remote sensing

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Communication

Earth Observation Contribution to Cultural Heritage Disaster Risk Management: Case Study of Eastern Mediterranean Open Air Archaeological Monuments and Sites

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Abstract: Disaster risk management (DRM) for cultural heritage is a complex task that requires multidisciplinary cooperation. This short communication underlines the critical role of satellite remote sensing (also known as earth observation) in DRM in dealing with various hazards for cultural heritage sites and monuments. Here, satellite observation potential is linked with the different methodological steps of the DRM cycle. This is achieved through a short presentation of recent paradigms retrieved from research studies and the Scopus scientific repository. The communication focuses on the Eastern Mediterranean region, an area with an indisputable wealth of archaeological sites. Regarding the cultural heritage type, this article considers relevant satellite observation studies implemented in open-air archaeological monuments and sites. The necessity of this communication article emerged while trying to bring together earth observation means, cultural heritage needs, and DRM procedures.

Keywords: cultural heritage; archaeology; earth observation; Eastern Mediterranean; Copernicus program; disaster risk management

1. Introduction

1.1. Basic Terminology

Risk management has long attracted the interest of scholars aiming to minimize the impact of threats to citizens and critical infrastructure [1,2]. Similarly, studies considering the protection of cultural heritage sites and monuments have been carried out [3]. However, in the literature, there are a plethora of terminologies used for risk management, mainly due to the wide range of applications, often creating confusion. Below, an overview of the definitions of risk management, as these have been defined by international organizations that deal with the management and protection of cultural heritage sites, is given.

According to the United Nations International Strategy for Disaster Reduction, the term disaster is defined as a severe disruption of the functioning of a community or a society causing widespread human, material, economic, or environmental losses that exceeds the ability of the affected community or society to cope using its resources [4]. Several international organizations and committees dealing with the protection of cultural heritage have adopted this terminology, such as the United Nations Educational, Scientific, and Cultural Organization (UNESCO); the International Centre for the Study of the Preservation and Restoration of Cultural Property (ICCROM); the International Council on Monuments and Sites (ICOMOS); and the International Union for Conservation of Nature (IUCN). They have also extended it in a way to include disaster impacts on people and properties, as well as on cultural heritage values of World Heritage property [5].

According to Emergency Management Australia 2000 [6], risk is defined as the chance of something happening that will have an impact upon objectives, while the United Nations [4] considers risk as the combination of the probability of an event and its negative consequences. Hazard is defined as a dangerous phenomenon, substance, human activity, or condition that may cause loss of life, injury, or other health impacts, property damage, loss of livelihoods and services, social and economic disruption, or environmental damage or any phenomenon, substance, or situation [4]. This phenomenon might have the potential to cause disruption or damage to infrastructure and services, people, their property, and their environment [7]. Vulnerability refers to the characteristics and circumstances of a community, system, or asset that make it susceptible to the damaging effects of a hazard [4]. Therefore, vulnerability can be identified as an inherent characteristic of the element of interest (community, system, or asset) independent of its exposure, or more frequently, including the element's exposure, specifically when it comes to cultural heritage (i.e., the location of a heritage property). Therefore, disaster risk can be described as the result of hazard and vulnerability [5]. More specifically, disaster risk is identified as the potential disaster losses to lives, health status, livelihoods, assets, and services that could occur in a community or a society over some specified future time period.

1.2. Literature Review

During recent years, an increase in the number of studies exploring the potential of space-based sensors for risk assessment has been observed (see below in Figure 1). In comparison to ground measurements, the use of satellite sensors provides significant advantages, such as the capability for systematic measurements. This is the case, for instance, for the Copernicus Sentinel-2 constellation, which can provide optical images with a revisit time of 5 days at the equator. Also, specific satellite observation programs such as the European Copernicus program can provide free and open access to medium resolution satellite data, with extensive coverage and almost worldwide coverage to support general earth observation studies [8]. The operational use of earth observation data for disaster management, such as with the Copernicus Emergency Management Services [9], the International Charter Space and Major Disasters [10], the United Nations Platform for Space-Based Information for Disaster Management and Emergency Response (UN-SPIDER) [11], or the Group on Earth Observation (GEO) [12] initiatives, can have the potential to affect cultural heritage objectives. This relates to all of the management stages, with more focus on the rapid response to all types of major disaster situations in general.

