Enhancing risk assessment and monitoring for cultural heritage sites through data cubes: a multidimensional approach

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ENHANCING RISK ASSESSMENT AND MONITORING FOR CULTURAL HERITAGE SITES THROUGH DATA CUBES: A MULTIDIMENSIONAL APPROACH

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ABSTRACT

The Eastern Mediterranean, Middle East, and North Africa (EMMENA) regions are rich in Cultural Heritage (CH) sites that have been subject to various threats, including conflicts, natural disasters, and urban development. Effective risk assessment and monitoring are essential to preserve and protect these assets. Towards that direction novel technologies and their integration can be valuable for a holistic framework of managing diverse datasets and providing a robust safeguarding of CH assets. A data cube is a multidimensional representation of data that allows for efficient and flexible analysis, designed to support online analytical processing (OLAP) and data mining. Data cubes can be regarded as a three-dimensional structure, with each cell representing a unique combination of values from the different dimensions. By creating a data cube that includes several satellite and geospatial data sources, organizations can gain a more holistic understanding of the risks and opportunities associated with CH sites as well as to identify patterns and trends that might not be apparent in individual data sets. Within this context, it becomes apparent that data cubes allow for a multidimensional view of the risk landscape and can be used to create data-driven predictive models forecasting risks and opportunities for CH assets, - in order for them to be preserved and protected for future generations. The risk assessment and monitoring framework used in this study can be easily transferred, in order to monitor CH sites in any sensitive region and can be adapted to include data from other sources and monitor different types of threats, including climate change related, environmental, and social risks.

Keywords: Cultural Heritage, Data Cube, Risk Assessment, EMMENA

1. INTRODUCTION

Cultural Heritage (CH) is vital for maintaining a sense of identity, transmitting knowledge, and shaping our understanding of the world around us. CH provides a window into diverse cultural practices, beliefs, and values, promoting cross-cultural understanding and appreciation. CH sites, monuments, and artifacts are often unique and irreplaceable, representing a tangible link to the past and inspiring future generations. Preserving and safeguarding CH is not only a matter of cultural importance but also a responsibility towards humanity's shared cultural legacy.

The Eastern Mediterranean, Middle East and North Africa (EMMENA) region is a vast area that spans across three continents: Europe, Asia, and Africa. It is a region of significant strategic importance for political and military forces, and it also holds immense archaeological and cultural significance due to its abundance of cultural wealth. The region has been an important crossroad for various civilizations during ancient times [1], which has contributed to its diverse cultural practices, beliefs, and values. However, the cultural heritage (CH) of the region is exposed to several risks [2] that can be sudden and catastrophic, like earthquakes and war conflicts, or gradual and long-term, such as climate change, erosion and pollution. Risk assessment is the process of evaluating potential hazards and their impact on cultural assets. This includes identifying risks, assessing the vulnerabilities of the site, and developing appropriate mitigation strategies [3]. Traditional methods, like questionnaires [4] as well as modern techniques, like GIS, damage recording tools [5] and remote sensing [6], can be used to develop risk assessment strategies. The risk assessment process (Figure 1) involves regularly monitoring the site for changes and new risks and developing emergency response plans with trained staff and appropriate equipment.

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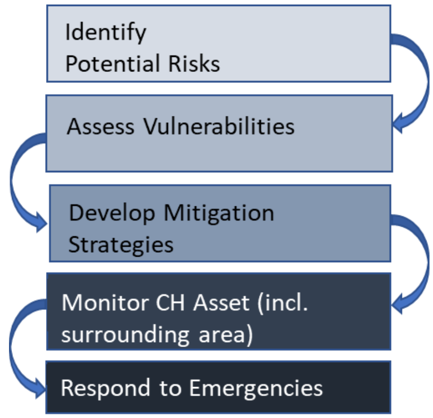

Figure 1. Risk assessment methodology typically followed in CH.

