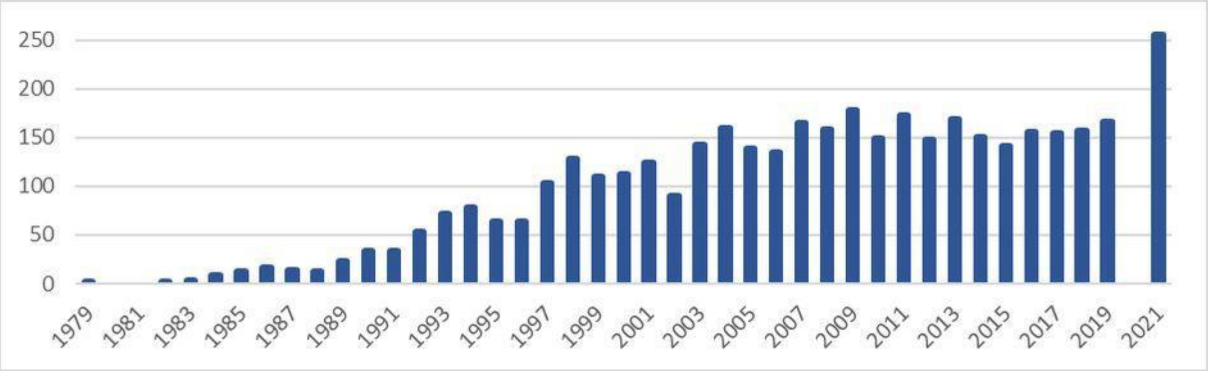


Fig. 1. Graph showing the number of UNESCO properties examined each year to assess the conditions at the sites
Source: State of Conservation System

Bearing in mind the present global situation, it is impossible to assume that 2020 was unusually heritage-friendly. On the contrary, recurring threats at numerous UNESCO sites were reported in various media. UNESCO also expressed its concern about their effect on World Heritage (see below). We can only conclude that the COVID-19 epidemic also affected heritage management. Whether it disrupted the monitoring system at its core or just reports publication and availability in SOC is another question which goes beyond the scope of this paper. In general terms, we face the situation where reliable reports from official bodies responsible for heritage management are unavailable, no other information exist and/ or alarming news about damage to heritage sites are circulated via newspapers or social media. Thus, this apparent reporting breakdown provides an interesting opportunity to test ESA'a mission claims to 'ensure autonomous, independent and reliable information' also for those well-monitored sites, despite current on-ground restrictions.

Materials and methods

Criteria. Sentinel-2 routinely generates information that is used to support a range of services such as risk management (e.g. floods and forest fires), natural hazards and global climate change monitoring, urban mapping, evaluation of land use/ land cover state and land use change (Martimort et al., 2007; Drusch et al., 2012). In UNESCO classifications those occurrences are categorized as the following threats to heritage:

buildings and development, climate change and severe weather events, transportation infrastructure, etc. (Veillon, 2014). We were also seeking categories of threats that would allow us to explore Sentinel-2's spatial, temporal and spectral resolution. These three basic characteristics are regarded as its major advantage, especially in comparison with other Earth Observation Programmes. Specifically Sentinel-2 is identified as providing "an unprecedented combination of systematic global coverage of land surfaces, a high revisit of five days (...), and a wide field of view for multispectral observations from 13 bands in the visible, near infra-red and short wave infra-red part of the electromagnetic spectrum" (Drusch et al., 2012) (Fig. 2).

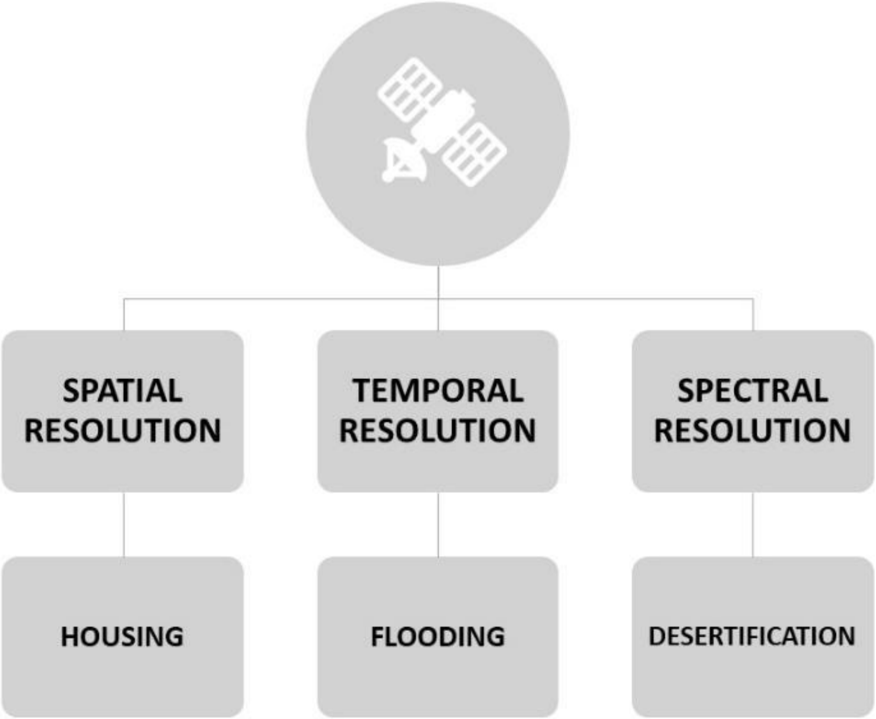


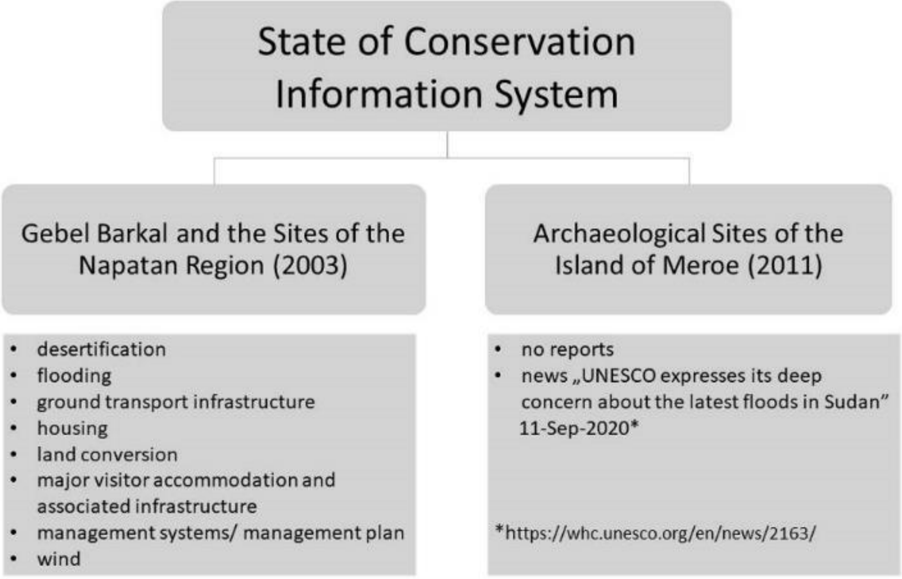
Fig. 2. The main characteristics of Sentinel-2 data and the specific threats they were applied to in our case studies
Source: own work

Case studies. Based on the above criteria, two World Heritage Sites were selected: Gebel Barkal and the Sites of the Napatan Region (inscribed in 2003) and Archaeological Sites of the Island of Meroe (inscribed in 2011). Both sites are located in Sudan, Northern states, province of Meroe (Fig. 3).

