

Article

Appraisal of Opportunities and Perspectives for the Systematic Condition Assessment of Heritage Sites with Copernicus Sentinel-2 High-Resolution Multispectral Imagery

Deodato Tapete *  and Francesca Cigna 

Italian Space Agency (ASI), Via del Politecnico snc, 00133 Rome, Italy; francesca.cigna@asi.it

* Correspondence: deodato.tapete@asi.it

Received: 5 March 2018; Accepted: 23 March 2018; Published: 5 April 2018



Abstract: Very high-resolution (VHR) optical satellite imagery (≤ 5 m) is nowadays an established source of information to monitor cultural and archaeological heritage that is exposed to hazards and anthropogenic threats to their conservation, whereas few publications specifically investigate the role that regularly acquired images from high-resolution (HR) satellite sensors (5–30 m) may play in this application domain. This paper aims to appraise the potential of the multispectral constellation Sentinel-2 of the European Commission Earth observation programme Copernicus to detect prominent features and changes in heritage sites, during both ordinary times and crisis. We test the 10 m spatial resolution of the 3 visible spectral bands of Sentinel-2 for substantiation of single local events—that is, wall collapses in the UNESCO World Heritage site of the Old City of Aleppo (Syria)—and for hotspot mapping of recurrent incidents—that is, the archaeological looting in the archaeological site of Apamea (Syria). By screening long Sentinel-2 time series consisting of 114 images for Aleppo and 57 images for Apamea, we demonstrate that changes of textural properties and surface reflectance can be logged accurately in time and space and can be associated to events relevant for conservation. VHR imagery from Google Earth was used for the validation and identification of trends occurring prior to the Sentinel-2 launch. We also demonstrate how to exploit the Sentinel-2 short revisiting time (5 days) and large swath (290 km) for multi-temporal tracking of spatial patterns of urban sprawl across the cultural landscape of the World Heritage Site of Cyrene (Libya), and the three coastal ancient Greek sites of Tocra, Ptolemais, and Apollonia in Cyrenaica. With the future development of tailored machine learning approaches of feature extraction and pattern detection, Sentinel-2 can become extremely useful to screen wider regions with short revisiting times and to undertake comparative condition assessment analyses of different heritage sites.

Keywords: optical remote sensing; multispectral imagery; Sentinel-2; Google Earth; feature extraction; change detection; damage assessment; cultural heritage; Syria; Libya

1. Introduction

Optical satellite images are nowadays established Earth observation data for research teams and practitioners to monitor cultural and archaeological heritage that is exposed to hazards and anthropogenic threats to their conservation. If clouds do not hamper the visibility of the area of interest, the features on the ground are usually clearly seen and the surface changes are detected. Thanks to these properties, optical remote sensing is regarded by the archaeological and heritage community as an objective source of information allowing for a conservative estimate of the condition on the ground [1]. However, the expertise of the individuals, their level of training in mapping and

interpreting features, as well as a priori knowledge and expectations on what to see, are all factors influencing the level of accuracy that can be achieved in the satellite-based assessment.

In the last years, optical remote sensing has proved extremely valuable in reducing the uncertainty about the condition of heritage assets across the Middle East and North Africa (MENA) region and, more generally, in the Mediterranean countries. Several initiatives at both the international and national level are ongoing. For example, the UNESCO Emergency Safeguarding of the Syrian Cultural Heritage project [2], the American School of Oriental Research Cultural Heritage Initiative (ASOR CHI) [3], the Association for the Protection of Syrian Archaeology (APSA2011) [4], and the Endangered Archaeology in the Middle East & North Africa (EAMENA) [5]. These projects collect information from satellite imagery not only to map the extent of damage and destruction incurred by built and movable heritage during crises, but also to assess the impact of modern human activities in ordinary times, such as agricultural exploitation of land, urban expansion, and infrastructure construction.

As recently recalled by Casana and Laugier [6], the above-mentioned projects demonstrate that the research and user communities are moving from site-based studies and single-incident substantiations to more systematic, regional-scale efforts over larger regions. However, such large spatial coverage and monitoring of a multitude of sites at the same time still pose operational challenges; first of all, the need to access large volumes of timely and updated satellite imagery at a suitable resolution. Satellite data uploaded onto open visualization platforms (for example, Google Earth and Bing maps) have partly contributed to solving this issue and are now Earth observation facilities incorporated into the image interpretation methodologies of some of these heritage initiatives (for example, Reference [5]).

The optical images used for such studies mostly come from satellites operated by commercial companies (for example, WorldView and GeoEye) because of their sub-meter spatial resolution. For instance, the potential for looting detection has been recently discussed in Reference [7]. To avoid confusion on terminology, in this work, we adopt the classification by which optical satellite imagery is referred to as ‘very high resolution’ (VHR) if characterised by a spatial resolution of 5 m to even less than 1 m, and ‘high resolution’ (HR) if the spatial resolution is between 5 and 30 m; see, for example References [8,9].

From the point of view of research development, the emphasis on the exploitation of VHR images—mostly driven by the need for searching for very small features—has led to very few publications that specifically investigate the role that regularly acquired HR images from constellations such as the Landsat missions may play in this application domain. It is also to be noted that most of these publications rather concentrate on land use impacts in the surroundings of the sites and/or their buffer zones and conservation areas. These often exploit broad classification schemes for their assessment (for example, urban versus agricultural [10,11]), but seldom focus on the recognition of specific man-made features and tracking of the temporal evolution of their patterns.

On the other side, the Sentinel-2 multispectral constellation of the European Commission programme Copernicus [12–14] is an Earth observation system that is increasingly gathering attention in archaeological remote sensing. The thirteen spectral bands (443–2190 nm) and HR imaging capabilities in visible and near-infrared bands at 10 m spatial resolution have been already tested for archaeological prospection (for example, References [15,16]). On the contrary, it is still to be assessed how Sentinel-2 can be used systematically to detect prominent features and changes in heritage sites during both ordinary times and crisis. To the best of our knowledge, no research has been published yet to test Sentinel-2 for this specific capability.

This is, therefore, the aim and overarching research question of this paper. In particular, we explore the value of Sentinel-2 time series for multi-temporal HR assessment for event verification and hotspot mapping. Our appraisal is structured around a selection of case studies in Syria and Libya that we investigated using Sentinel-2 and Google Earth time series (Section 2) to examine two scenarios (Section 3):

1. The local heritage has been impacted by event(s) known based on precise background information (that is, including the location, time of occurrence, and typology of the event). Therefore the

features to search for in the satellite images can be anticipated, are very distinctive, and easy to interpret in the cloud- and fog-free visibility conditions (Section 3.1);

2. The heritage site is known to be a hotspot of specific threats to conservation (for example, intense and repeated looting) and the history of incidents may suggest that further events can happen, and their manifestation can be captured even at HR (Section 3.2).

The results of the Sentinel-2 time series analysis were validated based on integration with VHR imagery—that is, DigitalGlobe and CNES/Airbus images available in Google Earth—and background knowledge from published literature and incident reports. When no Sentinel-2 data were available before a certain date of interest, we used the pre-existing Google Earth time series to identify the trends and dynamics of the investigated studies for further verification in the more updated Sentinel-2 time series.

This was the case in the demonstration site of Cyrene where there was an opportunity to investigate an anthropogenic process of a potential threat to heritage conservation that manifests at the surface through distinctive features changing in time. We, therefore, discuss how systematic Sentinel-2 acquisitions taken with short revisiting time can be used for the dynamic detection of such features (Section 3.3). We then test the regional scalability of the method by extending the analysis across the entire Libyan region of Cyrenaica with a focus on coastal heritage sites affected by urban sprawling (Section 4). We finally outline future research directions in this field accounting for the emerging opportunities offered by machine learning (Section 5).

2. Materials and Methods

To carry out our appraisal, we tested the Sentinel-2 HR imagery on the following heritage sites in Syria and Libya (Figure 1):

- the UNESCO World Heritage Site (WHS) of the Ancient City of Aleppo in Syria (centre coordinates: $36^{\circ}13'59''\text{N}$; $37^{\circ}10'00''\text{E}$);
- the Hellenistic site of Apamea in Syria ($35^{\circ}25'11''\text{N}$; $36^{\circ}24'05''\text{E}$), proposed for inscription on the UNESCO World Heritage List in 1999;
- the cultural landscape of Cyrene WHS and the modern town of Shahat in Libya ($32^{\circ}48'12''\text{N}$; $21^{\circ}51'46''\text{E}$);
- the ancient Greek towns of Apollonia (modern Susah; $32^{\circ}54'07''\text{N}$; $21^{\circ}58'11''\text{E}$), Ptolemais (modern Ad Dirsiyah or Tolmeita; $32^{\circ}42'24''\text{N}$; $20^{\circ}57'10''\text{E}$), and Tocra ($32^{\circ}32'20''\text{N}$; $20^{\circ}34'10''\text{E}$) in northern Cyrenaica, eastern Libya.

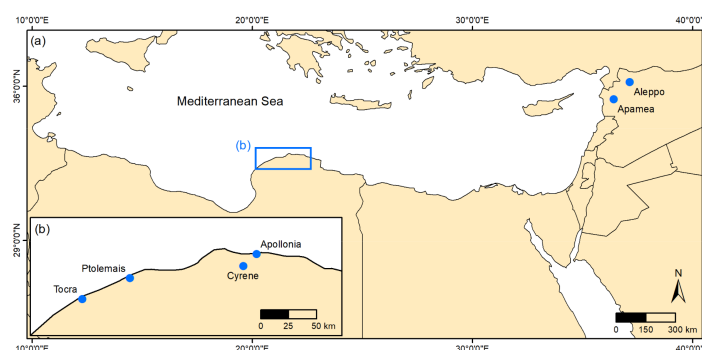


Figure 1. The geographic location of the heritage sites in the Mediterranean countries that represent the demonstration sites of this study (displayed on World Countries (Generalized), 2017 ESRI).

Table 1 summarizes the heritage category, status and type of damage, site disturbance or land cover–land use change processes affecting the above demonstration sites. The background knowledge

about the processes under investigation is based on published and grey literature, outcomes of previous satellite-based assessments, and information extracted from the news, reports, photos, and videos found in the web and social media. Specific citations are reported throughout the text and summarized in Table 1. Our selection of demonstration sites aims to cover processes of potential threat to heritage conservation that occur in ordinary times as well as during times of crisis. Sentinel-2 data were analysed against different sizes, spatial extents, severities, and temporal evolutions of human activities, as detailed in Section 3.