The hazards that might have a negative impact on cultural heritage are usually classified into either (a) natural or (b) anthropogenic, while both may synergistically trigger secondary hazards. As identified by the International Council for Science (ICSU) and the World Meteorological Organization (WMO), and as adopted by UNESCO, the most common categories of hazards are the following: meteorological, hydrological, geological, astrophysical, biological, and climate change [5]. For the current communication article, attention was given to hazards that most frequently occur in the Eastern Mediterranean region.

In light of the above and for the purposes of this communication, a literature review was conducted based on scientific articles found in the Scopus engine over the last decade (2010–2020), following similar studies in the past [13,14]. Scopus was selected among other scientific repositories since it is the largest relevant abstract and citation database of peer-reviewed literature, scientific journals, books, and conference proceedings. Various hazards, such as fires, earthquakes, landslides, soil erosion, floods, urbanization, war, conflicts, or looting, were queried in the specific engine. In addition to the hazard type, the term satellite was included, while the query was limited to articles published between the period 2010–2020.

Figure 1 presents the total number of pertinent publications from the last decade (2010–2020). An increase in publications is reported for all types of hazards using satellite observation means. The overall findings indicate that more than 3500 articles were published during the period 2010–2020 concerning earthquakes and floods (separately), while another 3300 articles related to fires and satellite observation were published. For landslides, more than 1900 articles were published in this period, while similarly more than 800 and 2000 scientific articles were published for soil erosion and urbanization hazards. It should also be mentioned that for the above hazards, a steady increase in the number of publications during these years is observed. Specifically, a mean relative increase of 7% per year was reported for publications related to fires, a 4% increase per year for earthquakes, an 11% increase per year for landslides, an 8% increase per year for soil erosion, a 12% increase per year for floods, and a 20% increase per year for urbanization. Surprisingly, regarding war, conflicts, and looting, the literature is relatively sparse (just over 100 published articles).

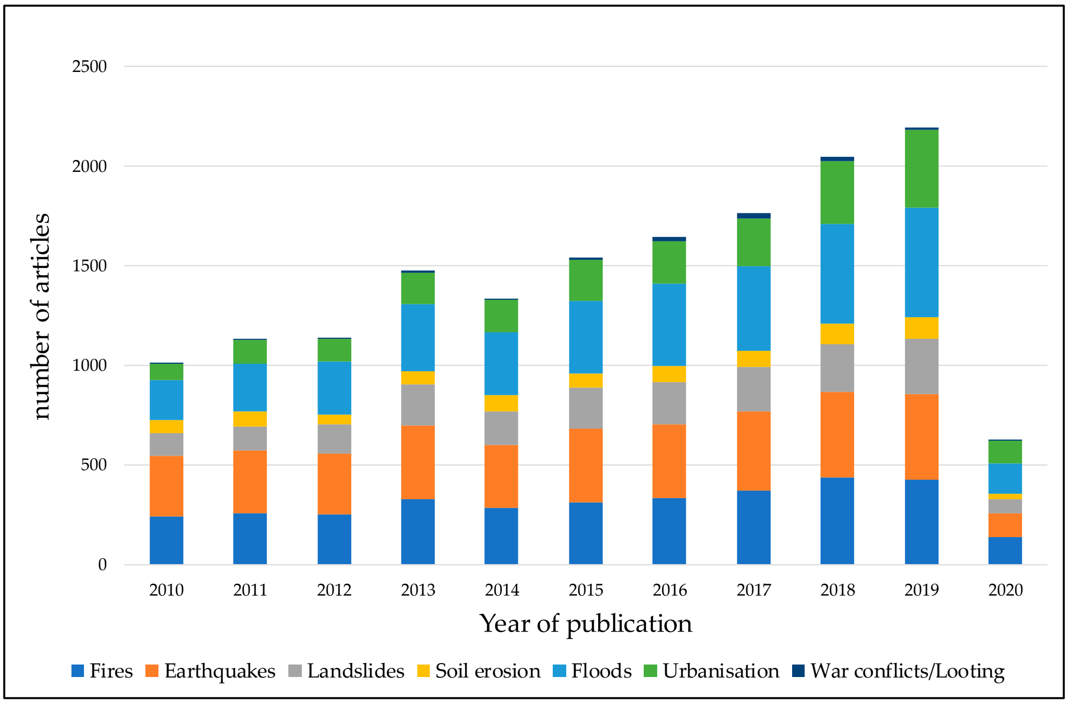

Figure 1. The total numbers of published articles related to various hazards with the support of satellite and space-based observations for the last decade (2010–2020) (results from Scopus engine database).