The European Union has emphasized the need [7] to integrate current short and long-term management plans and inspections into a more regular monitoring regime to provide a comprehensive view of the state of conservation and to initiate effective preventive conservation measures. Despite numerous attempts to classify and evaluate risk factors that may harm cultural heritage, the current monitoring and intervention methods are often outdated and lack state-of-the-art technology to quickly respond to any environmental or human-induced threats that could lead to deterioration and potential damage to the artifacts. This presents a pressing urgency for curators, scientists, and any actor involved in CH conservation/protection under polluting conditions and factors to evaluate novel but also cost-effective techniques, approaches, methodologies, and materials to recover the damages caused by natural and non-natural phenomena and protect the future of all the CH buildings. Addressing these challenges is crucial to ensure the sustainability of region's cultural heritage.

During the past few decades, there has been a remarkable increase in the usage of Geoinformatics, particularly in the field of archaeology, with significant advancements in Spatial Analysis (SA) and Remote Sensing (RS). This has resulted in the adoption of various geospatial tools such as GIS and satellite images for the efficient collection, integration, and management of spatial data [8]. These tools have enabled a more comprehensive approach to studying the past by providing a representational perspective. However, it is important to note that the past should not be viewed as a static and definitive entity but rather as a constantly evolving phenomenon that impacts both the present and the future[9]. Therefore, archaeology is transforming into a more spatially-aware [10] and dynamic science, as highlighted by the growing trend of performing exploratory spatial data analysis (ESDA) to identify meaningful patterns and trends [11].

2. UTILIZING A CULTURAL DATA CUBE TOWARDS A MORE EFFECTIVE RISK ASSESSMENT METHODOLOGY

A comprehensive understanding of the risks that are associated to the cultural assets in the EMMENA region requires a multidimensional approach that takes into account the complex interplay of natural, environmental, and human factors. To achieve this, a multidimensional cultural heritage risk assessment that utilizes multitemporal data is essential. Multitemporal data is critical for understanding the changing dynamics of the region and how they impact cultural heritage. This includes data on environmental and climate changes, natural disasters, and human activities such as urbanization and tourism. By analyzing data from multiple time periods, we can identify trends and patterns that can help us anticipate future risks and plan accordingly. Moreover, multitemporal data allows for the identification of vulnerable CH sites and monuments that may be at risk of damage or destruction. This data can help to prioritize mitigation efforts and ensure that limited resources are used effectively to protect the most valuable, if not all.

Due to the extensive availability of large geospatial and satellite datasets, it is possible for researchers to selectively analyze data from certain time intervals. However, this may lead to a fragmented understanding of the available information, which can subsequently impact the outcomes of the risk assessment process by failing to adopt a holistic approach. Tackling any existing constraints, the development of a Cultural Data Cube in its capacity as a multidimensional data structure can be used for efficient querying and analysis of large datasets. The organisation of data into a multi-dimensional grid, where each cell contains a summary or aggregation of data.

Our proposed workflow builds upon data cube's capacity on integrating efficient and faster query performance by pre-aggregating the geospatial data into smaller, more manageable summary tables. This enables more efficient querying of large datasets, saving time and improving overall analysis productivity. Secondly, a data cube allows for multidimensional analysis, enabling users to analyze data along multiple dimensions. This approach can reveal insights and relationships that may not be apparent from a single-dimensional view of the data, leading to a more comprehensive and accurate analysis. Thirdly, a data cube provides a simplified view of complex data, making it easier for users to access and understand. This simplified data access can improve data literacy and promote data-driven decision making. In addition, the structure of data cubes is highly scalable and can handle large or small datasets, making them a flexible solution for greater efficiency in data processing and analysis, regardless of the size of the dataset.

To underscore the significance of adopting a data cube-based multidimensional risk assessment workflow, we hereby briefly present selected case studies from the EMMENA region that are associated to two risks (air pollution and fires). These case studies are exemplary of different kinds of cultural heritage properties, each of which is susceptible to a range of risks emanating from diverse sources, such as natural, environmental, and human-induced hazards.