Table 1. The summary of the demonstration sites with an indication of the heritage status (if applicable); the heritage category; the type of process impacting the site conservation that is discussed in this paper; references for a historical, archaeological, and conservation introduction to the sites. Notation: WHS = World Heritage Site; TWHS = Tentative WHS.

Hotspot	Heritage Status	Heritage Category	Process	References
Aleppo (Syria)	WHS	Urban	Urban warfare	[1,17,18]
Apamea (Syria)	TWHS	Hellenistic town	Looting	[1,19,20]
Cyrene (Libya)	WHS	Greek town and cultural landscape	Urban development	[5,21,22]
Apollonia (Libya)	-	Greek town	Urban development	[23]
Ptolemais (Libya)	-	Greek town	Urban development	[23]
Tocra (Libya)	-	Greek town	Urban development	[23]

Our motivation to test the Sentinel-2 constellation for the condition assessment of heritage sites relies on the following image properties:

- (i) Systematic global acquisition of multispectral imagery with consistent imaging parameters;
- (ii) Spatial resolution of 10 m in the visible bands [12,13];
- (iii) Short revisiting time (up to 5 days) over Europe and the Mediterranean countries [24].

We used the Copernicus Open Access Hub to access the Sentinel-2 products acquired by the Multispectral Instrument (MSI) onboard the twin satellites Sentinel-2A and Sentinel-2B. This is the dedicated platform where Top-Of-Atmosphere (TOA) reflectance in cartographic geometry (that is, Level 1C, or L1C) products are regularly published by the European Space Agency (ESA) very soon after acquisition. Since April 2017, the Bottom Of Atmosphere (BOA) reflectance in cartographic geometry (that is, Level 2A, or L2A) products are also published 48–60 h after the L1C products, based on automated processing of the latter with the Sen2Cor processor and PlanetDEM Digital Elevation Model [25]. For each demonstration site, the temporal period of our observation spanned from the first image available in 2015 up to December 2017.

Of the 13 MSI spectral bands, we focused on the B2 (490 nm), B3 (560 nm), B4 (665 nm) bands and their Red-Green-Blue (RGB) colour composites at full resolution. We intentionally concentrated on these bands because the majority of archaeologists and practitioners assessing the condition of heritage sites based on optical satellite imagery mostly rely on the use of RGB information of VHR satellite images (for example, References [1,3,5,6,19]). A proof of concept on the visible bands, without further sophisticated processing of these and other bands, is expected to ease the initial uptake of Sentinel-2 by a wider spectrum of practitioners. We acknowledge though, that future research and implementation could take advantage of recently developed methods. For example, the sharpening of Sentinel-2 bands with spatial resolutions of 20 m and 60 m to a spatial resolution of 10 m, in order to obtain a full set of visible and near-infrared (VNIR) and shortwave infrared (SWIR) spectral bands with a spatial resolution of 10 m [26].

To carry out our analysis we discarded products where clouds hampered the visibility of the heritage sites.

Since Sentinel-2 is an HR satellite constellation, we did not expect to distinguish small to very small features (that is, <10 m). Instead, we aimed to demonstrate that Sentinel-2 data can be used for

the systematic and regular screening at the site scale to identify larger single features, clusters of small features, and accumulations of progressive (small) changes that eventually manifest as new prominent surface features. For example, while individual looting features could not be resolved in the Sentinel-2 data, clusters of several adjacent looting holes are clearly detectable (see Section 3.2).

We ran a multi-temporal analysis by using the full Sentinel-2 archive available for each of the demonstration sites that provides, at best, a 5-day revisiting time from one acquisition to the next. However, because Sentinel-2A was launched on 23 June 2015 and in consideration of the time needed for commissioning (that is, ~3 months from the end of launch and early orbit phase), in some cases, the earlier cloud-free images available for the demonstration sites were acquired in October 2015.

We spatially analysed the Sentinel-2 stacks against ancillary data including, but not limited to site plans, maps of heritage assets, and thematic maps. In particular, for each demonstration site, we defined the T_0 time reference, against which we detected the new features based on either their textural or surface reflectance properties. For this purpose, we applied the state-of-the-art change detection techniques currently used across the specialist community (for example, Reference [27]). In practice, for each pair of Sentinel-2 images acquired at T_{n-1} and T_n , the surface reflectance at bands B4, B3, B2 and the textural properties were compared and clusters of pixels indicating hotspots of change were highlighted and zoned through a conversion to polygons.

We interpreted the observed features following the same standard mapping methodologies that are commonly used by research teams and practitioners to assess the condition of a heritage site using optical satellite imagery [3,5,6,19]. To label the features and associate them to specific events of relevance for the site conservation, we browsed incident reports that are regularly issued by local heritage bodies, international organizations and initiatives (for example, ASOR, Syrian Directorate-General for Antiquities and Museums—DGAM, and Geospatial Technologies and Human Rights Project of the American Association for the Advancement of Science—AAAS), as well as the news in broadcasts and social media.

For validation and trend analysis, we accessed open-source VHR images through Google Earth (see Appendix A). These data provided the sub-meter spatial resolution and allowed us to upgrade the spatial definition of the identified features. However, their temporal coverage of the demonstration sites was discontinuous and not regular. In some circumstances, this implied the existence of temporal shifts with respect to the date of the reported incidents, as well as to the more regular temporal coverage provided by the Sentinel-2 time series. On the other hand, since Google Earth VHR images were acquired before June 2015, they were extremely useful to define the T_0 time reference, that is, the site condition prior to the first available Sentinel-2 image. The above-mentioned limitations are well discussed in the literature not only compared with the regular provision of VHR optical data through direct purchase, funds, sponsorships and agreements [6], but also with the regularly acquired time series of satellite imagery acquired by space-borne sensors operating with different wavelengths (for example, the Synthetic Aperture Radar—SAR [20]). We accounted for these advantages and limitations brought by VHR imagery when we interpreted them in combination with the Sentinel-2 time series (Sections 3 and 4).

3. Results

3.1. Detection and Substantiation of Damage Events: Wall Collapse at the Citadel of Aleppo WHS

Inscribed on the UNESCO WHS List in 1986, the Ancient City of Aleppo includes a wealth of urban heritage assets such as 17th-century madrasas, palaces, caravanserais, and hammams, as well as the 12th-century Great Mosque and the 13th-century Citadel (Table 1). The latter is probably the most iconic monument. The large medieval palace lies at the top of the prominent and steep elliptical hill (in archaeological terminology ‘tell’; about 150 m by 300 m wide, 425 m above sea level) which is a very distinctive landscape feature of the WHS, as observed in the ASTER Global Digital Elevation Model (Figure 2a). The palace is fortified with a fence of turreted walls crowning the entire tell (Figure 2b).

The Citadel, and more generally the whole WHS extending for ~365 ha across the old town (Figure 2a), has witnessed the consequences of armed conflict, with several incidents having occurred since the city became the theatre of the ‘Battle of Aleppo’ in 2012–2016. Accounts of war damages are reported in various documents (for example, References [17,18]). With specific regard to the Citadel, the major damage observed from space prior to 2015 was that to the roof formerly protecting the excavations of the Temple dedicated to the Storm God [1].

The site-specific question to address in this case was whether Sentinel-2 could be used to identify damages in the Citadel during the crisis. We analysed 114 Sentinel-2 images covering the Citadel of Aleppo from 8 July 2015 to 14 December 2017, a temporal and spatial subset of which is represented in Figure 3. In the Sentinel-2 image acquired on 11 August 2016 (Figure 3b) we detected a new distinctive feature along the northern slope of the tell consisting in a brighter strip (that is, an increased surface reflectance) extending from the section of the Citadel fortification walls behind the Citadel Museum up to the tell toe.

This feature was not visible on or before 4 August 2016 (Figure 3a) but it was permanent in the following Sentinel-2 images (Figure 3c–e), therefore it could be established that this was not an imaging artefact or an ephemeral feature. The feature extracted from the Sentinel-2 time series is indeed the mark of a wall collapse event that happened exactly on the date the Sentinel-2 image was acquired, that is, on 11 August 2016. As shown in a video published on YouTube on that date [28], the section of the Citadel fortification walls, once stretching between the Citadel Museum and the Great Mosque of the Citadel, collapsed on 11 August 2016. Further confirmation of the characteristics of the event was retrieved from the photographs and a video posted by APSA2011 on their website that were taken from outside the Citadel a few days after the collapse [29].

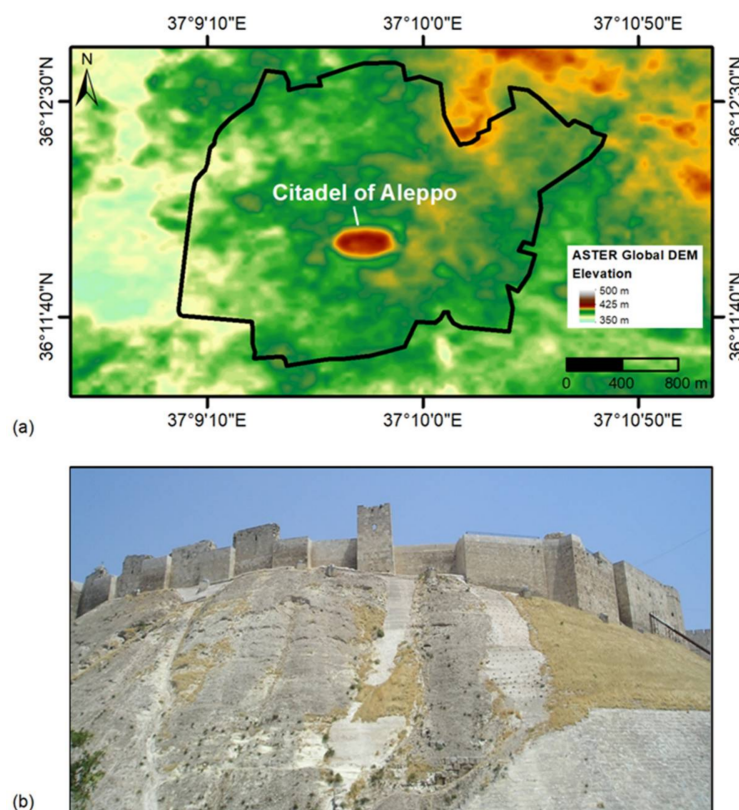


Figure 2. (a) Boundaries of the designated UNESCO World Heritage Site of the Ancient City of Aleppo displayed onto a 30-m resolution ASTER Global Digital Elevation Model (GDEM), with an indication of the elliptical tell of the Citadel. (b) View of the Citadel walls as of 1 August 2005 (photo source: Wikimedia Commons). ASTER GDEM is a product of METI and NASA.