Gebel Barkal and the Sites of the Napatan Region is a complex of five sites. Gebel Barkal, Kurru, Nuri, Sanam and Zuma extend over more than 60 km on both sides of the Nile in an arid area considered part of Nubia (https://whc.unesco.org/en/list/1073/). Archaeological Sites of the Island of Meroe consists of three sites, comprising Meroe (which includes the town and cemetery site), which is situated in a riverine landscape, and two associated settlements and religious centres at Musawwarat es-Sufra and Naqa, which are located in a semi-desert landscape between the Nile and Atbara rivers (https://whc.unesco.org/en/list/1336/).

Fig. 3. Location of Gebel Barkal and the Sites of the Napatan Region and Archaeological Sites of the Island of Meroe (image ©Microsoft Corporation)
Source: own work

In the last decade the Gebel Barkal complex has been repeatedly, albeit inconsistently, reported as exposed to multiple threats. SOC contains eight reports published between 2010-2021 (https://whc.unesco.org/en/soc/4074) that indicate eight different factors that fall within four threat categories defined by UNESCO (Veillon, 2014). Contrary to this, no reports could be found for Meroe. However, in September 2020 a devastating flood that was threatening this site was reported in the media (Reuters Staff, 2020). Accordingly, UNESCO expressed its concern about the latest floods in Sudan (UNESCO, 2020) (Fig. 4).



State of Conservation Information System

Gebel Barkal and the Sites of the Napatan Region (2003)

- desertification
- flooding
- ground transport infrastructure
- housing
- land conversion
- major visitor accommodation and associated infrastructure
- management systems/ management plan
- wind

Archaeological Sites of the Island of Meroe (2011)

- no reports
- news „UNESCO expresses its deep concern about the latest floods in Sudan" 11-Sep-2020*

*https://whc.unesco.org/en/news/2163/

Fig. 4. SOC-based analysis of threats reported to Gebel Barkal and Meroe complexes
Source: own work based on State of Conservation Information System

Methods. The overall approach to developing a remote monitoring method is composed of following steps: a) data preparation; b) classification and map production; c) analysis; d) interpretation of the results. Only the first step of preparing archaeological information for further work in GIS environment and acquisition of relevant Sentinel dataset was identical for all three cases. Maps showing property boundaries for individual sites were downloaded from the UNESCO website, georeferenced and polygonised using ArcGIS Pro software. Sentinel-2 L1C satellite imagery was downloaded from the Copernicus Open Access Hub (https://scihub.copernicus.eu) using the "Semi-Automatic Classification Plugin" (SCP) in QGIS. All images were clipped to the study area using the QGIS raster tool "Clip raster by mask layer". QGIS and ArcGIS Pro were used for further data processing and analysis. No comparison between the efficiency of these two GIS software packages was attempted although a preference was given to QGIS as it is open source. At later stages different methods were applied for data processing and analysis and will be presented for each case individually.

Spatial resolution. Only visual comparison of RGB composites for Landsat-8 and Sentinel-2 was carried out in this small study area.

Temporal resolution. Flooding analysis was carried out for images obtained between 5th August 2020 to 29th October 2020. Only cloud-free scenes over the study area were selected. At the first stage Normalised Difference Vegetation Index (NDVI) was used to identify flooded areas. It was calculated for each image using near-infrared and red band by the given equation:

$$NDVI = \frac{NIR - RED}{NIR + RED}$$

where NIR represents near infrared band (B8) of Sentinel-2 image and RED represents red band (B4).

NDVI values range from -1 to +1 where negative values or close to 0 (0-0,2) correspond to water or soil, whereas higher values (>0,2) correspond to vegetation (Abate et al., 2020).

Resulting images were combined into an animation which shows flood dynamics in the observed period against the location of major structures that were reported as threatened by high water level.

To verify observations based on the flood animation, a flood risk map was prepared using slope, hydrology and land cover factors for the observed area. The map was prepared in ArcGIS Pro software following workflow that is presented in Fig. 5.

Hydrology was derived from a Digital Elevation Model (DEM) provided by the United States Geological Survey (USGS) and calculated using the "Euclidean Distance" tool. Slope was derived from the DEM using the "Slope" tool. Land Cover and land use data can be accessed freely from ESRI using their application which provides access to the full 10-meter resolution GeoTIFF scenes for all land masses on the planet (Esri, 2020). The "Reclassify" tool was used to reclassify each layer used in analysis into five classes of flood risk from very low to very high. Finally, the "Weighted overlay" tool was used to create a final product of the flood risk map for the observed area (Fig. 13). In a "Weighted overlay analysis" values allocated to each of the factors in order of relevance were as follows: slope: 30; hydrology: 40; and land cover: 30.

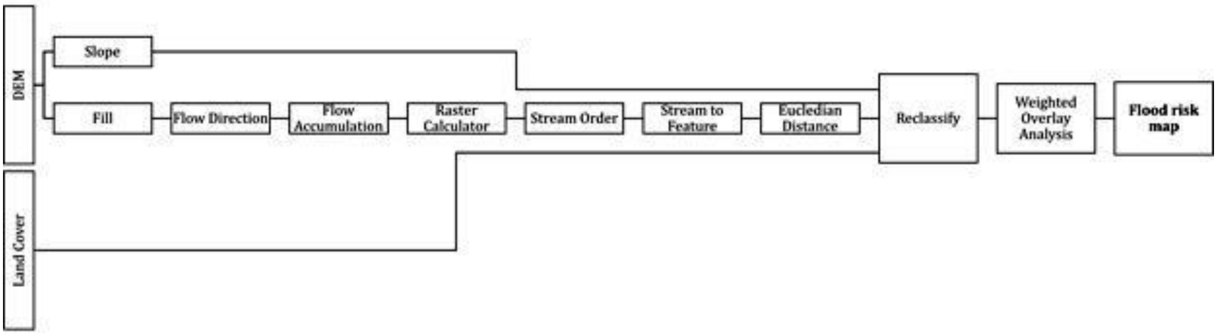


Fig. 5. Workflow for flood risk map
Source: own work

Spectral resolution. Remote sensing data were used for monitoring and assessment of desertification during the past three decades and several different analytical methods have been developed. Ground-truthing of those methods demonstrated that a "simple, robust, powerful, and easy to use for the (…) fragile arid and semiarid lands" method provided an overall accuracy around 93% (Lamqadem et al., 2018). Our choice of method was determined by a combination of four factors: relevance for semiarid areas; high accuracy of results; methodology developed specifically for Sentinel-2 imagery; and simplicity of proposed tools. Initially, the approach proposed by Lamqadem et al. (2018) was adopted. However, in due course some modifications of the original method were also proposed.

Following the original workflow, cloud-free scenes in summer (July) were selected. According to Lamqadem et al. (2018), desertification is most accurately assessed during the period when natural and annual vegetation is minimal. This approach avoids confusion with seasonal vegetation. Using the "Semi-Automatic Classification Plugin" (SCP) in QGIS3, all 13 bands of Sentinel-2 L1C data was downloaded, followed by preprocessing for atmospheric correction. At the next stage Tasselled Cap Transformation (TCT) was performed using QGIS 3's Raster Calculator.

TCT tool is used for landscaping, environmental threat mapping, estimating biomass, agricultural studies and identifying areas that exhibit desertification. It is an orthogonal transformation for the reduction of interpretability of the multispectral image to return three thematic indices: (1) brightness (TCB), which is sensitive to soil backgrounds and bright soils; (2) greenness (TCG), which is used to discriminate vegetation coverage; and (3) wetness (TCW), which provides information about water and soil moisture and vegetation conditions (Lamqadem et al., 2018).