These findings showcase the continuous increase of the exploitation of space-based instruments for hazard analysis, even with significant variations regarding the number of applications per type of hazard. It is also still difficult to distinguish within the existing literature those applications that exploited the benefits of satellite observations specifically for the topic of cultural heritage (apart from looting). For instance, the query results from the Scopus engine relate to earthquake hazard provided more than 3500 articles, as mentioned earlier. Based on the keyword data for all these articles, a co-occurrence method analysis was implemented in the VOSviewer software tool [15]. The results of this analysis are shown in Figure 2. Each color represents a different thematic cluster of the keyword data for all articles found in the search engine. The size of each circle represents the magnitude of each thematic cluster (i.e., how many times the specific term was used in the 3500 articles). The links between the clusters are also visualized. In total, more than 10,000 different keywords were used in the 3500 publications, indicating either the method or the data used in their studies.

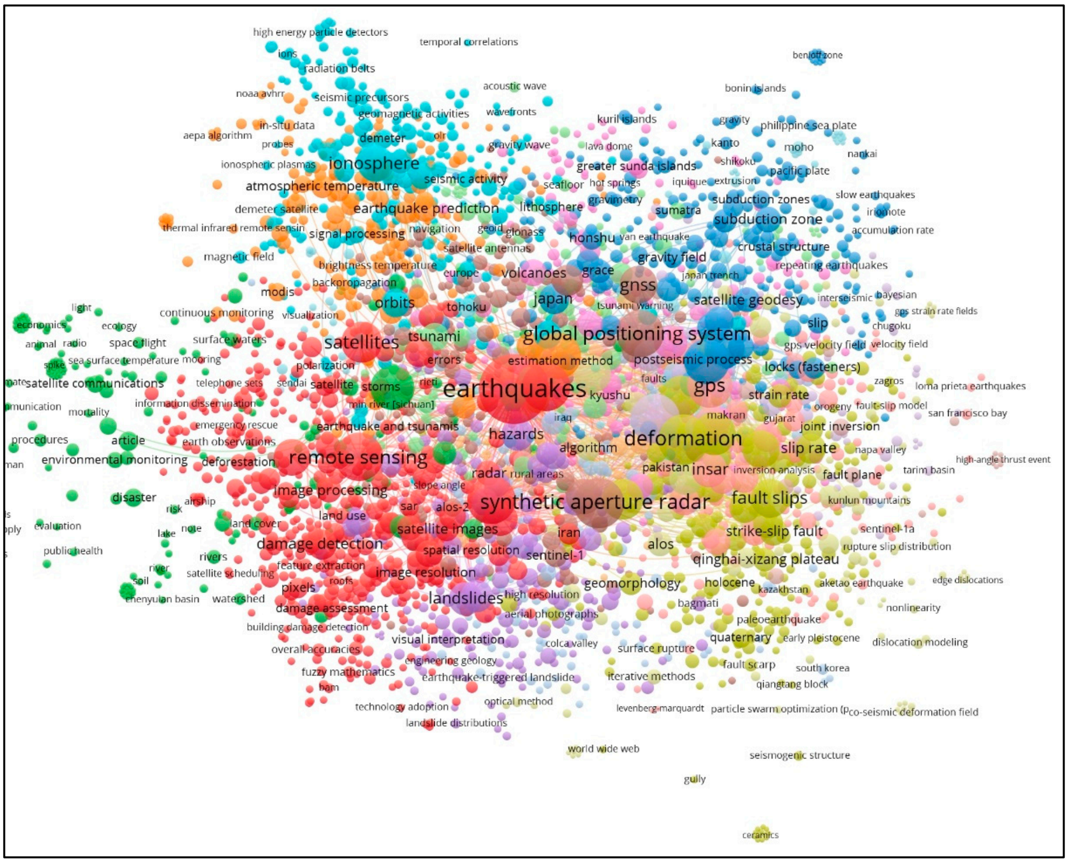

Figure 2. Visualization of the scientific studies related to earthquakes and satellite observations affecting cultural heritage. The database was extracted from the Scopus engine and visualized in the VOSviewer software.