2.1 Air pollutants

Air pollutants, including nitrous oxide, can have a negative impact on CH properties, as they can lead to physical and chemical deterioration of the materials. The effects of air pollutants depend on the type, concentration, and duration of exposure. Nitrogen dioxide (NO_2) is formed primarily from the burning of fossil fuels and is commonly found in urban areas with high traffic volumes. Figure 2 and Figure 3 present the mean concentration of NO_2 throughout the EMMENA region during two different years i.e., before-Covid and during-Covid. To illustrate the density of the pollutant, the use of Sentinel-5p images being acquired for 2019 (pre-Covid) and 2020 (during first lockdown) for the same time frame of one month and the same period to also account of any possible seasonal variations as i) from 20-03-2019 to 20-04-2019 and ii) from 20-03-2020 to 20-04-2020, respectively.

Figure 2. NO_2 concentration (before Covid) at the EMMENA region.

Figure 3. NO2 concentration (lockdown measures in effect) at the EMMENA region.

By briefly comparing the two images, it becomes visually apparent the concentration in several parts of the region is decreased (especially over Beirut in Lebanon). The following two histograms (Figure 4) depict the range of values for NO2 concentration, with the number of observations to fall within the bin range of 0.12-0.15 (in red for pre-Covid) and 0.088-0.096 (in green for the first lockdown period).

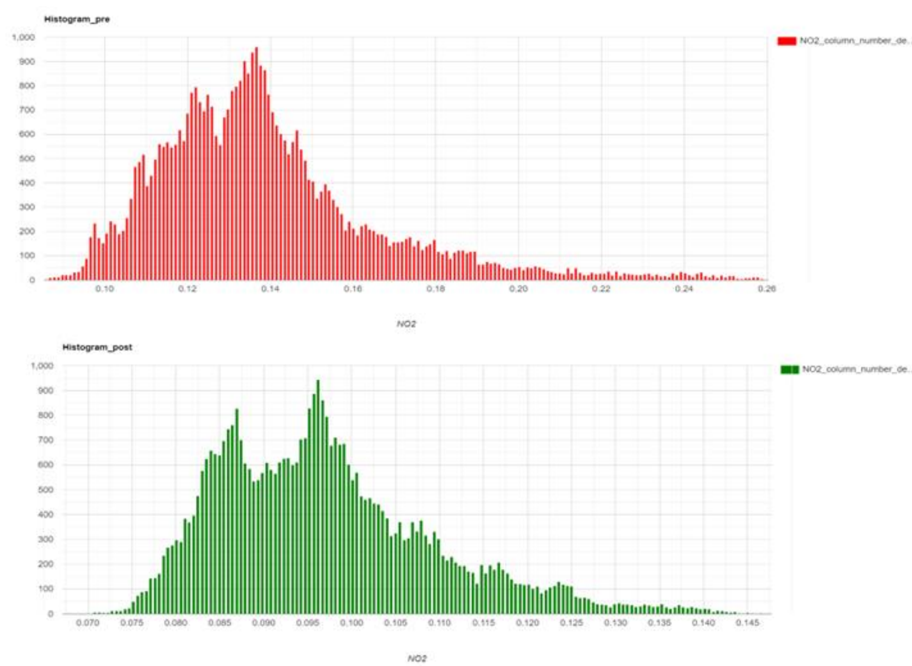

Figure 4. Histograms of the NO2 concentration during before-Covid period (in red) and ongoing lockdown measures(in green).

To better highlight the risks associated to air pollutants, the areas of Lebanon and Syria were selected as 5 UNESCO cultural sites are located therein (Crac des Chevaliers and Qal'at Salah El-Din, Rachid Karami International Fair-Tripoli, Ouadi Qadisha (the Holy Valley) and the Forest of the Cedars of God, Byblos, and Baalbek) and the NO2 concentration is quite high, hence the density of the pollution is expected to have a negative impact in the surrounding cultural landscapes.