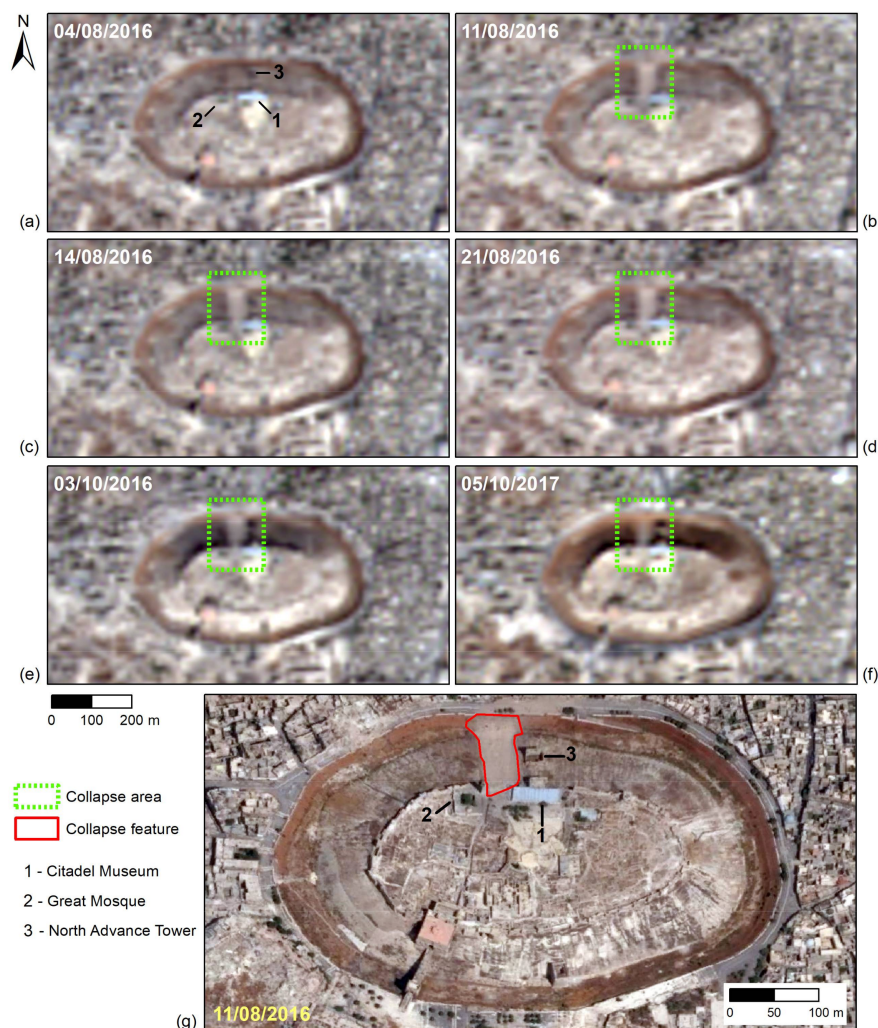


Figure 3. View of the Citadel of Aleppo (Syria) from Sentinel-2 images acquired on (a) 4 August 2016, (b) 11 August 2016, (c) 14 August 2016, (d) 21 August 2016, (e) 3 October 2016, (f) 5 October 2017, and from (g) very high resolution (VHR) Google Earth image taken on 11 August 2016. Labels and polygons indicate the monuments and buildings close to the area of the wall collapse that happened on 11 August 2016. Copernicus Sentinel-2 images in (a–f) © 2016–2017 European Space Agency—ESA; Google Earth image in (g) © 2018 DigitalGlobe.

Further corroboration that Sentinel-2 captured the collapse when it happened comes from the examination of a DigitalGlobe VHR image acquired on the same date and accessed through Google Earth (Table A1 in Appendix A). This image shows the same collapse feature and allows a more precise delineation of the footprint of the damaged area (red boundary in Figure 3g) to match the satellite-based assessment done by ASOR [30].

However, it is not currently possible to update the condition of the collapsed section of the walls after 24 December 2016 via Google Earth. On the contrary, the systematic monitoring with Sentinel-2 enables us to observe the feature of the wall collapse persistently in the imagery until the end of 2017 (Figure 3f) and therefore, infer that the condition of the wall has not changed in the present day.

3.2. Hotspot Monitoring: Site-Scale Assessment of Looting in Apamea

The archaeological site of Apamea is an example of ‘heritage hotspot’, that is, a site of high priority for heritage stakeholders and for which the risk of being damaged is considered high due to the combination of a high probability of incident occurrence, a high degree of exposure, and/or a high

stock of cultural elements at risk. Since the start of the Syrian civil war in March 2011, Apamea has been affected by extensive and repeated looting of archaeological goods [1,19]. Satellite optical and SAR imagery have been used to estimate that about 45% of Apamea was looted as of October 2014 with evidence of the intensification of looting and changing spatial patterns across the northern and eastern parts of the site, above the main Decumanus, in 2015 [20]. Table A2 in Appendix A lists the VHR satellite images viewable in Google Earth showing the situation from 2011 to mid-2014.

In such circumstance, the current approach of national and international heritage initiatives is to prioritize the site and task VHR satellite acquisitions to revisit the hotspot periodically, so as to be able to check the condition of the local heritage and update the records accordingly. From this perspective, freely accessible and regularly acquired HR datasets can contribute cost-effectively to the systematic monitoring of the heritage hotspot and highlight features and changes of new events or intensifications/repetitions of ongoing processes that have been previously mapped.

In our experiment, we screened the cloud-free archive of 57 Sentinel-2 images covering Apamea from 20 August 2015 to 17 December 2017 (Figure 4a,b) and we searched for any textural and/or surface reflectance changes occurring within the site walls. The site-specific research question that we could address with Sentinel-2 was whether new looting had affected the western and southern sectors of the archaeological site that were previously unlooted and, if so, whether this could have been seen at the 10 m resolution.

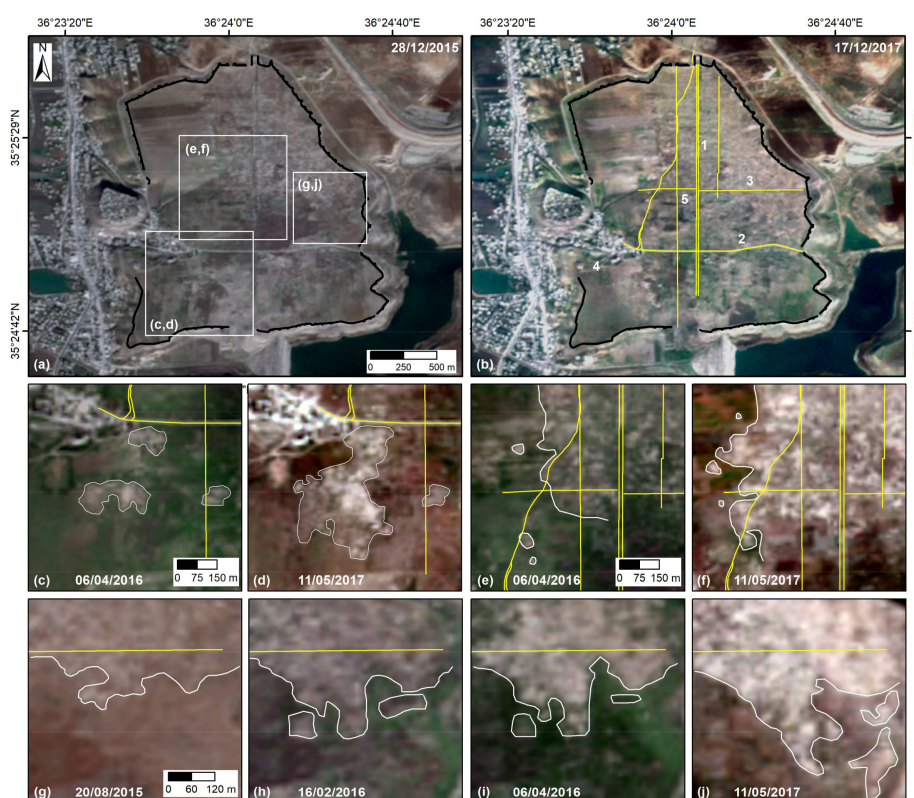


Figure 4. View of the archaeological site of Apamea (Syria) from Sentinel-2 images acquired on (a) 28 December 2015 and two years later on (b) 17 December 2017 with the locations as follows: (1) Cardo Maximus; (2) main Decumanus; (3) second main Decumanus; (4) Roman theatre; and (5) Agora. Zoomed images of the new looted areas detected with the Sentinel-2 time series analysis, southeast of the Roman theatre on (c) 6 April 2016 and (d) 11 May 2017; west of the Cardo Maximus and the Agora on (e) 6 April 2016 and (f) 11 May 2017; and east, along the second main Decumanus on (g) 20 August 2015, (h) 16 February 2016, (i) 6 April 2016, and (j) 11 May 2017. Copernicus Sentinel-2 images © 2015–2017 European Space Agency—ESA.

From 20 August 2015 until the end of 2015, no evidence of new looting clusters was detected at the spatial scale allowed by Sentinel-2 (Figure 4a). Starting from 16 February 2016, owing to a better contrast in the reflectance of looted areas with respect to the surrounding greening land, new looting is clearly visible in at least three sectors: (i) south-east of the theatre (Figure 4c,d); (ii) west of the Cardo Maximus and the Agora (Figure 4e,f); and (iii) in the eastern portion of the archaeological site, along the second main Decumanus (Figure 4g–j).

In particular, on 6 April 2016 higher reflectance was found in the fields located south-east of the theatre (Figure 4c), close to a cluster of looting pits that were already visible in November 2015. The remarkable increase in surface reflectance is compatible with new holes being dug and the associated brighter terrain being exposed by the excavation. Indeed the increase of reflectance due to earth movement and excavation of topsoil with the consequent exposure of the underlying ground is well known and reported in the literature [6,20].

In the eastern portion of the archaeological site, along the second main Decumanus, we also detected an expansion of the previously looted area from 20 August 2015 to 16 February 2016 (Figure 4g,h), as well as an intensification of looting starting on 6 April 2016 (Figure 4i). At this date, new looting also became apparent in the area of the Market (Figure 4e) where it expanded until 05 June 2016 (Figure 4f shows the situation on 11 May 2017).