The existing literature is primarily focused on the exploitation of satellite observation sensors for risk identification before and after the occurrence of an event. Also, the majority of these studies are technologically driven, and therefore aim to explore the potential of the space-borne sensors and to investigate their integration for monitoring purposes. Other studies are also focused on the development or evaluation of new methods and image processing techniques to improve the overall accuracy. In addition, the potential synergy between cultural heritage and existing space-based programs, such as the contribution of the free and open access policy of the European Copernicus program, have been already reported [16].

While these studies are of great importance for stakeholders and public bodies responsible for cultural heritage management, still more attention is needed to examine how satellite products and services can support specific steps of the disaster risk management (DRM) cycle for cultural heritage. This communication aims to fill this gap by firstly presenting the various steps of the risk management cycle for cultural heritage, as proposed by international organizations, and then highlighting potential synergies with satellite sensors through examples and existing applications.

2. Disaster Risk Management (DRM) Cycle

The DRM cycle concept was established following the recommendation of the International Strategy for Disaster Reduction [5]. Figure 3 shows the successive steps for the implementation of a DRM for cultural heritage, as suggested by international organizations and committees (represented by blue circles). Also, other accepted names for the components used in the DRM cycle beyond cultural heritage applications, namely the preparedness, response, recovery, and mitigation components, are also demonstrated in Figure 3 in the outer circle. A more detailed explanation of each step can be found in [5,17,18].

- **Step 1: Understanding the context**: Information collection regarding the various aspects relevant to the context in which a heritage site or monument is located. These aspects include the physical environment of a site or monument, as well as the administrative, legal, political, socio-cultural, and economic environment of the region.
- **Step 2: Identify risks**: Recognition of all relevant natural and man-made risks that might threaten cultural heritage within its context (as defined in step 1). During this step, the agents of deterioration and loss, the various layers of enclosures, as well as the risk occurrence are defined.
- **Step 3: Analyzing risks**: Estimation of the chance of occurrence and expected impact of all risks identified in step 2. Therefore, this step quantifies the potential impact of all considered risks, as well as any potential uncertainties of the analysis.
- **Step 4: Evaluation of risks**: Prioritization and classification of all potential risks, employing a multicriteria analysis and comparison.
- **Step 5: Treating risks**: Once the overall risks, their impacts, and their prioritization have been considered for a specific cultural heritage asset, effective measures can be planned to eliminate or minimize the negative impact. An adequate treatment plan is expected to be integrated into the broader management system for the organization or public authority that is responsible for executing these measures. For this reason, the various layers of the enclosure, as well as control measures, are formulated.
- **Step 6: Monitoring**: Monitoring also includes an update and improvement of the measures that were taken. Therefore, if anything changes the context of the cultural heritage site, this should be taken into consideration, as well as any inputs from the new knowledge or technology.

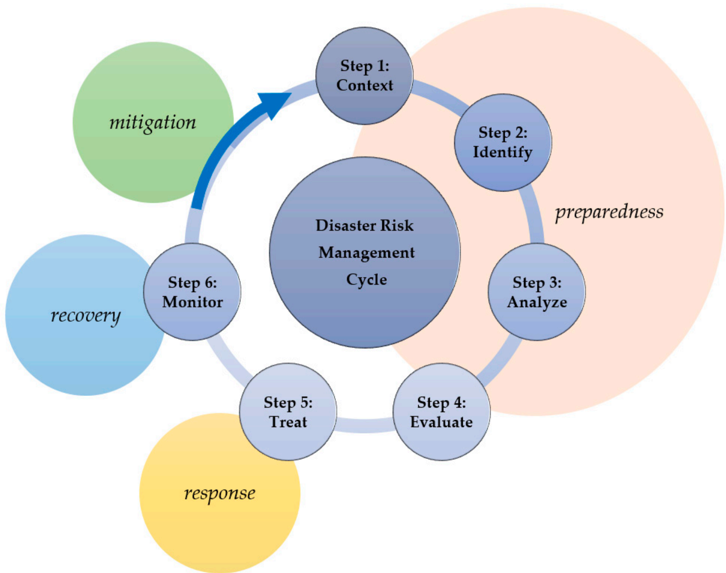

Figure 3. Disaster risk management (DRM) cycle steps (from [5,17,18]), represented by blue circles, while other accepted components of the DRM cycle used beyond cultural heritage applications are shown in the outer circle.