The dynamics of local restriction measures, due to COVID, had a positive impact towards reducing the NO2 concentration near the areas of cultural importance (Figure 5).

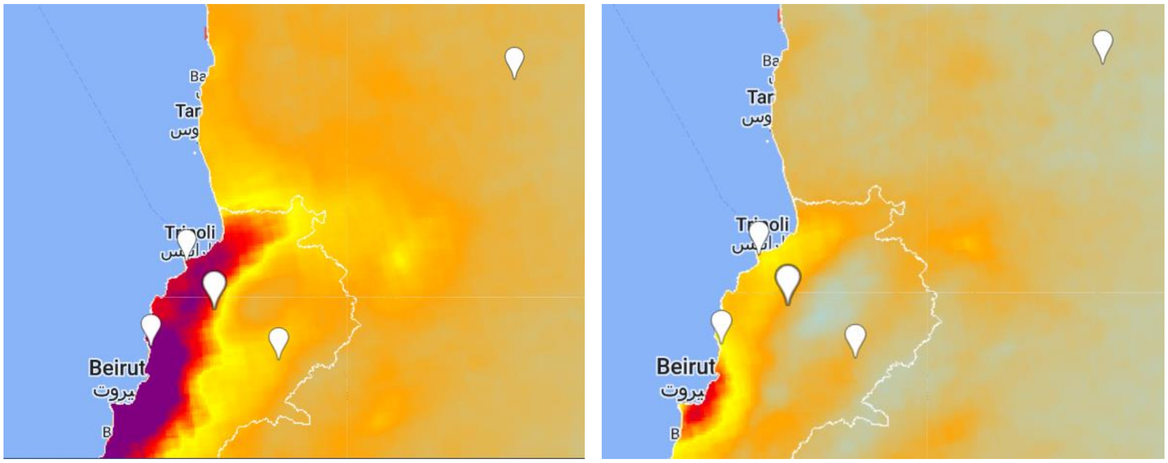

Figure 5. Left: High levels of NO2 around the areas of cultural interest ; Right: Decrease in NO2 concentration during lockdown measures.

2.2 Burn severity

Fires and the subsequent burn severity can have a significant impact on cultural heritage sites, leading to the alteration or destruction of the site's materials and structures. The effects of fires on CH properties depend on the intensity, duration, and proximity of the flames. In particular, high-intensity fires can cause direct damage, such as cracking or spalling, while lower intensity fires can result in thermal alteration and discoloration of materials. Moreover, fires can also lead to changes in the physical and chemical properties of materials, affecting their stability and long-term preservation. The risk of fire and burn severity should be considered as part of a comprehensive risk assessment approach for CH sites, and measures such as vegetation management, fire suppression systems, and emergency response plans should be put in place to minimize the damage caused by fires.

The region due its warm and dry climate, is prone to the appearance of severe fire risks, therefore is of critical importance to be able to map the burn severity near CH locations. Global Annual Burned Area Mapping (GABAM) service provides the burned areas on an annual basis using remote sensing data [12]. The data from GABAM can be used to assess the impact of fires on various ecosystems, including CH sites. This information is important for developing effective conservation strategies and mitigating the effects of fires on CH properties.

Figure 6 shows the total burned areas, for a period of 21 years (2000-2020). Throughout these years the spatial extent and severity of fires has grown exponentially, hence by observing closely the below figure, we may identify the areas that were greatly affected in the past and are presumed to be at higher risk of any future fire damage.