What was observed with Sentinel-2 anticipates the evidence gathered through an ad hoc DigitalGlobe image acquired on 20 June 2016 and used by ASOR to report the ongoing looting at Apamea [31]. Except for the different spatial detail in boundary delineation, as expected due to the different spatial resolution, the two satellite-based assessments at HR and VHR mutually match. Thus, proving the complementarity of these two Earth observation systems for hotspot mapping. Thanks to the high temporal frequency of its acquisitions, Sentinel-2 brings in a better capability to temporally log observations of looting.

Going through the Sentinel-2 time series up to the end of 2017, we found evidence that looting did not stop, but instead continued with new episodes. As captured on 11 May 2017, new looting had clearly manifested in the archaeological site west of the Cardo Maximus and the Agora (Figure 4f) and above the Decumanus Maximus (Figure 4j). The subsequent Sentinel-2 images did not highlight any apparent further expansion of the looting-affected areas. On the contrary, unexcavated sectors within the Justinian Walls that had not been previously looted (such as the north-western and south-eastern fields) did not appear to have been affected by looting until the end of the Sentinel-2 time series that we analysed, that is, mid-December 2017 (Figure 4b).

Owing to the short revisiting time of Sentinel-2, we were also able to observe the progressive weathering and ‘ageing’ of older looting clusters. This is a known effect and is described in the specialist literature using both optical and SAR satellite imagery [19,20]. In dry seasons, these holes may also become less visible due to low tone contrast with regard to the surrounding brown soil. Consequently, in absence of frequent satellite images, the spatial zoning of looted areas may be affected by an underestimation. In this regard, an example is provided in Figure 4h–j. A sub-rounded cluster of looting holes was timely detected in February 2016 (bottom left in Figure 4h) and was still visible a couple of months later (bottom left in Figure 4i). More than one year after, in May 2017, although the expansion and reworking of looting were clearly detected and mapped, the older cluster of looting holes was much less distinguishable from the brownish surrounding land (Figure 4j). The weathering of looting holes and subsequent underestimation of looted areas are environmental constraints that can affect both HR and VHR optical imagery, but the high temporal frequency offered by Sentinel-2 can help to cope with this inconvenience owing to the higher probability of timely detection and logging under conditions of good visibility and tone contrast.

3.3. Dynamic Detection of Changing Features: Urban Development around the WHS of Cyrene

The UNESCO WHS of Cyrene in Libya is famous for the archaeological ruins of the Greek city, with the Acropolis, the Agora, and the Temple of Zeus being located north of the modern town

of Shahat, while the necropolises extend across the cultural landscape. These suburban zones are currently the most vulnerable to threats to their conservation due to urban expansion of Shahat and the limited enforcement of planning regulations [21,22]. Rayne et al. [5] have recently published a geospatial analysis of the cultural landscape changes around the Cyrene WHS that were observed since 1986 by combining the full VHR image catalogue available through Google Earth (2006–2017) with two Landsat scenes (1986, 2000) and one Sentinel-2 image (2017). From this analysis, the authors concluded that Shahat has expanded massively and activities affecting the preservation of the WHS and its immediate hinterland have accelerated over the past five years following the unstable situation of the country.

The site-specific research question was whether we could use Sentinel-2 for its imaging capability at a high temporal frequency to log incidents of urban expansion as accurately as with ad hoc acquisitions. In the absence of Sentinel-2 images prior to mid-2015, we first re-examined the whole Google Earth dataset (Table A3 in Appendix A) to achieve a baseline knowledge scenario for the whole cultural landscape. Instead of classifying pixels according to ‘urban’ training samples as done in Reference [5], we ran a feature extraction analysis by searching for urban features (for example, new roads, new clusters of buildings, excavation sites) that typically appear when urban development is happening. As explained in Section 2, we compared the surface reflectance values between pairs of subsequent scenes (T_{n-1} versus T_n , where $n - 1$ and n are the epochs of the two Sentinel-2 images composing each pair) and zoned clusters of pixels spatially distributed as urban block patterns.

Using the above approach, we could track, both spatially and temporally, the urban expansion around Shahat through the appearance and, more importantly, the transformation of new town blocks. These appeared to be the basic units of new urban development. Their construction history can be summarised as per the example located east of Shahat that is reported in Figure 5. Initially, the topsoil is excavated to create the grid pattern of the new road network enclosing small lots of land (Figure 5a). The pavement of the roads is then laid down using more durable surface material (Figure 5b,c). In this case, a light brownish to whitish material is used, therefore, making the roads very distinctively visible from space (Figure 5c). Later, the land lots are populated by houses, concrete constructions and/or agricultural fields (Figure 5d,e).

The block feature reported in Figure 5 is just one of the tens that we have extracted from the Google Earth (2009–2015; Figure 6a) and Sentinel-2 (2016–2017; Figure 6b) time series as they progressively appeared in the last five years (2012–2017) east, south, and west of Shahat. Interestingly, this type of feature was not present from 2006 to 2012. Since then, this feature seems to have spread across the cultural landscape surrounding the WHS of Cyrene, according to a spatial distribution and trends that could not be fully appreciated using only a supervised classification mixing spectral signatures of different urban features within the same ‘urban’ class.

In 2012, the block features mostly appeared south of Shahat (purple polygons in Figure 6a). A year later similar features manifested east of the modern town, where archaeological records of the east necropolis are documented (green polygons in Figure 6a). In 2013, very limited incidents were observed west of Shahat, where the south necropolis was formerly located. In 2014, the spatial trend changed and urban development happened across the whole rural landscape (yellow polygons in Figure 6a), to a point of reaching the southern boundary of the Cyrene archaeological site (Figure 6c). In particular, works for new roads and blocks were ongoing in June 2014 and, after only one year, a new settlement was already developed very close to the ruins of the Sanctuary of Demeter and Kore (Figure 6c; see also References [5,22]). In the years covered by the Sentinel-2 time series (2016–2017), new block features were mostly concentrated in the landscape of the south necropolis (Figure 6b), thus, highlighting the increasing impact on this area up to present days (Figure 6d).

The two examples reported in Figures 5 and 6c prove that these urban feature patterns have a short life cycle. On average, from the first appearance to the full development, a cycle lasts one year in total, with the construction phases mostly happening during a few months. In this regard, the high temporal frequency provided by Sentinel-2 is extremely valuable to achieve high temporal

granularity to capture new incidents of urban development. It is worth acknowledging that, because of their size, the block features are equally well detected in both Sentinel-2 and Google Earth images, thus, resulting in no omissions of block feature mapping with HR and VHR data due to the different spatial resolution.

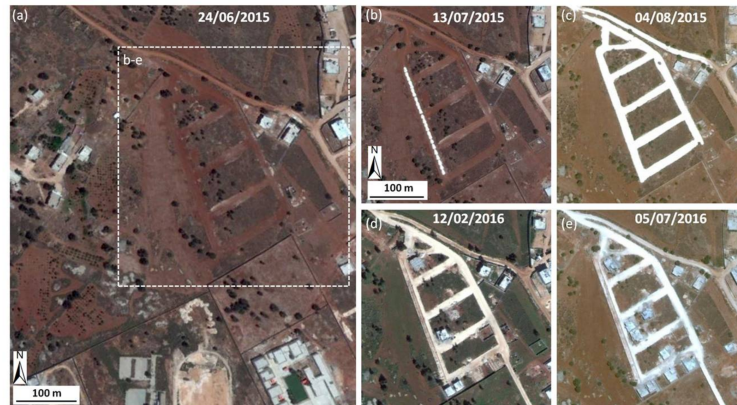


Figure 5. The life cycle of the typical block feature of new urban development in the cultural landscape surrounding the Cyrene WHS (Libya), as reconstructed based on the VHR Google Earth satellite imagery: (a) the topsoil is initially excavated (24 June 2015); (b) the road pavement is laid down (13 July 2015); (c) the road grid enclosing land lots is completed (4 August 2015); (d,e) the land lots are being populated by houses, dwellings, and farming activities (12 February 2016 and 5 July 2016). Google Earth imagery © 2018 DigitalGlobe.

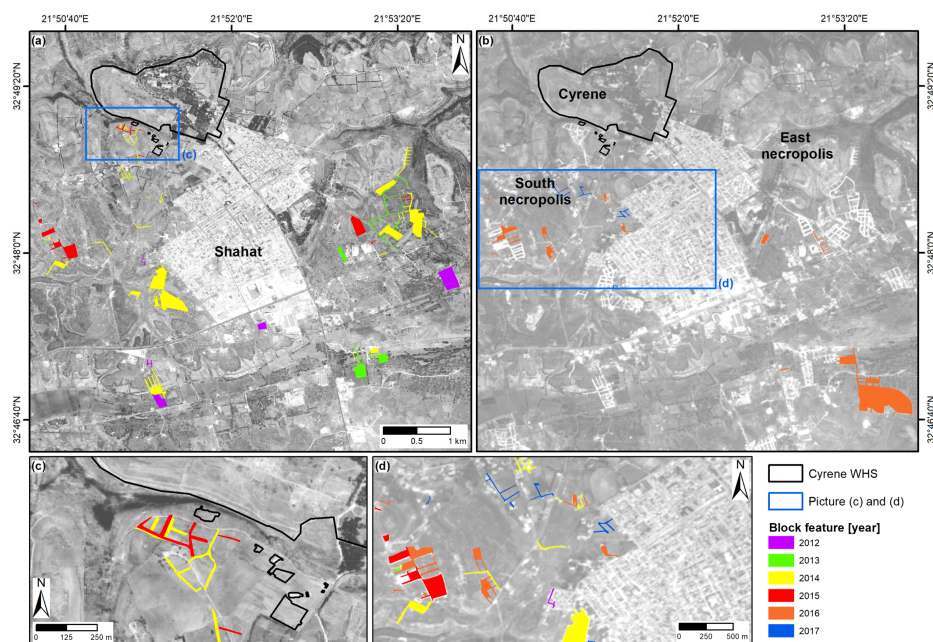


Figure 6. The spatial and temporal distribution of block features of new urban development across the cultural landscape of the Cyrene world heritage site (WHS) and in the surroundings of the modern town of Shahat (Libya), as mapped through (a) Google Earth (2009–2015) and (b) Sentinel-2 time series (2016–2017). Note that no block features were detected prior to 2012. Zoomed views of the urban development (c) close to the Sanctuary of Demeter and Kore and (d) west of Shahat, in the landscape of the south necropolis. Blocks in (a,c) are overlapped onto Google Earth imagery acquired on 25 December 2006, while blocks in (b,d) are overlapped onto Copernicus Sentinel-2 image acquired on 4 October 2015. (© 2015 European Space Agency—ESA). Google Earth imagery © 2018 DigitalGlobe.