These steps are interconnected, and therefore any assumptions and uncertainties at any stage might influence the subsequent stages during the implementation of the DRM cycle. The design and conceptualization of a DRM cycle plan is a collective effort made by several parties that can provide both specific information with local value, scientific knowledge for better characterization of a site, and technological understanding.

3. Satellite Observation and Disaster Risk Management (DRM) Cycle for Cultural Heritage

This section presents the potential correlation of satellite observations and DRM for cultural heritage. Figure 4 summarizes the contributions of satellite observations in the different steps of the DRM cycle for cultural heritage, as this will be described in more detail in the following paragraphs.

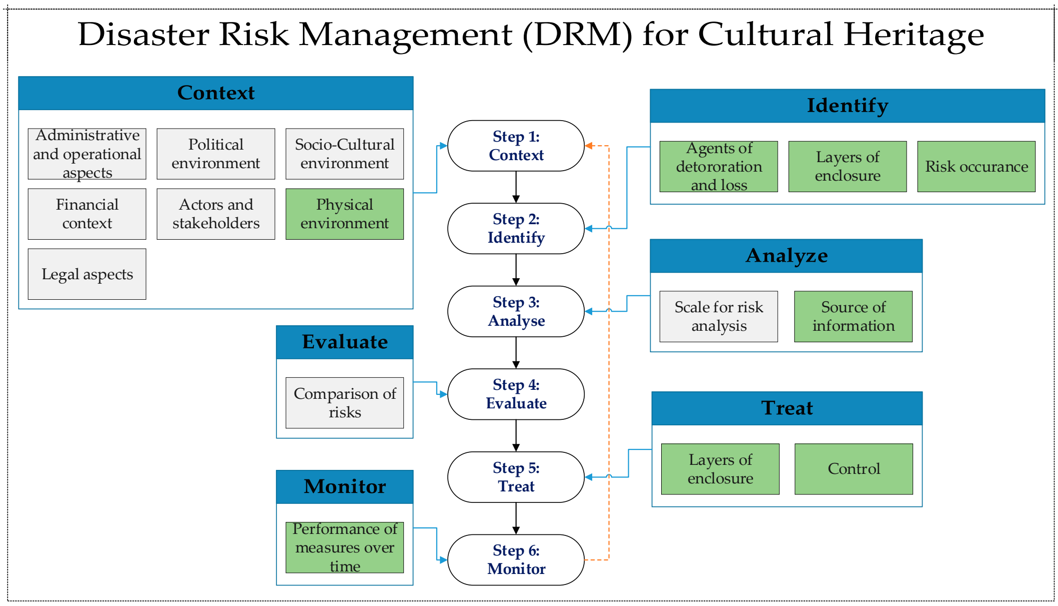

Figure 4. The potential contribution of satellite observation within the various steps of the risk management plan proposed by the International Centre for the Study of the Preservation and Restoration of Cultural Property (ICCROM) [17] is highlighted in the green rectangle.

3.1. Step 1: Context

The initial step of any action concerning cultural heritage is to understand its context. Satellite observation sensors can contribute to the understanding of the physical environment, a parameter that describes the context of a cultural heritage site or monument. For instance, sensors can be exploited for documentation purposes or mapping of land use, both within and the surrounding environment of an archaeological site or monument. Land use and land cover maps have been widely produced for general purposes for the classification of optical and radar images [19,20]. Such maps at a European level can be accessed through the Corine Land Use Land Cover (LULC) program [21]. LULC consists of an inventory of land cover in 44 classes. This classification provides a minimum mapping unit/width of 25 ha/100 m, while the Corine data are freely available, providing vector and raster datasets for the reference year 1990 (with updates for reference years 2000, 2006, 2012, and 2018). These maps, generated from satellite observations, can address the need to understand the contexts of archaeological sites and potential changes in their surroundings in the last 30 years (1990–2018).

Beyond this period, historical satellite images comprise a valuable source of information. The exploitation of declassified CORONA satellite images, with a repository of more than 800,000 images covering the period 1960–1972, offers the possibility to observe from space the environment of a cultural heritage site before any modern land use changes may have occurred, in the period before 1972 [22,23]. Also, stereo pairs of CORONA satellite images are useful in reconstructing the topography of landscapes before any recent alterations [24–26]. The unique potential of the CORONA satellite images is also detailed by Casana in a recent study [27].