Performing TCT requires 1) an input satellite image and 2) a set of transformation coefficients specific to the sensor that acquired the image. Transformation coefficients can be defined to work with either radiance or reflectance, and it is important to know which the transformation coefficients have been defined for (and which your image is using) (Tasseled-cap Transformation). Coefficients of transformation used in this study for the multispectral Sentinel-2 MSI to perform the TCT are given by Abate et al. (2020) and are shown in the following equations:

$$TCTb1 = 0.3037 * B2 + 0.2793 * B3 + 0.4743 * B4 + 0.5585 * B8 + 0.5082 * B10 + 0.1863 * B12$$

$$TCTw1 = 0.1509 * B2 + 0.1973 * B3 + 0.3279 * B4 + 0.3406 * B8 - 0.7112 * B11 - 0.4572 * B12$$

where B2, B3, B4, B8, B10, B11 and B12 represent different Sentinel-2 bands respectively: Blue, Green, Red, Near Infrared (NIR), Short Wave Infrared (SWIR) - Cirrus, SWIR and SWIR.

After obtaining TCB and TCW, the next step required their normalization. This was achieved using equations given by Lamqadem et al. (2018):

$$TCWnormalized = 100 * \frac{TCW - TCWmin}{TCWmin + TCWmax}$$

$$TCBnormalized = 100 * \frac{TCB - TCBmin}{TCBmin + TCBmax}$$

According to Lamqadem et al., the linear correlation aims to select the best combination that presents a highly negative correlation and good visualization of different land cover types. As they note “analysis showed a strong negative correlation between TCW and TCB (r = −0.812). TCW is highly correlated to the soil moisture and texture, which can give more information about the different types of soil. This result indicates that TCW decreases gradually with the increase in the desertification process, whereas TCB increases” (Lamqadem et al., 2018) (Fig. 6).

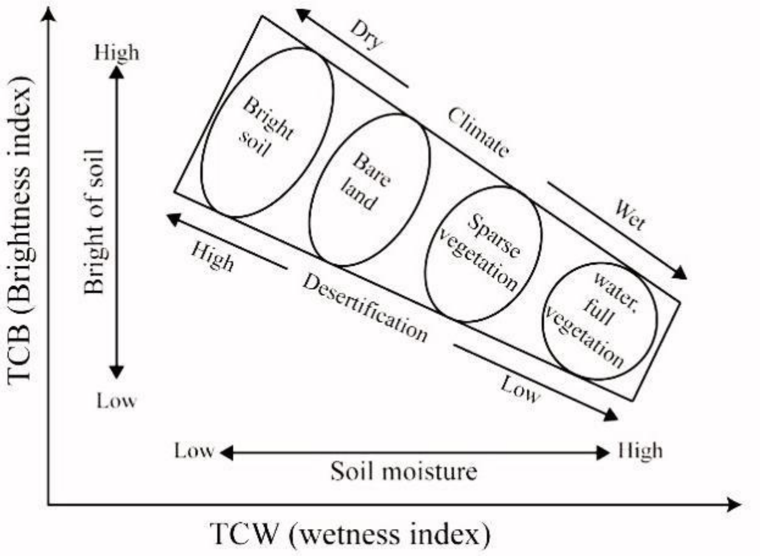


Fig. 6. TCW and TCB correlation
Source: Lamqadem et al., 2018

Using "r.regression.line" tool in QGIS3 parameters of regression equation between TCW and TCB were obtained, based on following equation: $TCB = a + b * TCW$ (Lamqadem et al., 2018). At the last stage, a Desertification Degree Index (DDI) was calculated using equation given by Lamqadem et al. (2018):

$$DDI = b \times TCWnorm - TCBnorm$$

Classification was also based on Lamqadem et al. (2018) (Table 1):

Table 1. The DDI values of different desertification classes

Desertification Class	**DDI value**
Non-desertification	> 64.95
Low	29.71 – 64.94
Moderate	3.79 – 29.70
Severe	-17.98 – 3.78
Extreme	< -17.99

Source: Lamqadem et al., 2018

Results and discussion

Housing. The spatial resolution of Sentinel-2 (10m GSD) provides greater detail than other Earth Observation satellites, such as Landsat (30m GSD). In some cases Landsat spatial resolution has proved adequate for documenting the changing extent of urbanization as demonstrated by comparative analysis of 2002 Landsat imagery and 1972 Corona images in the Middle Egypt which showed a 200 percent increase in urban extent in some areas (Parcack, 2009). This has led to irreversible landscape changes but the question remains, to what extent has urban sprawl also affected preservation of archaeological structures? An essential requirement for effective protection of World Heritage Sites is the delineation of boundaries which preserve the integrity of the property. Therefore, identification of general trends in urban development may be insufficient to estimate threats and/ or damage to sites. More detailed analysis should help identify instances of disturnbance with boundaries. One such instance is the Sanam site in the Gebel Barkal complex. At some point between 2003 and 2006, images in Google Earth (GE) show that the property's area was built over in north-east part and also cut by a road. We attempted to identify any further changes in Landsat and Sentinel images obtained in July 2021 (Fig. 7).

The Landsat image was sufficient to show general tendencies in urban development, including urban expansion into the north-east corner and a high density of buildings in western, southern and eastern areas adjacent to the property's boundary. However, its 30m spatial resolution, does not allow confident interpretation of the presence/absence of buildings within the area. On the other hand, the 10 m spatial resolution Sentinel provides sufficient detail to allow the identification of single house plots. It shows relationships between buildings and the site's boundary with sufficient precision to eliminate false alarms – although buildings still seem to be pressing on the boundary. Despite apparent higher building density in the immediate vicinity of the site, no further sprawl into its area was noted.

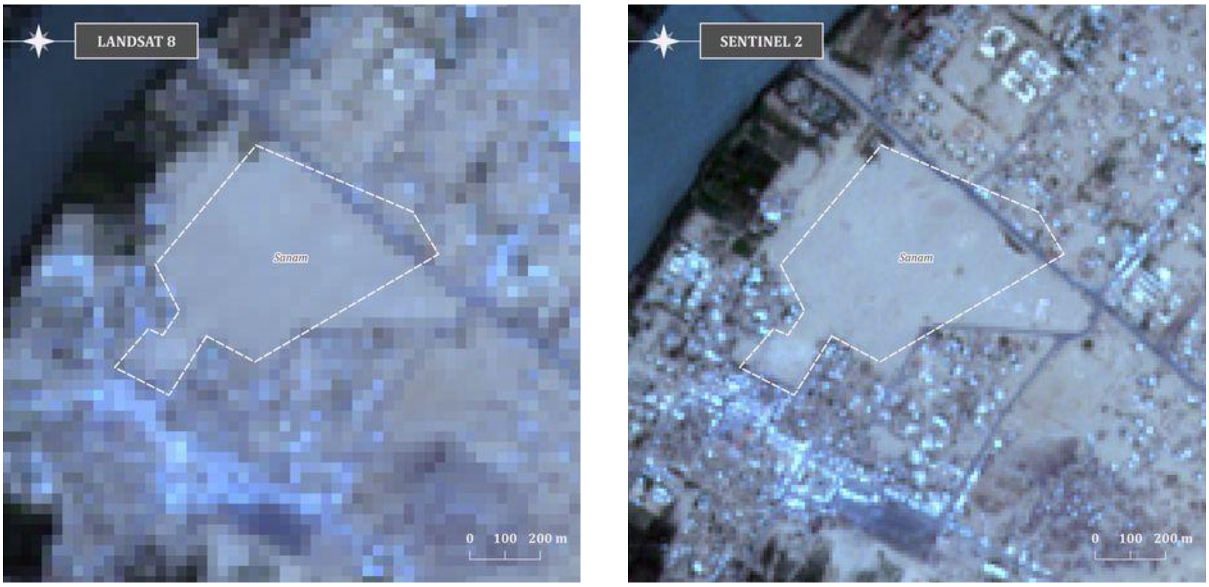


Fig. 7. A comparative analysis of Landsat-8 (left) and Sentinel-2 (right) spatial resolution for Sanam (image ©USGS, ESA, image acquisition: 19th July 2021)
Source: own work

However, Sentinel allowed us to identify the only instance of land cover change within the designated area. As early as 2017 some changes could be observed in the northern corner. A comparison with VHR images in GE demonstrated it to be developing vegetation (Fig. 8).