Of course, the level of detail achieved with Sentinel-2 for feature delineation is much lower than with VHR satellite images. However, even at very local scale, that is, focusing on hotspot areas to search for changes, the spatial resolution of Sentinel-2 can already be enough and the VHR imagery may not be necessary, at least to undertake the first assessment.

An example is found in the hotspot identified near the Sanctuary of Demeter and Kore (see Figure 6c). In March 2014, when Sentinel-2 images were not yet available, DigitalGlobe imagery showed no evidence of building construction in close proximity to the archaeological ruins (Figure 7a). Three months later, the first roads and dwellings were built (Figure 7b); after one year, the new block feature had already achieved a mature stage of development, with evidence of further excavation along the road facing the ruins (see blue polygon in Figure 7c). By coincidence, this situation was captured in a DigitalGlobe image that was acquired on 24 June 2015, that is, when the Sentinel-2A satellite was launched.

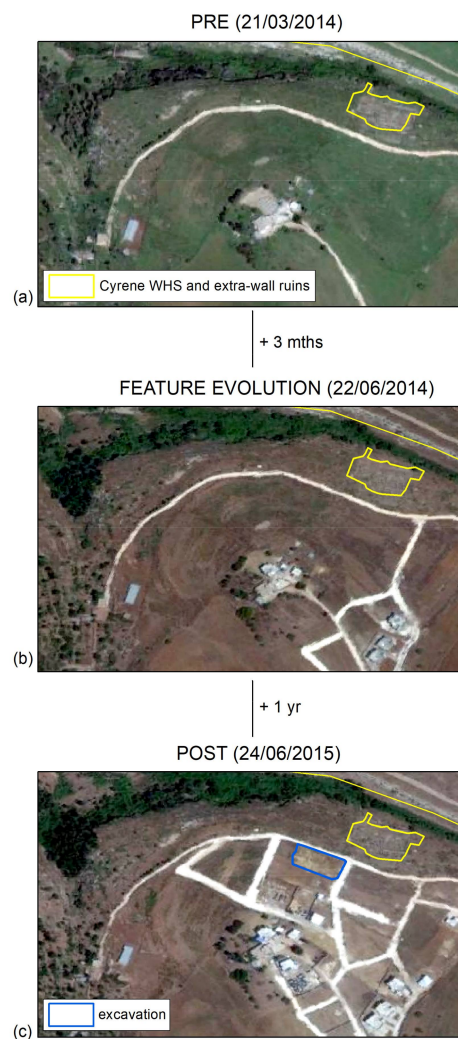


Figure 7. The evolution of the block feature detected in the proximity of the Sanctuary of Demeter and Kore, south of the Cyrene WHS hilltop site (see Figure 6c for location), based on the VHR Google Earth imagery time series: (a) 21 March 2014; (b) 22 June 2014; and (c) 24 June 2015. Google Earth imagery © 2018 DigitalGlobe.

The first cloud-free Sentinel-2 image taken on 4 October 2015 depicts the same situation (Figure 8a). However, the analysis of the Sentinel-2 image acquired on 12 January 2016 highlights new excavations and earth movement in the land lot next to the one where excavations were already ongoing (see red

polygon in Figure 8b). Therefore, the Sentinel-2 imaging capability proves to be of a sufficient spatial resolution to highlight this local land use change. The availability of more frequent acquisitions allows us to date the new excavation one month earlier than the Google Earth image acquired in February 2016 (Figure 8c). Excavations do not appear to have developed any further, after 9 (Figure 8d), 18 (Figure 8e,f) and 20 months (Figure 8g) since then, suggesting a sort of inactivity in the process of urban development.

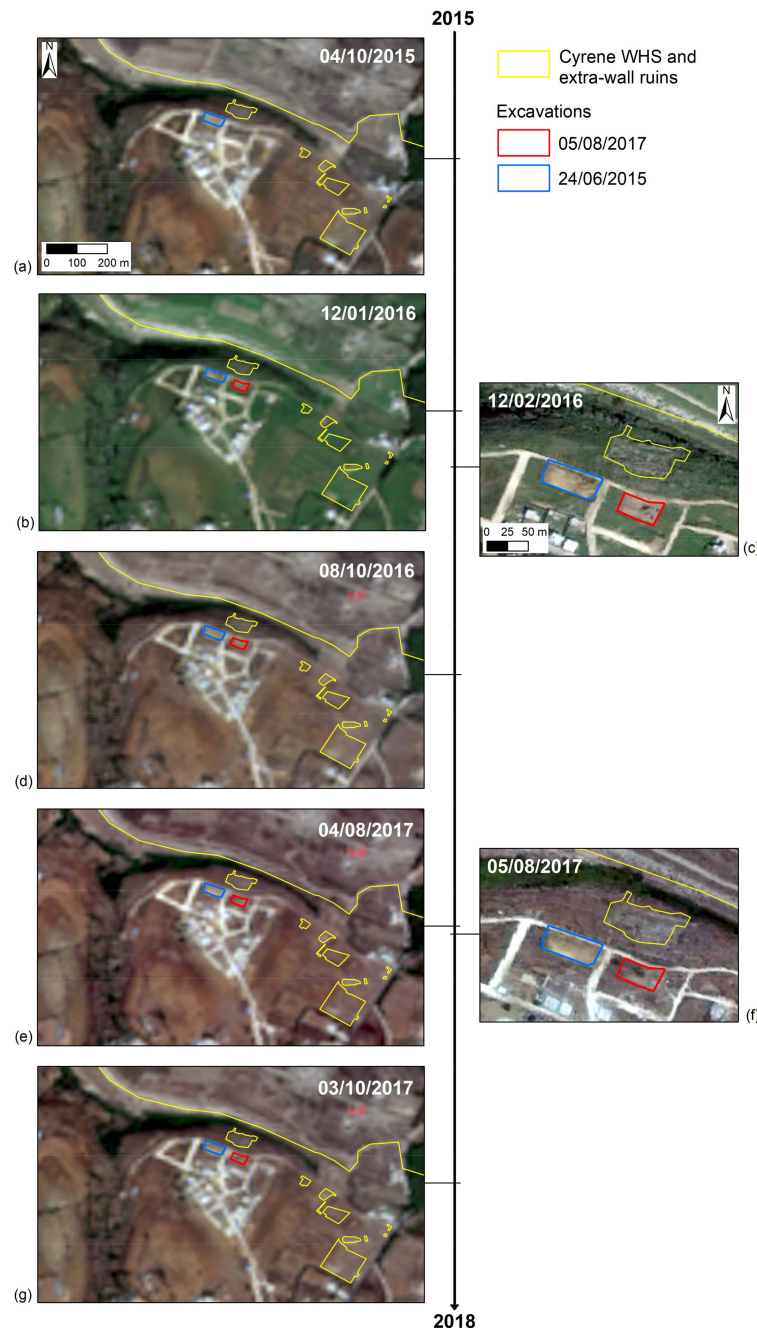


Figure 8. The evolution of the block feature detected in the proximity of the Sanctuary of Demeter and Kore, south of the Cyrene WHS hilltop site, based on Sentinel-2 time series: (a) 4 October 2015; (b) 12 January 2016 compared with (c) the VHR Google Earth image taken on 12 February 2016; (d) 8 October 2016; (e) 4 August 2017 compared with (f) the VHR image taken on 5 August 2017; and (g) 3 October 2017. Copernicus Sentinel-2 images in (a,b,d,e,g) © 2015–2017 European Space Agency—ESA; Google Earth images in (c,f) © 2018 DigitalGlobe.

The large swath of the analysed Sentinel-2 images (290 km) allowed us to widen the field of view beyond the cultural landscape of Cyrene and modern Shahat. We found that the block features were widespread and suggested that the urban sprawl is an accelerating process across the whole region of Cyrenaica. Therefore, the situation around the WHS of Cyrene and Shahat was a local manifestation of a wider regional phenomenon that is discussed in Section 4.

4. Discussion

The demonstration on the 2016 wall collapse in the Citadel of Aleppo WHS is an example of systematic examination of the regularly acquired optical satellite imagery, even at HR, that can provide objective evidence to detect impacts of damaging events on the conservation of local heritage assets, and substantiate incident reports and in situ observations. It is, of course, understood that we were able to capture this damaging event through the systematic monitoring with Sentinel-2 against the baseline reference of the Citadel of Aleppo because the collapse feature was clearly visible to the satellite, and its size and extent were large enough to be resolved at a 10 m spatial resolution.

It can be argued that, under different conditions, no feature could have been detected with Sentinel-2 due to its spatial resolution. In this regard, we recall the previous collapse that occurred along the eastern section of the Citadel walls on 11 July 2015. This event was reported and documented in the broadcast media the following day [32] and also by ASOR [33]. Based on published photographs taken from outside the Citadel, it can be observed that the collapse affected a few metres of the walls and the rubble accumulated in the upper part of the slope, just at the toe of the former walls. Therefore, this collapse generated a smaller event footprint than the event in August 2016.

Google Earth does not provide an image taken on the day or soon after the 2015 collapse happened (see Table A1 in Appendix A). We can only compare two DigitalGlobe images acquired on 15 December 2014 and 26 October 2015 (Figure 9a,b) to analyse the collapse at a VHR. Although the visibility and illumination conditions are not ideal, the 26 October 2015 image somehow allows for the identification of the area affected by the collapse that occurred in July (Figure 9b). A concave feature is also visible at the toe of the collapsed wall section that was not visible previously.