3.2. Step 2: Identify

Once the context is defined, then the agents of deterioration and loss, the different layers of enclosures, as well as the risk occurrence need to be determined. For this step, existing geo-datasets, services, or products derived from the analysis of satellite images can be used as sources of information to identify potential risks. Monitoring temporal land use changes within and in the surroundings of a cultural heritage site can map gradual changes in the landscape over a given period of time. For instance, in [28] an increase of 300% in the surroundings of archaeological sites showed the dramatic changes in the landscape over a period of 30 years, while the land use and land cover changes in the wider area of Itanos, Crete, for the period 2013–2016 were investigated by Dawson et al. [29]. In both cases, optical satellite images were used. In [30], radar images were processed in order to monitor temporal changes through a time series analysis.

During step 2, existing geo-datasets that were produced with the support of satellite-based information can be used for sea level rise, climate change impact, micromovements, risk maps for geo-hazards, and others. These geo-datasets can be accessed through various online geo-catalogues. Cases of these are currently offered by the European Environment Agency (EEA) platform and the Geologic Hazards Science Center (GHSC). For example, datasets concerning soil loss by water (soil erosion) can be accessed and used as an indication of the specific threats for archaeological sites. Soil erosion data were generated using empirical soil loss models (revised universal soil loss equation—RUSLE), with inputs from satellite images [31]. The specific European atlas of soil loss was recently used by [32] to visualize and quantify soil loss in potential subsurface remains. Examples from the literature regarding the identification of other risks based on satellite image analysis beyond soil erosion can be found in [28,30,33,34].

3.3. Step 3: Analyse

While the identification of risks is necessary to understand the potential threats to cultural heritage sites and monuments, we also need to quantify the frequency (how often each risk occurs), the size of the loss (how big it is), and the extent of the threat (the size of the risk). Additionally, the uncertainty of the various inputs used to estimate these threats needs to be quantified to understand potential errors. From the literature, analysis of risk properties from satellite images and products is usually done when modelling floods studies, such as in [35]. In that specific case, the researchers estimated the uncertainty of the datasets used in the flood prediction models, improving the flood modelling accuracy [36]. Similarly, synthetic aperture radar (SAR) interferometric products were used to study landslides affecting cultural heritage [37]. In that study, the intensity of the landslides was estimated based on the exposure and vulnerability of the elements at risk. In addition, the potential loss due to a landslide of a given intensity was calculated for an area in Northwestern Italy. Satellite observation can also support analysis in order to understand the frequency and the extent of looting in conflict areas. As [38] showed for the archaeological area of Apamea in Syria, new looting areas can be detected from the processing of high-resolution satellite radar images, which can be used to map the extent of the looted area. An indicative reference discussing the role of earth observation for risk analysis can be found in [39].

3.4. Step 4: Evaluate

The evaluation of risks is the next step, and even though it is not in the core activities of satellite observation, there are many examples in the literature suggesting the use of multi-criteria analysis of risks data generated from satellite observation products and outcomes. For example, the analytical hierarchy process (AHP) is a multi-criteria objective decision-making approach that allows the user to arrive at a scale of preferences drawn from a set of alternatives by comparing different factors and their relative importance [40,41]. Therefore, satellite image products can be used in the evaluation procedure in order to classify the risks and prioritize hazards. For instance, in [42] the overall risk evaluation of different hazards, such as soil erosion, salinity, tectonic activity, urban expansion, and fires, was processed for heritage site clusters in the western part of Cyprus. Most of these hazards were elaborated with the use of freely distributed satellite data, such as the Landsat series, while an AHP methodology was implemented to identify the "weights" (prioritization) of each risk per cluster.