Fig. 8. A comparison of vegetation development into the designated area on Sentinel-2 images between 20th July 2017 and 19th July 2021 (image ©ESA)
Source: own work

Flooding. Two satellites of the Sentinel-2 constellation record the same area at frequent intervals and enable short-term changes to be observed. On 8th September 2020 Reuters published an article with the alarming headline of "Record floods threaten pyramid sites in Sudan" (Reuters Staff, 2020). Three days later a similar news item was released on the UNESCO website (UNESCO 2020). Both articles were reporting on the situations at the Meroe complex (Fig. 9) and at Nuri in the Gebel Barkal complex.

Fig. 9. Property boundaries of the Meroe complex and location of principal structures that were mentioned in press releases (image ©ESRI)
Source: own work

Some discrepancies between and within articles, concerning in particular parts of sites which were under immediate threat, were interesting enough to attempt flood development analysis and estimation of flood risk level for the Meroe complex. Nuri, where the threat was due to a rise in groundwater related to tombs which were buried 7-10 metres under pyramids (Reuters Staff 2020), was excluded from further analysis due to immense complexity of the case.

The Nile river flooding is a natural event that takes place every year from June to October (https://www.britannica.com/place/Nile-River/Climate-and-hydrology).
However, floods in 2020 were reported as unusually severe and threatening archaeological structures on an unprecedent scale. We assumed that the crucial criterion for imagery selection was for temporal resolution that would permit the observation of changes at short intervals. We also aimed to obtain imagery within the date ranges of the news items from Reuters and UNESCO. Undoubtedly, with five days returns Sentinel has a considerable advantage over other Earth Observation datasets.

This approach provided images over the period from 20th August to 29th September 2020 when water was at its highest level and encroaching on the site's area (Fig. 10 – Fig. 12).

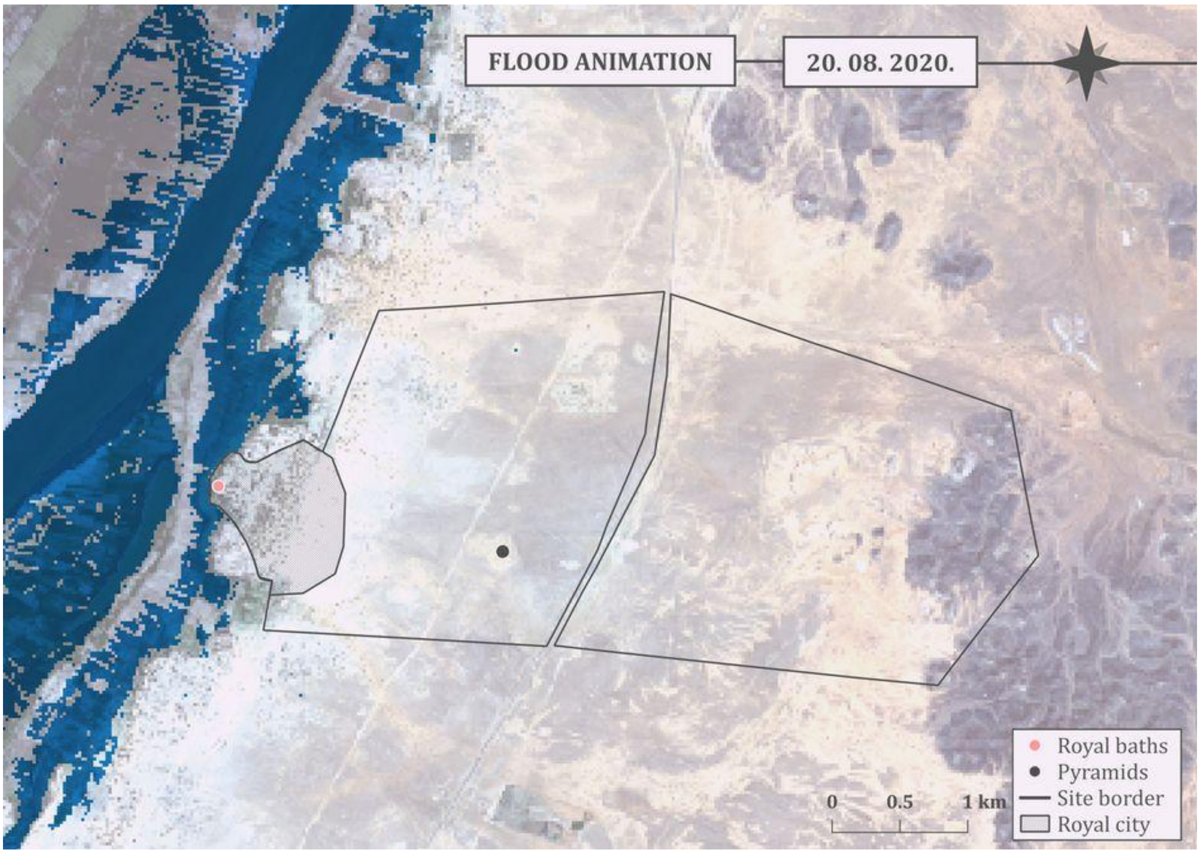


Fig. 10. NDVI analysis showing water level (blue) on 20th August 2020 (image ©ESA)
Source: own work