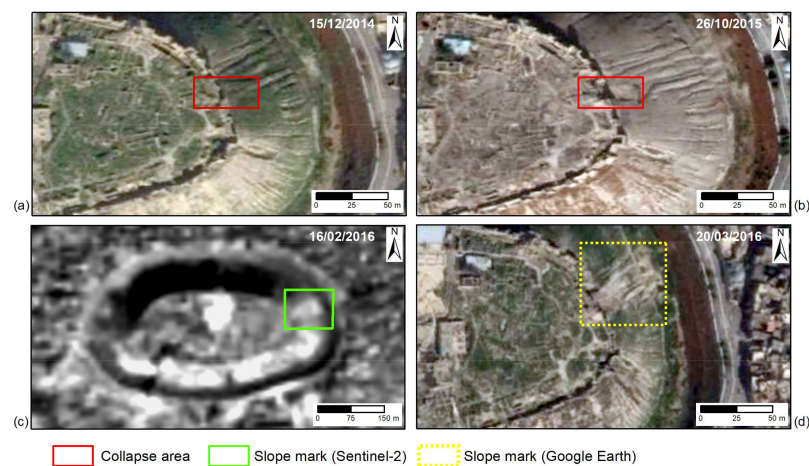


Figure 9. View of the eastern walls of the Citadel of Aleppo (a) several months before (15 December 2014) and (b) a few months after the 11 July 2015 collapse (26 October 2015). The red rectangle indicates the area affected by the collapse and the concave feature that developed on the slope after the collapse. (c) Grey-level representation of Sentinel-2 image acquired on 16 February 2016 with an indication of the area of higher surface reflectance probably caused by the weathering and erosion of the slope and rubble that moved further down the slope (green rectangle). (d) The VHR Google Earth image acquired on 20 March 2016 confirms the presence of the slope mark identified in the Sentinel-2 time series (yellow dashed rectangle). Google Earth images in (a,b,d) © 2018 DigitalGlobe; Copernicus Sentinel-2 image in (c) © 2016 European Space Agency—ESA.

The comparison between the Sentinel-2 images acquired on 8 July 2015 and 17 August 2015 suggests that the collapse may not have been detected with Sentinel-2 without a priori knowledge. However, if the lower resolution of Sentinel-2 was a limiting factor for the event detection, subsequent Sentinel-2 images proved the benefit of having systematic acquisitions to follow the cascading effects of the wall collapse on the condition of the tell slope. By screening the Sentinel-2 dataset, it can be observed that the condition of the eastern slope of the tell does not change until 16 February 2016 when a feature resembling the track and toe deposit of collapsed debris becomes distinctively and permanently visible (Figure 9c). This suggests that, in the absence of remediation works and due to the exposure to weathering, the slope further eroded and some rubble moved further down the slope. DigitalGlobe images acquired on 20 March 2016 and 23 March 2016 validate our Sentinel-2-based assessment (Figure 9d), thus, implicitly providing proof that Sentinel-2 is valuable to track relevant changes in the heritage site beyond the detection of a single event.

Multi-temporal tracking is, undoubtedly, the key functionality that Sentinel-2 provides for hotspot monitoring, thanks to the combined high revisiting time of the two satellites. Our test on Apamea not only contributes to updating the information on the condition of this archaeological site as the last records date back to June 2016 [26], but more importantly, it demonstrates that the Sentinel-2 constellation allows for monitoring looting and similar anthropogenic activities at this scale. While single small holes can be resolved only by means of VHR satellite imagery, the experiment on Apamea suggests that we do not need exclusively VHR images to track new and expanding looting with temporal accuracy. Far from stating that Sentinel-2 or other HR optical space missions should and could be used as a replacement for VHR Earth observation solutions, we instead propose the joint use of these systems making the best of their respective advantages (that is, freely accessible regular acquisitions on one side; higher spatial resolution on the other).

In Cyrene, we also proved that dense cloud-free Sentinel-2 time series can allow changes affecting cultural landscapes to be monitored and mapped with similar spatial accuracy and temporal granularity that can be achieved with an ad hoc VHR time series. Cyrene was a fortunate case study owing to the wealth of VHR images available via Google Earth. However, in cases in which the temporal coverage is discontinuous or cases in which such a dense VHR is not available, regularly acquired Sentinel-2 images become an asset for WHS condition monitoring.

While supervised classification with broad classes (for example, ‘urban’ versus ‘undeveloped land’) is an agile mapping approach, our test of feature extraction proves that an insightful analysis can be carried out with Sentinel-2 data to geospatially assess the changing degree of exposure of vulnerable heritage. With this method, it was clear that not all the areas of the cultural landscape surrounding the WHS of Cyrene were vulnerable at the same time. Prior to 2014, the urban sprawl was predominant east of Shahat and could potentially impact only the east necropolis. Starting from 2014 it appears that the urban sprawl became an increasing threat also for the conservation of the south necropolis, west of the modern town. Our experiment suggests that, if a dynamic assessment was undertaken in near real-time as new Sentinel-2 images were ingested in the time series analysis, the satellite-based condition assessment may inform the decision-making process and help to monitor the compliance of local land use changes with planning and landscape policies and regulations.

As found in Cyrene, the distinctive features relating to land cover and land use changes may be local manifestations of more regional phenomena. These situations can be captured over wide regions by exploiting the large swath of single scenes or mosaics of multiple (but coeval) Sentinel-2 images.

To simulate how Sentinel-2 could be used for this purpose, we ran the same test to extract and map block features due to the urban sprawl across Cyrenaica in Libya. We analysed a multi-temporal mosaic that we made by combining Sentinel-2 images available over Cyrenaica, from 29 July 2015 to 4 October 2015 (Figure 10a). Our analysis suggests that in 2015 a number of block features were already widespread and common features in all the major urban settlements of Cyrenaica. The comparison with the Google Earth VHR time series pre-dating the Sentinel-2 mosaic confirms that the number and

density of these block patterns started increasing since 2013, according to a general trend that can be observed in many other locations.

By intersecting the block features extracted from the Sentinel-2 mosaic and the location of known archaeological sites, three hotspots are found in the ancient Greek towns of Apollonia, Ptolemais, and Tocra (Figure 10a). These are coastal sites embedded in the urban environments of the modern towns that have historically developed nearby [23]: Susah, Ad Dirsiyah, and modern Tocra, respectively (Figure 10b–d).

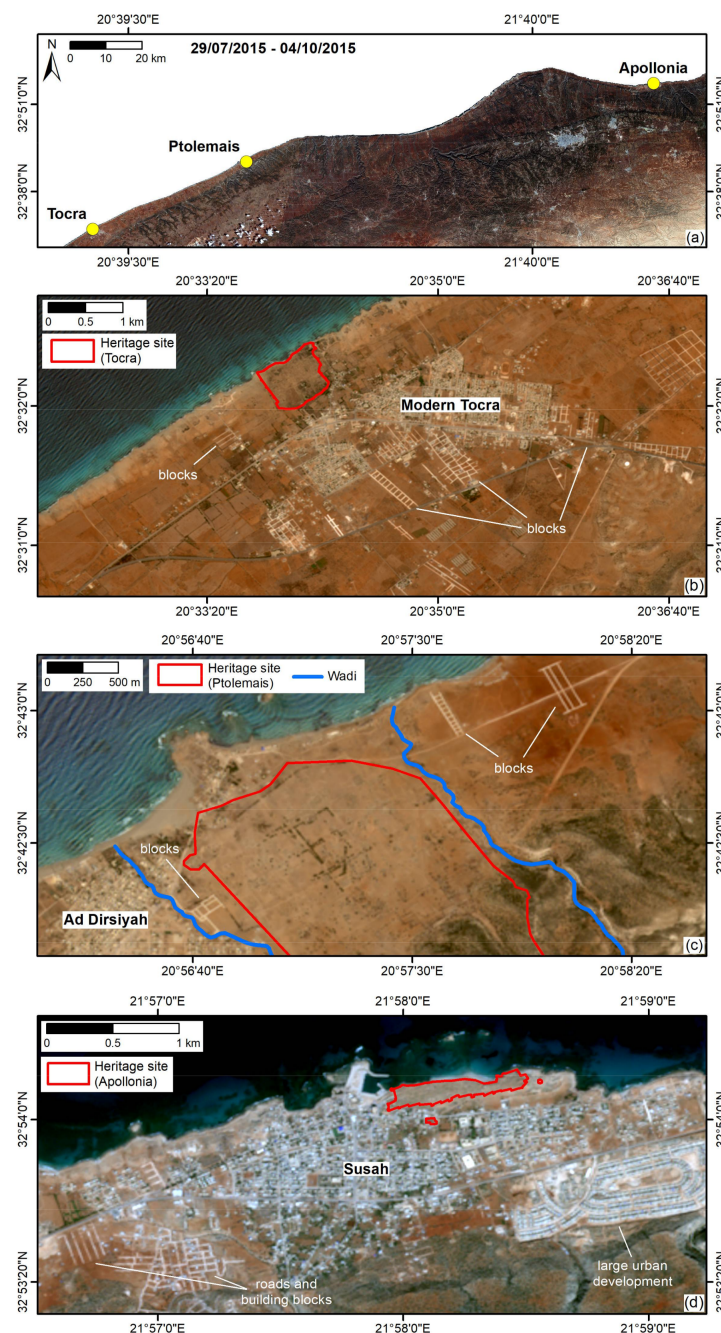


Figure 10. (a) Synoptic view of Cyrenaica (Libya) and the archaeological sites of Tocra, Ptolemais, and Apollonia through a multi-temporal mosaic of cloud-free Sentinel-2 images acquired from 29 July 2015 to 4 October 2015. The zoomed views on (b) Tocra, (c) Ptolemais, and (d) Apollonia. Block features and the proximity of the modern towns are clearly visible. Copernicus Sentinel-2 images © 2015 European Space Agency—ESA.

The synoptic view achieved with only two Sentinel-2 images allowed us to highlight slightly different situations in these three sites. In 2015, in Tocra and Apollonia, recent urbanisation was not immediately affecting the archaeological sites, although this was already an anthropogenic process that was apparently re-shaping the wider landscape (Figure 10b,d). In particular, Susah expanded through one large project of urban development in the south-east and through new roads and building blocks in the south-west, but no new block features were developed at that time in the proximity of the archaeological site of Apollonia (Figure 10d). However, some properties were already built very close to the southern boundary of the site (see also Figure 11d). Similarly, there was no evidence of new blocks built in the proximity of the ruins of Tocra in 2015, but outside the modern town, several road-blocks had already appeared (Figure 10b). Conversely, in mid-2015 urbanisation was already affecting the archaeological site of Ptolemais (Figure 10c). A new road-block enclosing land lots had been already created close to the western boundary of Ptolemais, in a portion of land west of the Wadi Khambis that was previously vacant (see also Figure 11b). Other road-blocks had been laid down along the coast, north-east of the site, beyond the Wadi Ziwana (Figure 10c).