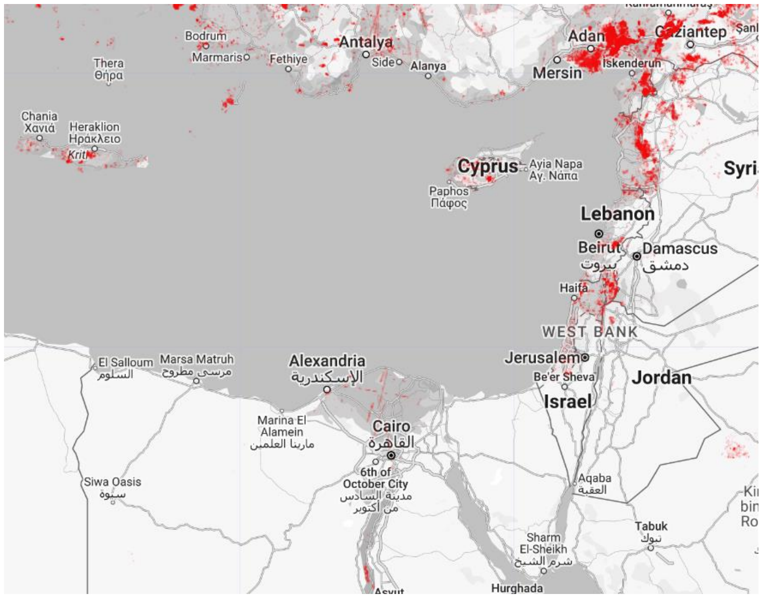

Figure 6. GABAM data for the period of 2000-2020 for the EMMENA region.

Although there were multiple foci of fire for the aforementioned period, it is important to mention that our results showcased that for the 2020 (Figure 7) there were no fires mapped due to lockdown measures in effect.

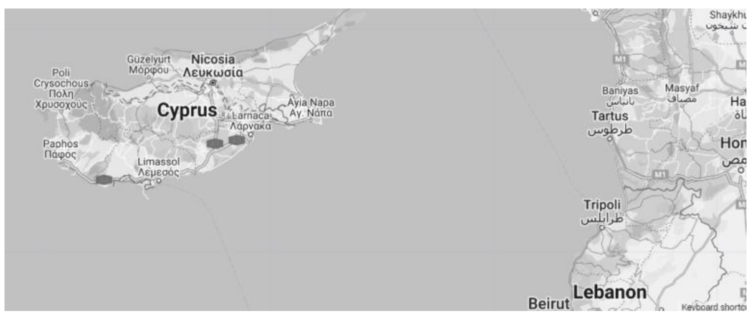

Figure 7. GABAM data for 2020

Based on a previous work [13] the use of hyperspectral imagery and more specifically DESIS data was considered to map and analyse the burn severity at the Arakapas village in Cyprus. The area affected by the fire is designated as an area of special aesthetic value of the Troodos Mountain range to the Southwest Shores and is included in the Troodos UNESCO global geo-park, which characterizes it as a natural heritage landscape. The findings of this study indicate that the DESIS data provide highly precise burnt area maps. Additionally, multispectral Sentinel-2 images consisting of 10 spectral bands were used to calculate various indices commonly utilized for burned area assessment using EO data, such as the Normalized Burn Ratio (NBR), Burned Area Index (BAI), and differential NBR (dNBR), with a spatial resolution ranging from 10 m to 20 m and a swath width of 290 km. The results of these broadband indices were found to be accurate and were subsequently compared to the narrowband outcomes from DESIS.

The multitemporal results shown above, along with pre-processed at analysis ready satellite data (especially timeseries) from the various sources (Copernicus, NASA, etc.), any available spatial data (including but not limited to generated risk maps, shapefiles), files' metadata, UAV imagery, enviornmental and atmospheric data obtained every x time intervals are ingested to the cube to become available for retrieval in case of a disaster risk scenario. Upon retrieval of both geospatial and satellite data for initiliasation of the proposed workflow (Figure 8), these data will further be enriched with available stakeholders' data concerning the cultural property (if any) as well as with any existing knowledge coming from 'traditional' practices (documented oral traditions, old maps, digitised archives, etc). The schematic output follows the structure of a typical disaster management circle that is expected to be used during every step of a risk assesment scenario encompassing all three steps:

i) Before disaster, where the constant risk assessment monitoring is taking place. Moreover, at this step, the data cube acts also as a solid ground, where tools in development will be based to visualise the stored information in the form of WebGIS platforms and/or Decision Support Systems (DSS), thus aiding to the extraction and understanding of pottential patterns lied in the data.