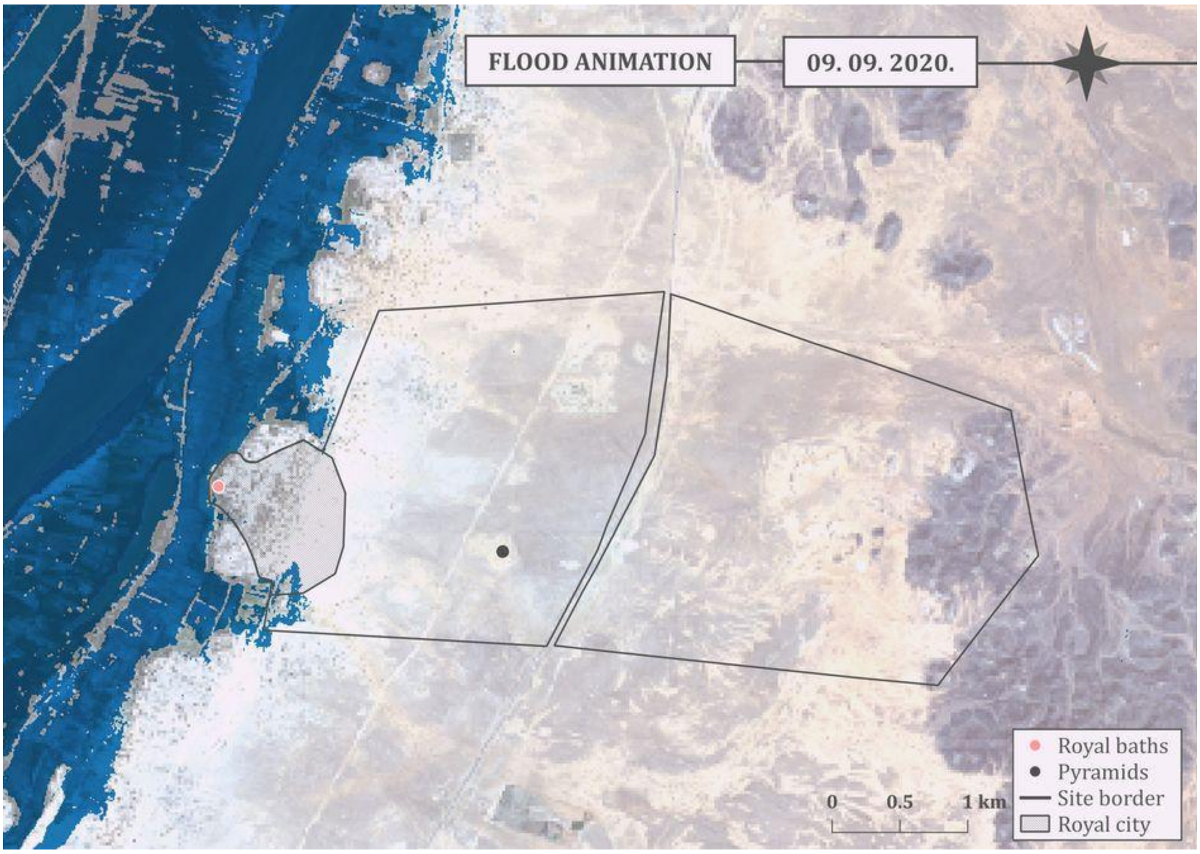


Fig. 11. NDVI analysis showing water level (blue) on 9th September 2020 (image ©ESA)
Source: own work

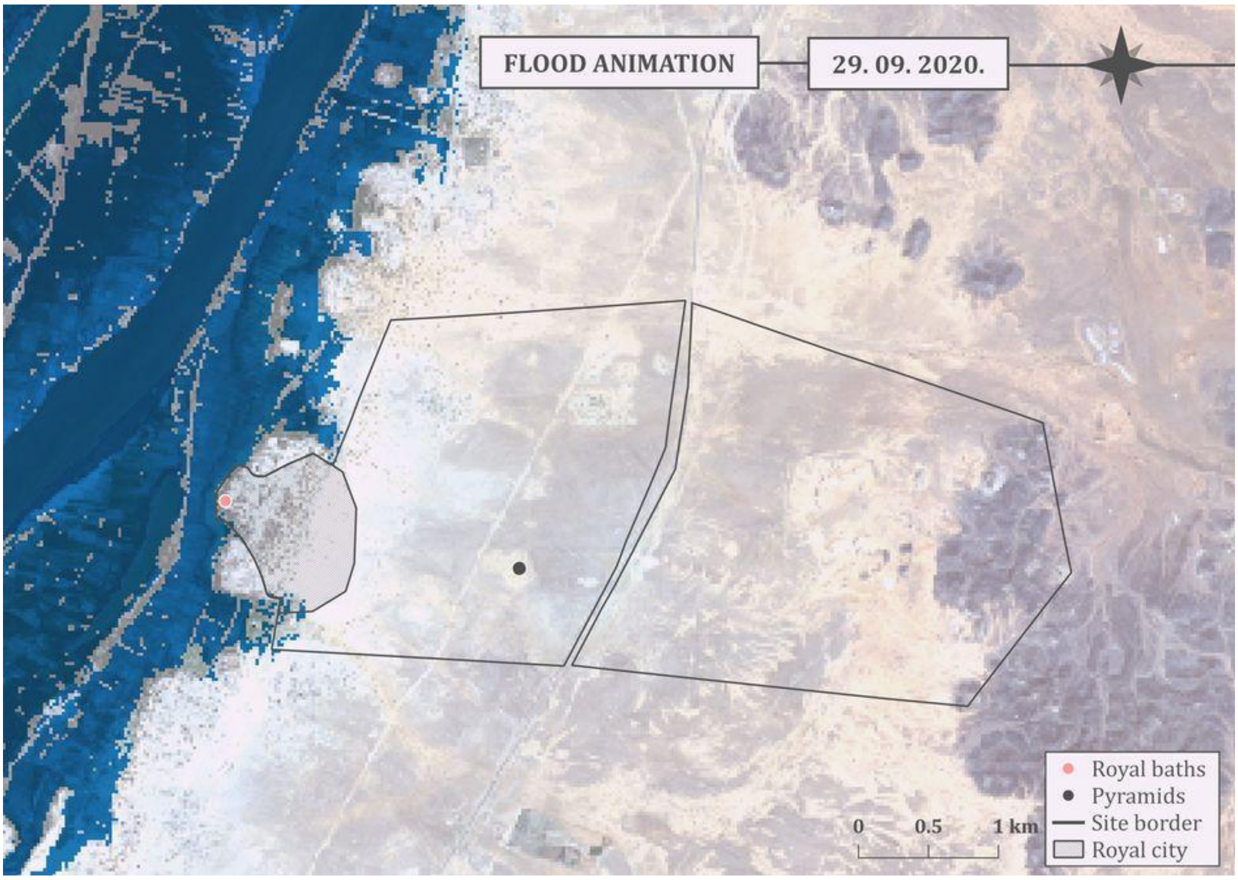


Fig. 12. NDVI analysis showing water level (blue) on 29th September 2020 (image ©ESA)
Source: own work

Two points from this analysis require emphasis. Firstly, observation of flood dynamics in areas that are regularly threatened gives useful early warnings for likely imminent flooding. The first flooding peak can be observed in the Sntinel-2 imagery in August (Fig. 10), though news was released by Reuters and UNESCO three weeks later (Reuters Staff 2020). Mere observation of flood development may give the advantage of early notification and offer more time for reaction. Secondly, it is worth noting that the southern part of the royal city was indeed flooded during this period (Fig. 11, Fig. 12). The royal baths that were reported at risk from being swamped, seem to be bordering on flooded area although they were not directly covered by water. However, the pyramids had not been at any danger from high water level.

The second point requires further consideration due to some confusion that was caused by imprecise description of endangered structures in the Reuters news. Therefore, this observation was verified against a flood risk map (Fig. 13).

A comparison of the flood risk map with the images showing the extent of the flooding between 20th August and 29th September 2020 (Fig 10 – 12) demonstrates that during the record floods in 2020 only zones of very high and high risk were flooded. Based on our analysis, nearly the entire site is under high or medium flood risk. However, different archaeological structures can be affected to various degrees by high water levels. The royal baths that were reported at risk from flooding, seem to be situated on land that is mostly medium risk and next to high flood risk area.