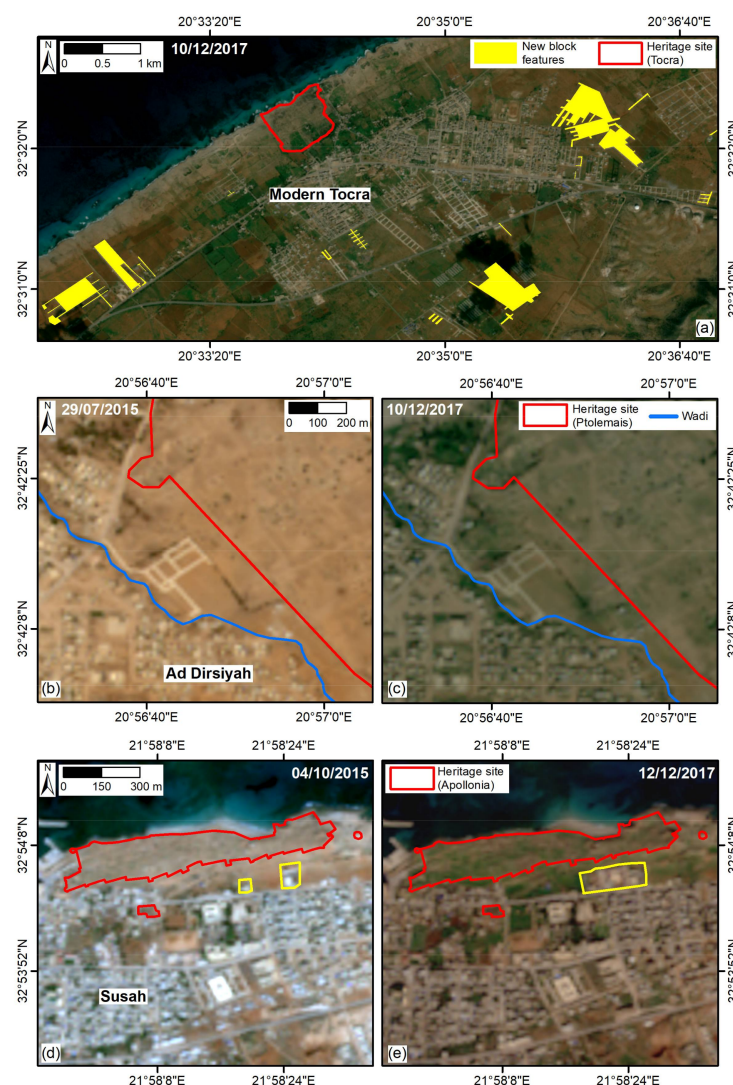


Figure 11. The condition on the ground in (a) Tocra, (b,c) Ptolemais and (d,e) Apollonia as captured by Sentinel-2 in 2015 versus 2017. (a) New block features (yellow polygons) are visible around the modern town of Tocra; (b,c) no change is detected over the existing block feature close to Ptolemais; (d,e) the development of previously vacant land lots along the southern boundary of Apollonia (yellow polygons). Copernicus Sentinel-2 images © 2015–2017 European Space Agency—ESA.

By analysing Sentinel-2 data until the end of 2017, no further changes were found within the footprints or along the boundaries of the archaeological sites of Tocrá and Ptolemais (Figure 11a–c). In particular, the urban sprawl continued south and east of the modern town of Tocrá (Figure 11a), so only continuous monitoring could show the future direct impacts on heritage conservation. In Ptolemais, the block feature that was observed in 2015 (Figure 11b) did not appear to have been populated yet with buildings or farming activities in 2017 (Figure 11c), so it had still not developed into a mature stage according to the cycle discussed in Section 3.3 (see also Figure 5). Conversely, we detected clear changes in the surface reflectance along the southern boundary of Apollonia that matched with the development of previously vacant land lots from late 2015 to mid-2017 (Figure 11d,e). Therefore, we could update our assessment of the degree of exposure of these three sites to the impacts due to urban expansion and land use changes.

5. Conclusions

In this paper, we prove that, at the right spatial scale and for features that are a few meters in size, Sentinel-2 can be successfully applied for the condition assessment of heritage sites. The results of our research suggest that the general idea that ‘high resolution’ Earth observation sensors are of limited use compared to sensors operating at ‘very high resolution’ should be reconsidered.

We tested Sentinel-2 on both single localised events (for example, wall collapses) and sequences of recurrent incidents (for example, illegal excavations of archaeological sites), also searching for features of different size, spanning from clusters of meter-scale features (for example, looting holes) to single medium-size urban features (for example, road and building blocks, with dimensions of a few tens of meters). Despite the obvious constraint in the spatial resolution that we acknowledge in the discussion of the results (see Sections 3 and 4), Sentinel-2 allowed for the detection of events of potential relevance for heritage conservation in all the demonstration sites investigated in this paper.

In renowned hotspots, the availability of prior knowledge of the processes to expect and of the baseline condition of the local heritage increases the likelihood for Sentinel-2 to capture textural anomalies or changes of surface reflectance properties that could relate to site disturbances or incidents of potential damage. In this regard, the case studies of Aleppo and Apamea (Syria) provide a clear demonstration.

However, to investigate processes such as urban development that manifest through spatial and temporal patterns of distinctive features, approaches of feature extraction making the best use of the two properties that make Sentinel-2 quite advantageous compared to VHR satellite imagery—the very short revisiting time between two consecutive acquisitions and the large swath width—are promising. These conditions cannot always be achieved using VHR data, as acknowledged in the literature [6]. Sentinel-2 could contribute to addressing this limitation in the framework of a multi-scale condition assessment of heritage sites. For instance, a multi-temporal HR satellite-based condition assessment could provide information to schedule a targeted survey with ad hoc VHR imagery.

The test that we ran on the block features associated with urban sprawl in Cyrenaica (Libya) suggests that Sentinel-2 can well become an extremely useful source of information to screen wider regions and undertake comparative analyses of the condition of different heritage sites.

The approach that we demonstrate in this paper with Sentinel-2 may be applied to other satellite missions, such as Landsat-8. However, it is worth mentioning that the spatial resolution of Landsat-8 is coarser than that of Sentinel-2 (15 m for the panchromatic band and 30 m for the visible to short-wave infrared channels), the revisiting time longer (16 days) and the swath smaller (185 km). Therefore, Sentinel-2 appears to be a good candidate among the current freely accessible space solutions to bridge the gap between HR and VHR optical imagery for the condition assessment of heritage sites.

We can easily anticipate that the implementation of automatic processing chains searching for and extracting features through long time series would be a technological development accelerator towards the systematic use of Sentinel-2 for the condition assessment and monitoring of local to wide areas of study. This automation should provide a complement to the analyst-driven methods

that currently represent the state-of-the-art methods in this field [6] and, ideally, help to mitigate the drawbacks of manual examination. The latter is still a common practice across the archaeological and heritage community. However, although this approach has been proved to lead to reliable and successful mapping results, the community has started to question it from a methodological point of view. The reason is that, at equal conditions of feature visibility and imaging definition, the mapping accuracy achievable strongly depends on the operators' skills and expertise. Casana and Laugier [6] have recently reviewed this aspect specifically based on published exercises.

However, even in situations when operators are fully trained, manual examination remains a time-consuming task and is therefore not sustainable over large areas or for analysis of long time series. It is beyond the scope of this paper to demonstrate how automated processing for the detection and extraction of features should be designed and deployed. It is instead worth spending a few words on the possible technical requirements and recommendations that future research could take into account to develop such automated processing tools. In particular, the preparation of training data that are required to develop an effective machine learning approach appears to be a critical step. The experience gained by the community on different geographic locations is now being translated into reference catalogues of disturbance/threat/damage types and associated databases of documented incidents (see the example presented in [5]). These are repositories from which it is possible to derive categories of simple, distinctive and frequently ubiquitous features and to define, for example, the labelled training data necessary to instruct supervised learning for the automatic recognition of patterns due to a certain process relevant for heritage conservation. Training data that are built according to the above-mentioned criteria (and specifically the distinctiveness of the pattern from other unrelated objects) should help to reduce the occurrence of false positive errors and mismatching. Recent publications presenting the first attempts of automation on feature detection in VHR multi-spectral satellite images have addressed this technical requirement by proposing algorithms searching for repeated featural motifs and building upon existing methods of supervised classification and unsupervised localization [34]. Although these methods have been applied at VHR level, they outline one of the possible directions along which to develop methods suited for HR time series such as those provided by Sentinel-2.

Acknowledgments: Sentinel-2A/B scenes were sourced as open data from the European Space Agency (ESA) Copernicus Open Access Hub. The VHR images (© 2018 DigitalGlobe and CNES/Airbus) were analysed in Google Earth Pro. ASTER GDEM is a product of METI and NASA and was made available by USGS via the LP DAAC Global Data Explorer.

Author Contributions: D.T. and F.C. conceived, designed, and performed the experiments; analysed the data; and wrote the paper.

Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

Table A1. Very high resolution (VHR) optical satellite data (© 2018 DigitalGlobe; * © 2018 CNES/Airbus) accessed through Google Earth covering the UNESCO WHS of Aleppo, Syria and referred to in Section 3.1.

Date of Acquisition					
15/12/2014	06/04/2016	12/06/2016	19/07/2016	18/09/2016	17/11/2016
26/10/2015	15/04/2016	20/06/2016 *	23/07/2016	10/10/2016	27/11/2016
22/11/2015	17/04/2016	21/06/2016	26/07/2016	12/10/2016	24/12/2016
11/12/2015	19/04/2016	24/06/2016	03/08/2016	13/10/2016	
20/03/2016	22/04/2016	27/06/2016 *	06/08/2016	19/10/2016	
23/03/2016	25/04/2016	29/06/2016	11/08/2016	03/11/2016	
29/03/2016 *	24/05/2016	09/07/2016	13/09/2016	08/11/2016	

Table A2. VHR optical satellite data accessed through Google Earth covering the UNESCO TWHS of Apamea (Syria) and referred to in Section 3.2.

Date of Acquisition	Source
20/07/2011	Image © 2018 DigitalGlobe
04/04/2012	Image © 2018 DigitalGlobe
28/09/2012	Image © 2018 DigitalGlobe
06/03/2014	Image © 2018 CNES/Airbus
02/05/2014	Image © 2018 CNES/Airbus

Table A3. VHR optical satellite data (© 2018 DigitalGlobe; * © 2018 CNES/Airbus) accessed through Google Earth covering the UNESCO WHS of Cyrene and the modern town of Shahat (Libya) and referred to in Section 3.3.