ii) During disaster, to raise awareness and response about the risk status of the cultural asset.

iii) After disaster, where the final products will be used for the damage assessment. Furthermore, the establishment of proposed recovery plans will feed the cube in order to update any future prevention/mitigation strategies based on deployed forecasts.

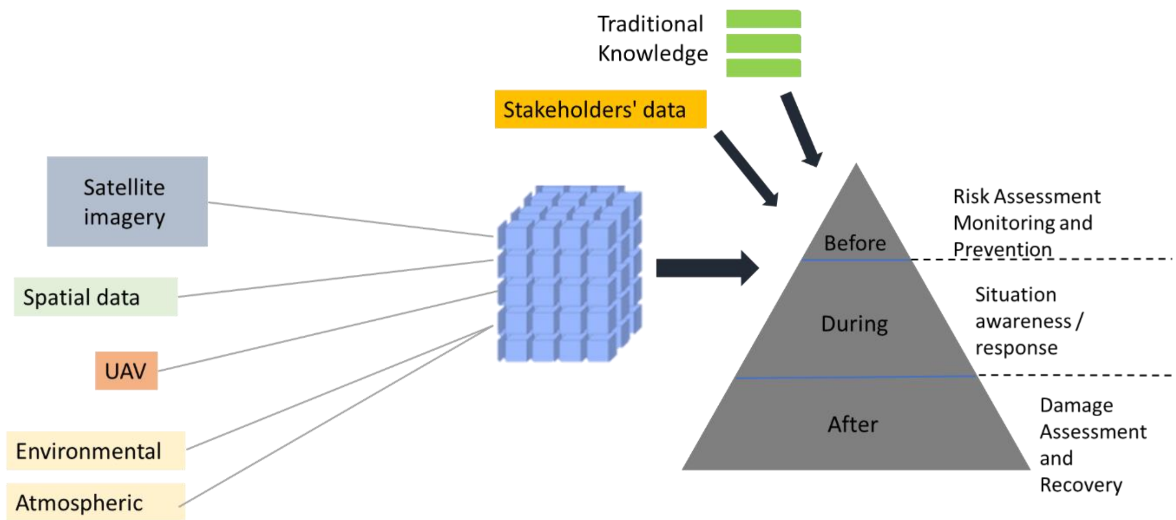

Figure 8. Cultural Data Cube workflow for risk assessment and monitoring.

3. CONCLUSIONS

Overall, the multidimensional risk assessment approach in cultural heritage conservation is a critical tool for safeguarding cultural heritage properties, and the use of data cubes can significantly enhance the efficiency and effectiveness of this approach. As showcased in this study, several risks threaten the integrity of cultural assets e.g., air pollutants, such as nitrous oxide, can have a negative impact on cultural heritage properties by causing physical and chemical deterioration of the materials, as well as fires and burn severity can cause physical damage and alter cultural asset's value. The use of satellite data and geospatial information aid in assessing the impact of such risks.

Within this context, it becomes obvious that data cubes allow for a multidimensional view of the risk landscape and can be used to create data-driven predictive models forecasting risks and opportunities for cultural heritage assets, - in order for them to be preserved and protected for future generations to enjoy. The risk assessment and monitoring framework used in this study can easily be transferred, in order to monitor cultural heritage sites in any other sensitive region and can be adapted to include data from other sources and monitor different types of threats, including climate change related, environmental, and social risks. By leveraging the power of data cubes and geospatial analysis techniques, organizations and policy makers can therefore create a more efficient, effective, and sustainable approach to risk assessment and monitoring.

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