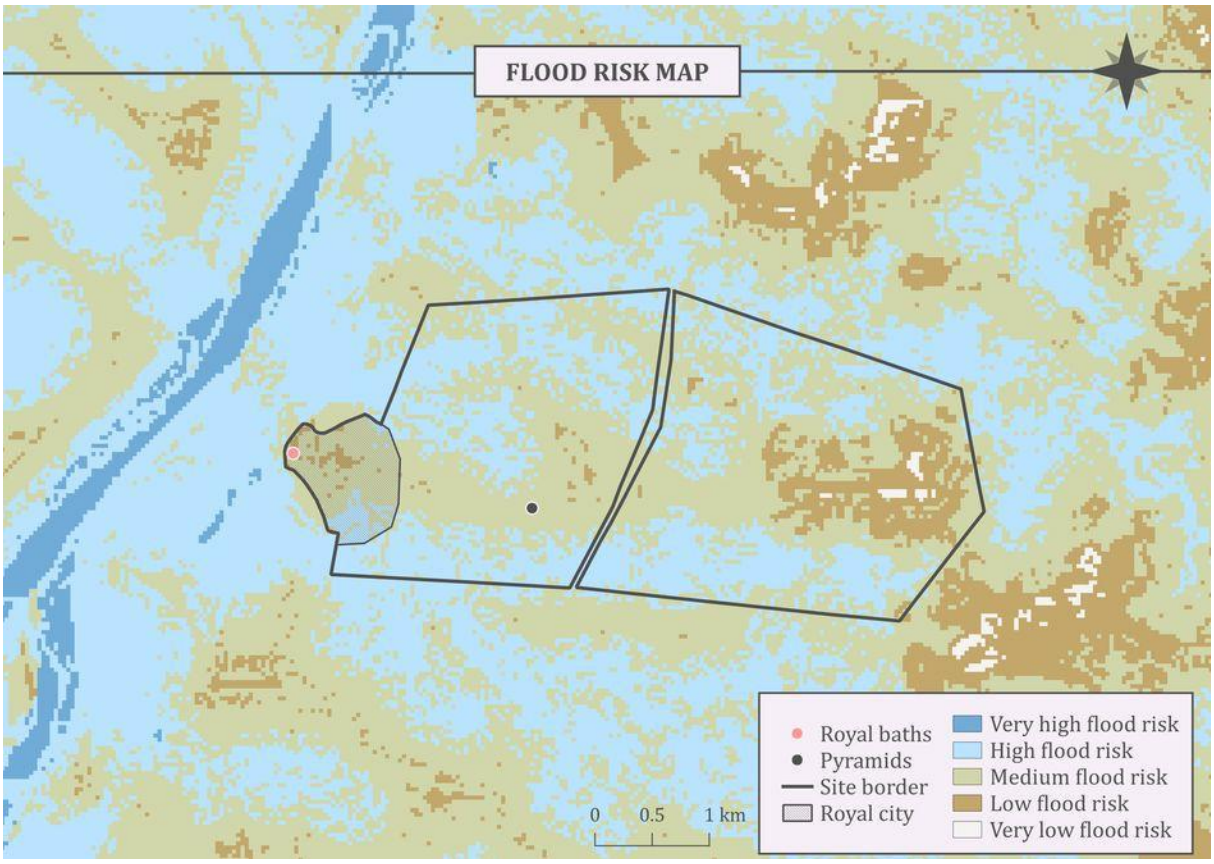


Fig. 13. Flood risk map for the Meroe complex (data ©USGS, ESRI)
Source: own work

The pyramids are situated in an area of medium flood risk which was not reached by water even at the flood peak. If this unusually severe flood could be used as a reference point to estimate the extent of the flooding threat to the Meroe complex then we can safely assume that pyramids are not under immediate threat. Probably more detailed studies are required (preferably with high-resolution DEM) to better understand the situation at the royal baths. Nonetheless, analysis of this type can help pinpoint areas that need closer monitoring and further actions to secure archaeological structures from recurring floods.

Desertification. The higher resolution of Sentinel-2's spectral bands may have a greater precision in the detection of edges of change than is possible at coarser resolution and so highlight slow-moving threats such as desertification. Generally speaking, desertification is defined as a form of land degradation in arid, semiarid and dry sub-humid regions caused by a combination of various factors, such as climatic variations and human activities (United Nations Convention to Combat Desertification 1994, after: Lamqadem et al., 2018). It is not the most frequently reported threat among World Heritage properties, with concerns noted at less than 30 sites (Veillon, 2014) (Fig. 14). Moreover, desertification has been reported as a threat mainly to cultural sites. This observation may be slightly surprising as desertification has been recognized in environmental sciences as a worldwide problem (Lamqadem et al., 2018). However, this threat has been regularly reported for the Gebel Barkal complex (Fig. 15) and it poses a few interesting problems regarding correlation of results obtained by on-ground observations and remote sensing analysis.

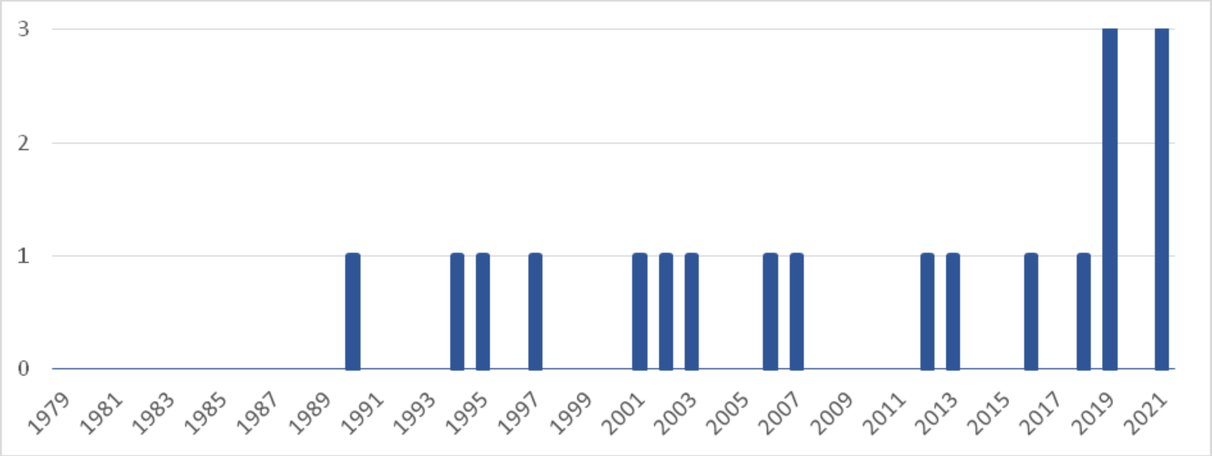


Fig. 14. Number of properties reported for desertification
Source: UNESCO, https://whc.unesco.org/en/soc/?action=list&id_threats=129

Fig. 15. Location and boundaries of five sites belonging to Gebel Barkal and the Sites of the Napatan Region (image ©ESRI)
Source: own work

Analysis of Desertification Degree Index (DDI) for the Gebel Barkal complex in 2018 (Fig. 16) and 2019 (Fig. 17) when this threat was reported showed extreme values in considerable areas in 2018 but in 2019 the situation seemed to improve.

The DDI was also calculated for 2020 when ground-based reports were not available (Fig. 18) and 2021 when they started to appear again (Fig. 19). Interestingly enough, in 2020 the threat from desertification as shown by DDI was even lower than in the previous years, falling into the 'low' range for most sites, and moderate to low range for Gebel Barkal. In 2021 the situation seems to revert to the extreme values noted for 2018.

At the most general level, this analysis helped estimate the desertification threats for individual sites. The Gebel Barkal complex is reported collectively for all five sites. However, as this analysis demonstrated, even in the most extreme year 2018, only one site (Gebel Barkal) fell into the severe to extreme desertification class. Three sites (Zuma, El-Kurru and Sanam) range between moderate and low while Nuri remained at a low desertification class.