Date of Acquisition					
28/07/2009	24/03/2013	22/06/2014	28/02/2015	15/02/2016	06/03/2017
18/10/2010	26/04/2013	08/07/2014	24/06/2015	18/03/2016	10/06/2017
04/03/2011	29/07/2013 *	26/07/2014	08/07/2015	21/03/2016 *	28/06/2017
17/03/2012	09/09/2013	11/08/2014	13/07/2015	22/03/2016 *	05/08/2017
25/09/2012	12/10/2013	11/11/2014	18/07/2015	06/04/2016 *	20/08/2017
14/11/2012	20/01/2014 *	30/11/2014	04/08/2015	05/07/2016	
26/02/2013	21/03/2014	31/01/2015	12/08/2015	04/10/2016	
01/03/2013	16/06/2014	01/02/2015	12/02/2016	05/01/2017	

References

1. Cunliffe, E.; Pedersen, W.; Fiol, M.; Jellison, T.; Saslow, C.; Bjørge, E.; Disclaimer, G.B. *Satellite-Based Damage Assessment to Cultural Heritage Sites in Syria Contributors*; UNITAR/UNOSAT: Geneva, Switzerland, 2014; Available online: http://unosat.web.cern.ch/unosat/unitar/downloads/chs/FINAL_Syria_WHS.pdf (accessed on 20 August 2015).
2. The Emergency Safeguarding of the Syrian Cultural Heritage Project. Available online: <https://en.unesco.org/syrian-observatory/emergency-safeguarding-syrian-cultural-heritage-project> (accessed on 31 January 2018).
3. Danti, M.; Branting, S.; Penacho, S. The American Schools of Oriental Research Cultural Heritage Initiatives: Monitoring Cultural Heritage in Syria and Northern Iraq by Geospatial Imagery. *Geosciences* **2017**, *7*, 95. [CrossRef]
4. Association for the Protection of Syrian Archaeology (APSA2011). Available online: <http://apsa2011.com/apsanew/about-us/> (accessed on 31 January 2018).
5. Rayne, L.; Bradbury, J.; Mattingly, D.; Philip, G.; Bewley, R.; Wilson, A. From Above and on the Ground: Geospatial Methods for Recording Endangered Archaeology in the Middle East and North Africa. *Geosciences* **2017**, *7*, 100. [CrossRef]
6. Casana, J.; Laugier, E.J. Satellite imagery-based monitoring of archaeological site damage in the Syrian civil war. *PLoS ONE* **2017**, *12*, e0188589. [CrossRef] [PubMed]
7. Agapiou, A.; Lysandrou, V.; Hadjimitsis, D. Optical Remote Sensing Potentials for Looting Detection. *Geosciences* **2017**, *7*, 98. [CrossRef]
8. Overview on High Resolution Optical Satellite Systems. Available online: <http://dib.joanneum.ac.at/edtr/satsys.html> (accessed on 31 January 2018).
9. Heege, T. DSD-INT 2015—Satellite Based Near-Real Time Information Services for Aquatic Systems. Available online: https://www.slideshare.net/Delft_Software_Days/dsd-int-2015-satellite-based-nearreal-time-information-services-for-aquatic-systems-thomas-heege (accessed on 31 January 2018).
10. Banerjee, R.; Srivastava, P.K. Reconstruction of contested landscape: Detecting land cover transformation hosting cultural heritage sites from Central India using remote sensing. *Land Use Policy* **2013**, *34*, 193–203. [CrossRef]

11. Lasaponara, R.; Murgante, B.; Elfadaly, A.; Qelichi, M.M.; Shahraki, S.Z.; Wafa, O.; Attia, W. Spatial open data for monitoring risks and preserving archaeological areas and landscape: Case studies at Kom el Shoqafa, Egypt and Shush, Iran. *Sustainability* **2017**, *9*, 572. [CrossRef]
12. Introducing Sentinel-2/Sentinel-2/Copernicus/Observing the Earth/Our Activities/ESA. Available online: http://www.esa.int/Our_Activities/Observing_the_Earth/Copernicus/Sentinel-2/Introducing_Sentinel-2 (accessed on 31 January 2018).
13. Sentinel-2—Data Products—Sentinel Handbook. Available online: <https://sentinels.copernicus.eu/web/sentinel/missions/sentinel-2/data-products> (accessed on 31 January 2018).
14. Drusch, M.; Del Bello, U.; Carlier, S.; Colin, O.; Fernandez, V.; Gascon, F.; Hoersch, B.; Isola, C.; Laberinti, P.; Martimort, P.; et al. Sentinel-2: ESA's Optical High-Resolution Mission for GMES Operational Services. *Remote Sens. Environ.* **2012**, *120*, 25–36. [CrossRef]
15. Agapiou, A.; Alexakis, D.D.; Sarris, A.; Hadjimitsis, D.G. Evaluating the potentials of sentinel-2 for archaeological perspective. *Remote Sens.* **2014**, *6*, 2176–2194. [CrossRef]
16. Bini, M.; Isola, I.; Zanchetta, G.; Ribolini, A.; Ciampalini, A.; Baneschi, I.; Mele, D.; D'Agata, A.L. Identification of Leveled Archeological Mounds (Höyük) in the Alluvial Plain of the Ceyhan River (Southern Turkey) by Satellite Remote-Sensing Analyses. *Remote Sens.* **2018**, *10*, 241. [CrossRef]
17. Geospatial Technologies and Human Rights Project—Scientific Responsibility, H.R. and L. P. of the A. A. for the A. of S. (AAAS). Conflict in Aleppo, Syria: A Retrospective. Available online: https://www.aaas.org/aleppo_retrospective (accessed on 31 January 2018).
18. Geospatial Technologies and Human Rights Project—Scientific Responsibility, H. R. and L. P. of the A. A. for the A. of S. (AAAS). Ancient History, Modern Destruction: Assessing the Current Status of Syria's World Heritage Sites Using High-Resolution Satellite. Available online: <https://www.aaas.org/page/ancient-history-modern-destruction-assessing-current-status-syria-s-world-heritage-sites-using> (accessed on 31 January 2018).
19. Casana, J. Satellite Imagery-Based Analysis of Archaeological Looting in Syria. *Near East. Archaeol.* **2015**, *78*, 142. [CrossRef]
20. Tapete, D.; Cigna, F.; Donoghue, D.N.M. "Looting marks" in space-borne SAR imagery: Measuring rates of archaeological looting in Apamea (Syria) with TerraSAR-X Staring Spotlight. *Remote Sens. Environ.* **2016**, *178*. [CrossRef]
21. Sharpe, E. Farmers bulldoze ancient tombs at Cyrene to sell plots to developers. In *Heritage at Risk; World Report 2011–2013 on Monuments and Sites in Danger*; Machat, C., Petzet, M., Ziesemer, J., Eds.; Bäßler Verlag: Berlin, Germany, 2013; pp. 92–93. ISBN 978-3-930388-24-0. Available online: <http://www.icomos.de/admin/ckeditor/plugins/alphamanager/uploads/pdf/HatR2011-13.pdf> (accessed on 31 January 2018).
22. Abdulkariem, A.; Bennett, P. Libyan Heritage under threat: The case of Cyrene. *Libyan Stud.* **2014**, *45*, 155–161. [CrossRef]
23. Kenrick, P.M.; Buzaian, A. *Libya Archaeological Guides: Cyrenaica*; Silphium Press: London, UK, 2013; ISBN 9781900971140.
24. Sentinel-2A Acquisition Plans—Sentinel Online. Available online: <https://sentinel.esa.int/web/sentinel/missions/sentinel-2/acquisition-plans> (accessed on 31 January 2018).
25. Sentinel-2 L2A Products Available on Sentinel Hub. Available online: <https://www.sentinel-hub.com/blog/sentinel-2-l2a-products-available-sentinel-hub> (accessed on 31 January 2018).
26. Park, H.; Choi, J.; Park, N.; Choi, S. Sharpening the VNIR and SWIR bands of Sentinel-2A imagery through modified selected and synthesized band schemes. *Remote Sens.* **2017**, *9*, 80. [CrossRef]
27. Cerra, D.; Plank, S.; Lysandrou, V.; Tian, J. Cultural Heritage sites in danger-Towards automatic damage detection from space. *Remote Sens.* **2016**, *8*, 781. [CrossRef]
28. Thiqa Agency. Youtube Video. Available online: <https://www.youtube.com/watch?v=khhl-e5SMYE> (accessed on 31 January 2018).
29. APSA2011 Aleppo: The Actual State of the Aleppo Citadel 20.08.2016—APSA. Available online: <http://apsa2011.com/apsanew/aleppo-08-2016/> (accessed on 31 January 2018).
30. Danti, M.D.; Cuneo, A.; Penacho, S.; Al-Azm, A.; Rouhani, B.; Gabriel, M.; Kaercher, K. ASOR Cultural Heritage Initiatives Weekly Report 105–106 (August 3, 2016–August 18, 2016)—ASOR Cultural Heritage Initiatives. Available online: <http://www.asor-syrianheritage.org/asor-cultural-heritage-initiatives-weekly-report-105-106-august-3-2016-august-18-2016/> (accessed on 31 January 2018).

31. Danti, M.D.; Al-Azm, A.; Cuneo, A.; Penacho, S.; Rouhani, B.; Gabriel, M.; Kaercher, K.; O'Connell, J. ASOR Cultural Heritage Initiatives Weekly Report 97–98 (June 8, 2016–June 21, 2016)—ASOR Cultural Heritage Initiatives, 2016. Available online: <http://www.asor-syrianheritage.org/asor-cultural-heritage-initiatives-weekly-report-97-98-june-8-2016-june-21-2016/> (accessed on 31 January 2018).
32. Syria Civil War: Bomb Damages Aleppo's Ancient Citadel—BBC News, 12 July 2015. Available online: <http://www.bbc.com/news/world-middle-east-33499609> (accessed on 8 February 2018).
33. Danti, M.D.; Ali, C.; Cuneo, A.; Kaercher, K.; Gordon, L.B.; Gessel, E. Van ASOR Cultural Heritage Initiatives (CHI): Planning for Safeguarding Heritage Sites in Syria and Iraq 1 NEA-PSHSS-14-001 Weekly Report 49—14 July, 2015. pp. 7–11. Available online: <http://www.asor-syrianheritage.org/syrian-heritage-initiative-weekly-report-49-july-14-2015/> (accessed on 31 January 2018).
34. Bowen, E.F.W.; Tofel, B.B.; Parcak, S.; Granger, R. Algorithmic Identification of Looted Archaeological Sites from Space. *Front. ICT* **2017**, *4*, 4. [CrossRef]



© 2018 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<http://creativecommons.org/licenses/by/4.0/>).