3.5. Step 5: Treat

Once the risks and their prioritization are defined, several measures are taken by actors and stakeholders towards their elimination or reduction. Such actions are necessary to avoid risk; to detect, monitor, and stop the agents that deteriorate the site; and to respond to the damage. The final stage is the recovery of the site and the heritage asset. While in this step of the DRM cycle the role of satellite observation seems to be limited, a closer look indicates that in some events, such as the case of monitoring sites and monuments in conflict zones, these datasets can provide unique information for the detection and monitoring of the areas. An example is the systematic monitoring of looted areas, especially in regions where physical access is difficult, such as conflict zones [30,43]. Unfortunately, looting and other illegal activities have been reported worldwide [44], including in the Mediterranean region [45], creating an ever-increasing need to explore new technological means and efficient ways to monitor areas of cultural wealth and provide systematic observations over vast landscapes. The latter can be achieved through the exploitation of high-resolution optical satellite and radar observations. However, these observations need to be analyzed with great caution, due to the lack of ground truthing. Despite this, these space-based observations cannot prevent the illegal actions on the ground. The identification of newly looted areas, probably unknown to local stakeholders, is considered a critical step towards increasing the awareness of potential illegal trafficking.

3.6. Step 6: Monitor

Satellite observation can play a critical role at the last step of the DRM cycle for cultural heritage sites, namely the monitoring phase. The monitoring step refers to the evaluation of all the measures that have been taken to protect the site and minimize the impact of the risk. The literature review for this step is inexhaustive; therefore, bibliographic references mentioned in the previous sections (Sections 3.1–3.5) can also be considered for part of the monitoring step, for continual monitoring of the site after the measures taken by the stakeholders. The spatial extent, along with the continuous observation of cultural heritage sites, can be easily achieved using remote sensing techniques, as these have been individually described above for each step of the management cycle. For example, Copernicus program products, such as those acquired from the Sentinel-1 radar and Sentinel-2 optical sensors, as well as other data with higher spatial resolution from the Copernicus Contributing Missions [46], provide the possibility of systematic monitoring and continuous updating of stakeholders for extensive areas. The high temporal revisit time of the Copernicus satellite sensors is ideal for the systematic observation of heritage sites and monuments over time, even for areas that are not physically accessible, since they can continuously provide new data.

4. Discussion

DRM intended for cultural heritage requires a plethora of inputs and information from various sources to eventually lead to comprehensive implementation of the DRM plan. As shown in the previous sections, satellite observation can contribute to all steps of a DRM cycle, particularly for monitoring and detection purposes.

Two important properties of satellite observation data and products that make their use unique for management plans is that they are geo-referenced, having almost global coverage. In addition, satellite remote sensing can provide systematic and diachronic observation with a high revisit period, thus creating a unique multi-temporal dataset, which is ideal for cultural heritage applications. Additionally, the free access and use policy that characterizes data and products need to be taken into consideration, especially when dealing with large areas. The use of space-based data is also ideal when considering other factors, such as budget constraints and limitations of in situ inspections that prohibit proper ground observations (i.e., war-conflicted areas). Towards this direction, the European Copernicus program implements a full, free, and open access (FFO) data policy, which allows user free access, use, and re-use of data and information, while eliminating any barriers in order to ensure extensive re-use of these datasets. While this is true for the medium-resolution Sentinel-1 and Sentinel-2 datasets (providing radar and optical images, respectively), access to higher resolution images from the Copernicus Contributing Missions [46] is not free (with exceptions for research grants). The beneficial properties of satellite observation products for cultural heritage are summarized in Figure 5.

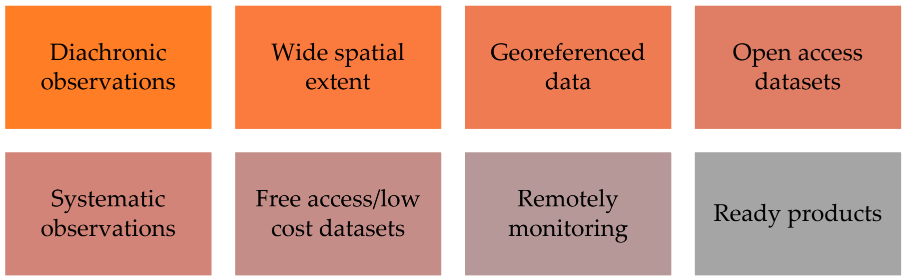

Figure 5. Favorable characteristics of satellite observation datasets for DRM of cultural heritage.

Of course, satellite observation is not a panacea for the implementation of a DRM plan, and limitations do exist for the use of these data, such as their spatial resolution. It is, however, an important input variable that can fill gaps and provide further information in all steps of a DRM cycle. Figure 6 summarizes some of the critical remote sensing processing chains that can be used in each of the steps of a DRM cycle for cultural heritage. This figure is not exhaustive, rather it is indicative of the potential of earth observation.