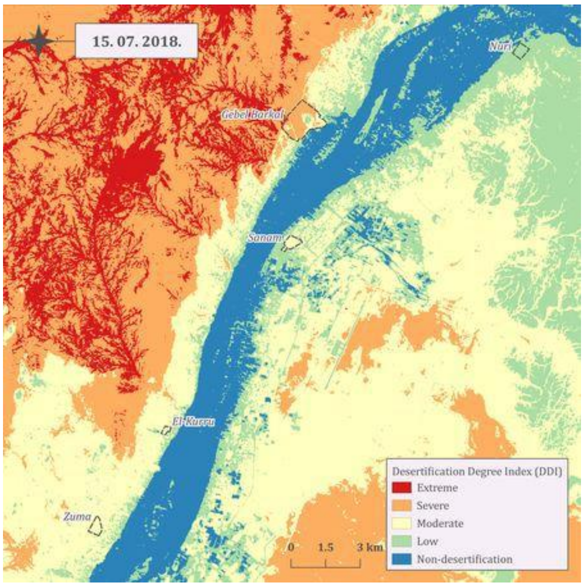


Fig. 16. DDI for 2018 (image ©ESA)
Source: own work

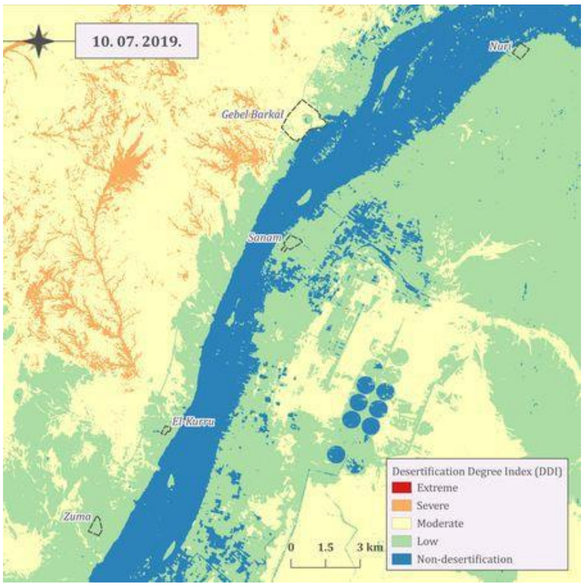


Fig. 17. DDI for 2019 (image ©ESA)
Source: own work

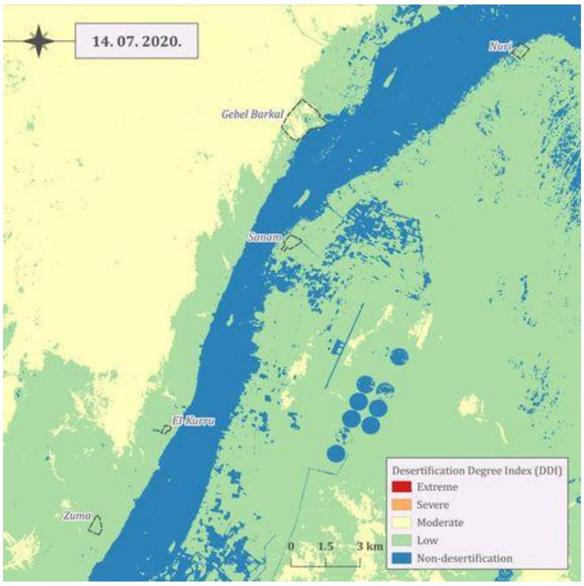


Fig. 18. DDI for 2020 (image ©ESA)
Source: own work

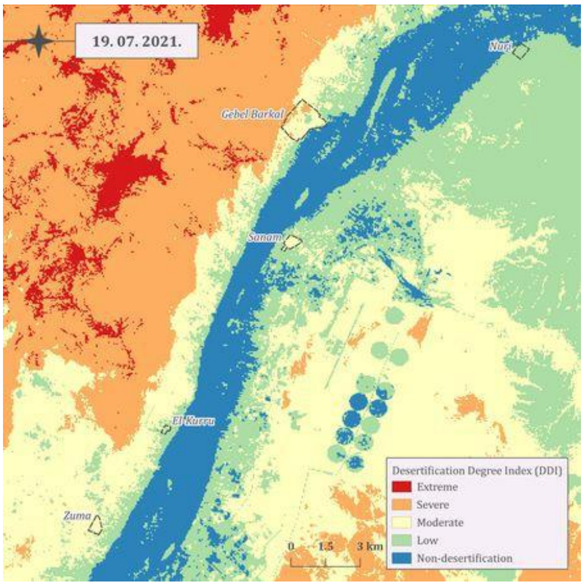


Fig. 19. DDI for 2021 (image ©ESA)
Source: own work

However, interpretation of tendencies that were observed in a four-year time span and their effect on archaeological structures that was noted in ground observation is yet another issue. The following graph shows DDI changing trends between 2018 and 2021 for Gebel Barkal (Fig. 20). It starts at severe desertification class (15th July 2018), drops to moderate a year later (10th July 2019), goes down to low (14th July 2020) and back again to moderate in the current year (19th July 2021). Therefore, we can note changing trends in DDI but no further support is offered to help understand those results in terms of desertification processes. Lamqadem et al. aimed to develop desertification degree index and elaborate desertification grades using a single image obtained in 2017 and a series of ground control points that were measured in the same year (Lamqadem et al., 2018). Whether repeated analysis in subsequent years would show similar fluctuations and how it would be interpreted remains unknown as no such work has been found.

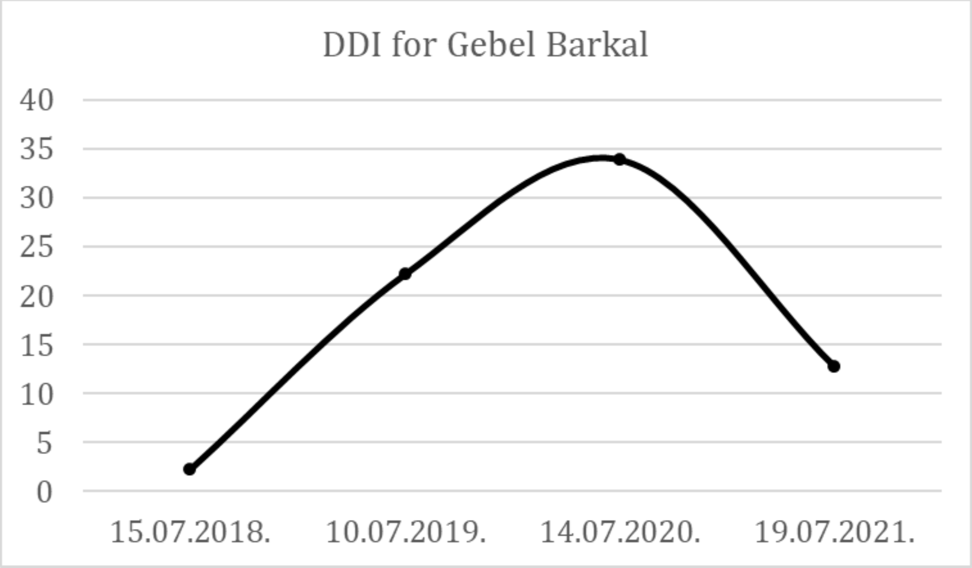


Fig. 20. DDI trend between 2018 and 2021 for Gebel Barkal
Source: own work

Even more difficult to understand is the effect of such changes on archaeological structures. Unlike for Lamqadem et al., no ground control measurements are available for the Gebel Barkal complex. Moreover, criteria to estimate the effect of desertification on archaeological structures that were used in the UNESCO reports have not been yet identified by authors. Perhaps due to low frequency of threat reporting, UNESCO analysis proved rather unhelpful in understanding this threat for cultural heritage. Only sand encroachment has been explicitly identified as a threat (Veillon, 2014). In case of shifting dunes, encroaching sand covers the surface of the sites and then slowly moves forward with wind action (Zaina, 2019) – a process that has been recorded on spectacular photographs of the Meroe pyramids (Reuters Staff, 2020). In itself it was described as not damaging archaeological structures but making them inaccessible for an undetermined period. Whether this threat or some other threat related to desertification is present at Gebel Barkal remains to be determined. Doubts have arisen about the reliability of this method and the results in this section are open to discussion.

Conclusions

In the 2020 response to the World Heritage Committee's concern over the overall condition of Gebel Barkal and the Sites of the Napatan Region, the National Corporation of Antiquities and Museums of Sudan (NCAM) emphasized that its actions were greatly complicated by the April 2019 revolution in Sudan, the appointment of a new transitional government in September 2019, and efforts to reform policies and procedures (NCAM, 2020). In addition, the current coronavirus pandemic has further affected regular monitoring of cultural heritage by putting serious limitations on visiting sites on the ground. However, easily accessible information that is provided by Sentinel-2 missions and open source GIS systems may help overcome at least some of the restrictions that are imposed by the changing world.

However, to use this potential certain changes are required.

1. *In-depth studies of Sentinel-2 potential (and other Copernicus products) preceded by changes in remote sensing agenda for heritage strategies.*

As noted by Zaina (2019) both academic researchers and the global media have focused mainly on threats caused by violent events such as war destruction and looting. This is reflected in preferences for VHR satellite imagery that allows easier identification of such occurrences. Less prominence is given to other equally destructive threats related to land use changes and environmental processes for which the Copernicus mission was designed.

2. *Further developments in methods of data processing.*

Several methods and techniques can be applied to map and assess a given process. Applications based on Copernicus products are probably the most dynamic due to the relative novelty of the programme. However, as our analysis also demonstrated, these methods need further development and adjustment to suit various contexts. The same category of threat may require applications of different sets of analytical tools due to varying characteristics and dynamics in different parts of the world.

3. *One step further: from analysis towards interpretation.*

Methodologically explicit analysis is crucial to reproducibility and testing if it is to reliably identify ongoing processes such as flooding or desertification. However, their effect on cultural heritage is likely to be complex and nuanced and needs to be explained (interpreted) from those results. There is certainly a need to translate indices and threshold values from remote sensing analysis into terms that are meaningful as degrees of threats to cultural heritage. However, this work requires input from heritage management and remote sensing, especially in case of threats that have been seriously underrepresented or neglected.

A value of Sentinel-2 is the combination of spatial, temporal and spectral resolution that can highlight small and local changes. By themselves these processes may be fairly insignificant but cumulatively can threaten archaeological heritage. Use of Sentinel-2 in ways that have been demonstrated in this paper may guide future mitigation strategies.

Acknowledgements

We would like to thank dr Mariusz Drzewiecki for drawing our attention to the Meroe and Gebel Barkal complexes and problems in heritage management arising from the latest developments in Sudan.

References

Archaeological Sites of the Island of Meroe, https://whc.unesco.org/en/list/1336/ [access: 20.12.2021].

Abate N., Elfadaly A., Masini N., Lasaponara R. (2020). Multitemporal 2016-2018 Sentinel-2 data enhancement for landscape archaeology: The case study of the Foggia province, Southern Italy. Remote Sensing, 12(8), 1309.

Beck A., Philip G., Abdulkarim M., Donoghue D. (2007). Evaluation of Corona and Ikonos high resolution satellite imagery for archaeological prospection in western Syria. Antiquity, 81(311), pp. 161–175.

Cowley D., Traviglia A., Verhoeven G. (ed.) (2021). Archaeological Remote Sensing in the 21st Century: (Re)Defining Practice and Theory, Remote Sensing, MDPI, Barcelona, pp. 1–4.

Cowley D. (ed.) (2011). Remote Sensing for Archaeological Heritage Management. EAC, Brussels.

Drusch M., Del Bello U., Carlier A., Colin O., Fernandez V., Gascon F., Hoersch B., Isola C., Laberinti P., Martimort P., Meygret A., Spoto F., Sy O., Marchese F., Bargellini P. (2012). Sentinel-2: ESA's Optical High-Resolution Mission for GMES Operational Services. Remote Sensing of Environment 120, pp. 25–36.

Esri 2020 Land Cover Downloader, https://www.arcgis.com/apps/instant/media/index.html?appid=fc92d38533d440078f17678ebc20e8e2 [access: 20.12.2021].

Gebel Barkal and the Sites of the Naptan Region, https://whc.unesco.org/en/list/1073/ [access: 20.12.2021].

Lamqadem A.A., Saber H., Pradhan B. (2018). Quantitative assessment of desertification in an arid oasis using remote sensing data and spectral index techniques. Remote Sensing, 10(12), 1862.

Lasaponara R., Masini N. (2008). Advances on Remote Sensing for Archaeology and Cultural Heritage Management, Aracne, Rome.

Martimort P., Berger M., Carnicero B., Del Bello U., Fernandez V., Gascon F., Silvestrin P., Spoto F., Sy O. (2007). Sentinel-2 The Optical High-Resolution Mission for GMES Operational Servics, ESA Bulletin 131 (August), pp. 18–23.

NCAM 2020, https://whc.unesco.org/en/list/1073/documents/ [access: 20.12.2021].

Nile River. Climate and hydrology, https://www.britannica.com/place/Nile-River/Climate-and-hydrology [access: 20.12.2021].

Parcak S.H. (2009), Satellite Remote Sensing for Archaeology, Routledge, Abingdon.

QGIS 3, https://www.qgis.org/en/site/about/index.html [access: 05.08.2021].

Reuters Staff 2020 Recent floods threaten pyramid sites in Sudan, https://www.reuters.com/article/uk-sudan-floods-idUKKBN25Z266 [access: 20.12.2021].

Tapete D. (ed.) (2018a). Remote Sensing and Geosciences for Archaeology, MDPI, Barcelona.

Tapete D. (2018b). Remote Sensing and Geosciences for Archaeology. In: D. Tapete, Remote Sensing and Geosciences for Archaeology, MDPI, Barcelona, pp. 1–10.

Tapete D., Cigna F. (2018). Appraisal of Opportunities and Perspectives for the Systematic Condition Assessment of Heritage Sites with Copernicus Sentinel-2 High-Resolution Multispectral Imagery, Remote Sensing, 10(4), 561.

SOC Gebel Barkal and the Sites of the Naptan Region https://whc.unesco.org/en/soc/4074 [access: 20.12.2021].

State of Conservation Information System (SOC), https://whc.unesco.org/en/soc/ [access: 20.12.2021].

Tasseled-cap Transformation, https://wiki.landscapetoolbox.org/doku.php/remote_sensing_methods:tasseled-cap_transformation [access: 20.12.2021].

UNESCO 2020, UNESCO expresses its deep concern about the latest floods in Sudanhttps://whc.unesco.org/en/news/2163/ [access: 20.12.2021].

Veillon R. (2014). State of Conservation of World Heritage Properties. A statistical analysis (1979-2013), https://whc.unesco.org/en/documents/134872 [access: 21.12.2021].

Zaina F. (2019). A Risk Assessment for Cultural Heritage in Southern Iraq: Framing Drivers, Threats and Actions Affecting Archaeological Sites, Conservation and Management of Archaeological Sites, 21:3, 184–206, https://doi.org/10.1080/13505033.2019.1662653 [access: 21.12.2021].