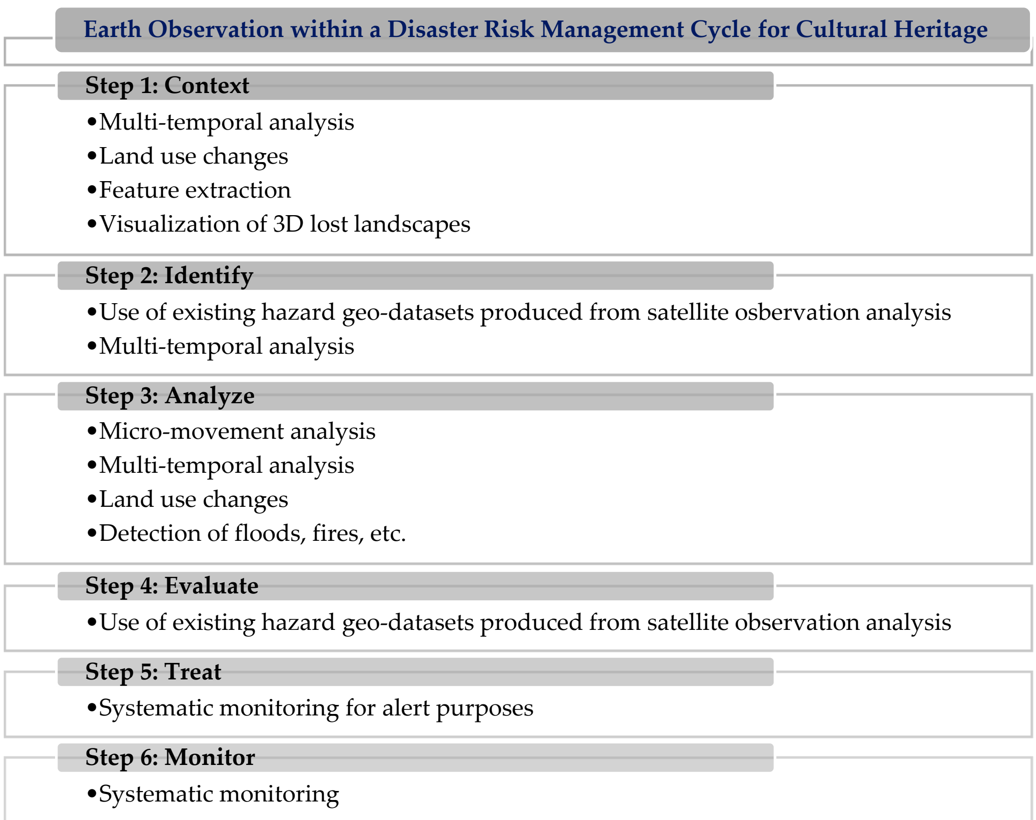

Figure 6. Indicative key satellite observation processing chains beneficial for the various steps of a DRM cycle intended for cultural heritage.

5. Conclusions

The DRM cycle for cultural heritage sites and monuments, which is used for their protection, is composed of six consecutive steps. The implementation of these steps requires various inputs, starting from the context and ending with the systematic monitoring of a site or monument.

This communication article underlines the effective roles that satellite observation can play in all stages of a DRM cycle for archaeological sites and monuments. The contributions of satellite observation and the opportunities raised from its use are showcased through indicative examples from existing literature.

In all DRM cycle steps, earth observation datasets and products can play important roles, starting from a comprehensive understanding of the context of an archaeological site or monument and moving into the identification and analysis of potential risks and their evaluation. In addition, earth observation can support measures and actions taken for the protection of the archaeological sites and monuments, with a special contribution in the monitoring phase of the DRM cycle.

The plethora of available satellite sensors and satellite observation processing chains can support local and regional stakeholders responsible for cultural heritage management for the implementation of local DRM cycle plans. The Copernicus program can be further utilized to support the special needs of archaeological sites and monuments by providing access to the high-resolution satellite images available through the Copernicus Contributing Missions, thus enabling the development of sophisticated holistic image-based methods for the DRM cycle. Future research could include the development of Copernicus-based algorithms and techniques, exploiting the entire spectrum of the Copernicus potential, namely the Sentinel missions, the Copernicus Contributing Missions, and the Copernicus Emergency Management Services.

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